

Evaluation of Homestake Mining Company's Tailings Flushing Program and Seepage of Contaminants from the Large Tailings Pile

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February 16, 2014

1) Introduction

This report evaluates the effectiveness of Homestake Mining Company's (HMC) large tailings pile (LTP) flushing program, and HMC's estimates of future seepage from the LTP. It also presents an alternate estimate of seepage and its effect on groundwater quality. This report was produced for the Multicultural Alliance for a Safe Environment (MASE).

The LTP is about 5.5 miles north of Milan, New Mexico, at HMC's former uranium mill. The mill operated from 1958 to 1990 and processed uranium ore from several local mines.¹ The LTP covers 234 acres and contains about 21 million tons of tailings². It is about 4400 feet long, 2200 feet wide³, and 70 feet to 90 feet tall⁴. Additional information on the LTP is given in appendix 1.

The water (tailings solution) in the LTP contains high concentrations of contaminants including molybdenum, selenium, and uranium⁵. The tailings solution seeps through the LTP and has contaminated the underlying alluvial aquifer, as well as the upper, middle, and lower Chinle aquifers⁶.

The purpose of the flushing program is to force the tailings solution to extraction wells or drains where it can be collected and treated. Flushing water is pumped into the LTP by approximately 190 injection wells, and pumped out by approximately 150 extraction wells⁷. Water that isn't captured by the extraction wells seeps through the LTP where it is either collected by toe drains or enters the underlying alluvial aquifer. The flushing program began in 2000⁸. HMC plans to continue it through 2014⁹.

The flushing program has removed contaminants from the LTP. But, has this made a practical difference? And, will the LTP cease to be a significant source of groundwater contaminants after flushing ends? Based on currently available information, the answer to both of these questions appears to be no. The analyses that led to these conclusions are presented below.

¹ HMC, 2012a, page 1-1.

² HMC, 2012a, page 2-3.

³ HMC, 2013a, figure 2.1-9.

⁴ HMC, 2012a, page 2-3.

⁵ Arcadis, 2012, table 4.

⁶ HMC, 2012a, figures 4.2.3-1 and 4.2.3-9, and page 5-5; and HMC, 2013a, page 1.1-2. The contaminants include molybdenum, selenium, uranium, chloride sulfate, and TDS (HMC, 2012a, page 4-2).

⁷ HMC, 2012a, page 5-6.

⁸ HMC, 2012a, page 6-2 and figure 6.2-1; and HMC, 2013b, page 9-33.

⁹ HMC, 2012a, page 6-2 and figure 6.2-1; and HMC, 2013b, page 9-33.

2) Mass of uranium in LTP

Uranium in the LTP exists in three forms:

- Uranium in the tailings solution. This uranium is dissolved in the water that is present in pore spaces between tailings grains. It is transported along with the tailings solution as it seeps through the LTP. This is the most mobile form of uranium.
- Uranium adsorbed to the surface of tailings grains. This uranium is attached to tailings grains by electrical forces. The force of attachment may be weak or strong. Weakly adsorbed uranium can readily become detached and dissolve into the tailings solution. Strongly adsorbed uranium may also be detached, but not as readily as weakly adsorbed uranium. The weakly adsorbed uranium is more mobile than the strongly adsorbed uranium.
- Uranium in minerals. This uranium remains in ore minerals that were not completely leached by the milling process. The uranium may be slowly released as the minerals are dissolved by tailings solution, or by rainwater that infiltrates through the LTP. This is the least mobile form of uranium.

In this report, the dissolved and weakly adsorbed uranium are referred to as mobile uranium.

HMC has underestimated the mass of uranium in the LTP. This underestimate is based, in part, on an incorrect assumption regarding the form of uranium in the LTP. HMC assumes that most of the uranium exists in the dissolved form, and that little is adsorbed to tailings grains¹⁰. However, the data in table 1 show that after flushing¹¹, ten times more uranium exists in the adsorbed form than in the dissolved form. Table 1 also contains data for molybdenum and selenium.

¹⁰ HMC 2010a, pages 6 and 11.

¹¹ The data in table 1 are from the area of the LTP where flushing was stopped for the rebound evaluation (Arcadis, 2012, page 3).

Table 1
Concentrations of Mobile Contaminants
Remaining in the LTP after Flushing¹²

Contaminant	Dissolved in tailings solution (mg/kg)	Weakly adsorbed to tailings grains (mg/kg)¹³	Total dissolved plus weakly adsorbed (mg/kg)
Molybdenum	16.83	6.77	23.60
Selenium	0.08	49.92	50.00
Uranium	3.63	37.33	40.96

The values in table 1 were used to estimate the mass of mobile uranium in the LTP, as well as the masses molybdenum and selenium. These are shown in table 2. The calculations performed to estimate the masses are shown in appendix 2.

Table 2
Masses of Mobile Contaminants in the LTP

Contaminant	Mass dissolved (mg)	Mass weakly adsorbed (mg)	Total mobile mass (mg)
Molybdenum	3.2×10^{11}	1.3×10^{11}	4.5×10^{11}
Selenium	1.5×10^9	9.5×10^{11}	9.5×10^{11}
Uranium	6.9×10^{10}	7.1×10^{11}	7.8×10^{11}

Table 2 is based on a sample collected in 2012. For 2012, HMC estimated the amount of dissolved uranium in the LTP to be 8.0×10^8 mg (1757 lbs)¹⁴. However, as shown in the table, 6.9×10^{10} mg (150,000 lbs) uranium existed in the dissolved form, and an additional 7.1×10^{11} mg (1,560,000 lbs) existed in the weakly adsorbed form. Thus, the mass of mobile uranium in the LTP was 7.8×10^{11} mg (1,710,000 lbs). This is more than 900 times greater than HMC's estimate.

The total mass of uranium in the LTP is the sum of mobile uranium, plus strongly adsorbed uranium, plus uranium in minerals. The total mass of uranium is given in table 3. The calculations performed to estimate the mass are shown in appendix 2.

¹² Flushing was stopped in a portion of the LTP in May of 2011 as part of the rebound evaluation (Arcadis, 2012, page 3). The data in this table are from core #1 (Arcadis, 2012, table 4). The core was collected in March 2012 in a saturated zone of relatively low permeability tailings (Arcadis, 2012, page 6). It should be noted that the tailings are highly variable and core #1 may not be representative of the entire LTP. But, these are the only tailings solution values available (tailings solution could not be extracted from the second core). Thus, they will be assumed to be representative until additional samples become available.

¹³ Concentration of weakly adsorbed contaminant calculated by subtracting tailings solution concentration from extraction 1 concentration (Arcadis, 2012, pages 7 and 8, and table 4).

¹⁴ HMC, 2012a, appendix G, attachment A, table A-3.

Table 3
Total Masses of Contaminants in the LTP¹⁵

Contaminant	Mass (mg)
Molybdenum	9.5×10^{11}
Selenium ¹⁶	1.8×10^{12}
Uranium	4.5×10^{12}

3) Effectiveness of Flushing

A recent estimate of the amount of uranium flushed from the LTP was not found. However, HMC has stated that 7.7×10^{10} mg (170,000 lbs) of uranium was removed from the LTP between 1992 and 2009, and that the rate of removal has been relatively steady.¹⁷ Assuming this is correct, uranium is being removed at a rate of about 4.3×10^9 mg/yr (9500 lbs/yr). Then, from 2000 through 2013, the flushing program removed about 6.0×10^{10} mg (132,000 lbs) of uranium. This is about eight percent of the mobile uranium (1,710,000 lbs), and one percent of the total uranium (9,900,000 lbs) in the LTP. Figure 1 compares the amount of uranium removed by flushing with the amount of mobile uranium remaining in the LTP.

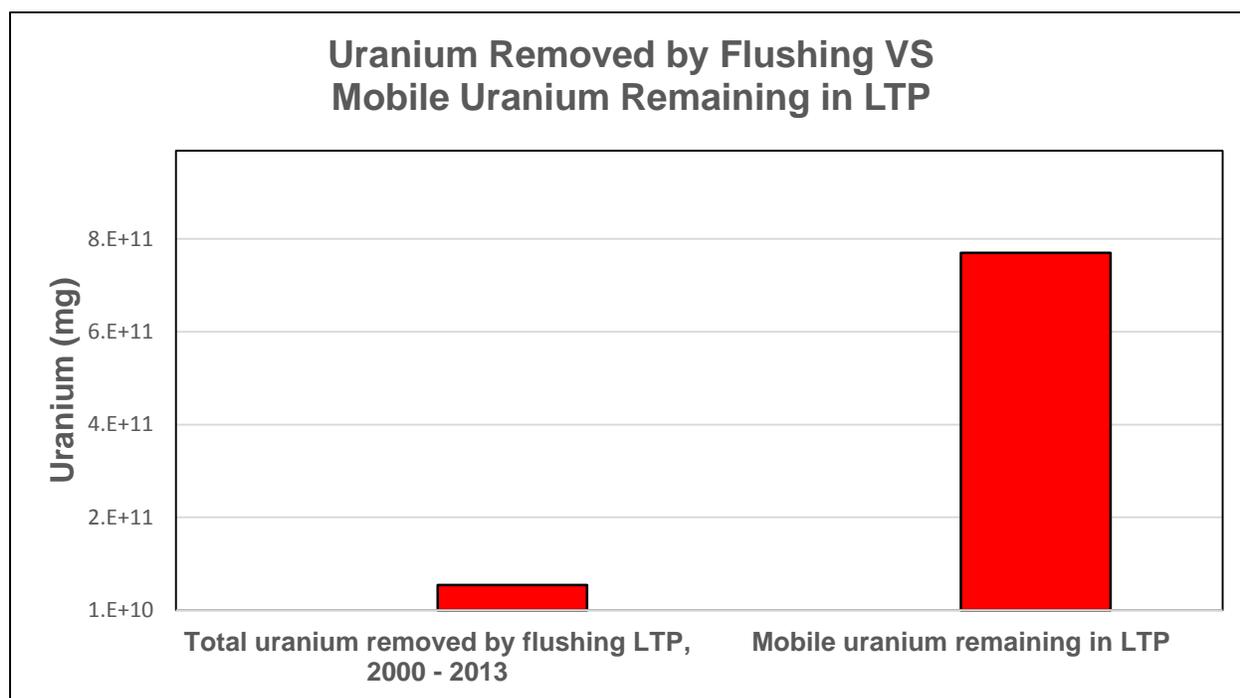


Figure 1
Uranium Removed by Flushing VS Mobile Uranium Remaining in LTP

¹⁵ Data for core #1, Arcadis, 2012, table 4.

¹⁶ Does not include mass in silicate minerals. Value not reported for selenium (Arcadis, 2012, table 4).

¹⁷ HMC 2010a, page 12, and figure 5.

4) Rate of seepage from LTP

Seepage of tailings solution from the LTP has contaminated the underlying groundwater. This seepage will continue for the foreseeable future. The amount of contamination it causes will be proportional to the rate of seepage and the concentration of contaminants in the seepage.

HMC used a saturated/unsaturated flow model (VADOSE/W) to estimate the rate of seepage from the LTP¹⁸. The input required by the model includes initial conditions (e.g., moisture content), boundary conditions (e.g., recharge rate), and soil water characteristic (SWC) data¹⁹. HMC has not reported the input it used in the model²⁰. In addition, HMC does not appear to have measured SWC data for samples from the LTP²¹. The lack of LTP-specific SWC data casts doubt on the reliability of HMC's seepage estimates.

Due to the lack of the information cited above, it was not possible to directly evaluate HMC's seepage rate modeling. Therefore, an alternate estimate of seepage rates was performed. This was done using the model VS2DTI. A description on the modeling is contained in appendix 3.

Figure 2 shows the results of the seepage rate modeling performed for this report and the results of HMC's seepage rate modeling²². Depending on the time, the modeling done for this report produced estimates of seepage rates that are two to 12 times higher than the rates estimated by HMC.

¹⁸ HMC, 2012a, appendix G, attachment A, page G.A-1.

¹⁹ SWC data describe the relationship between moisture content and matric suction. The SWC data are used to determine the parameters of SWC equations, e.g., van Genuchten, Brooks-Corey. These parameters are required input for saturated/unsaturated flow models such as VADOSE/W. See Tuller and Or, 2003 for a discussion of SWC data and equations.

²⁰ HMC, 2012a, appendix G.

²¹ SWC data were not presented in either the *Updated Corrective Action Program* (HMC 2012a), or the *Decommissioning and Reclamation Plan* (HMC 2013b).

²² HMC, 2012a, appendix G, attachment A, tables A-1 and A-3.

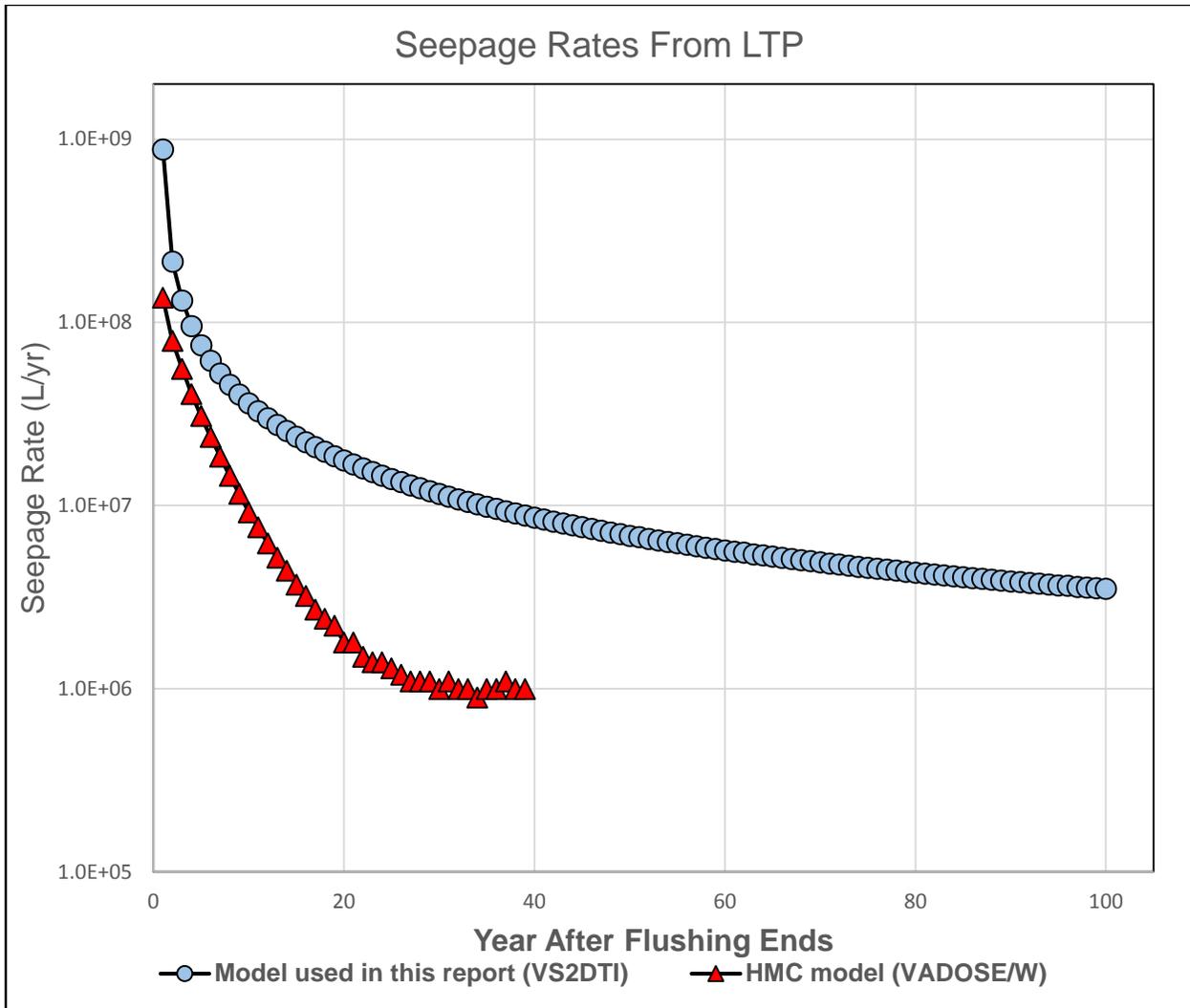
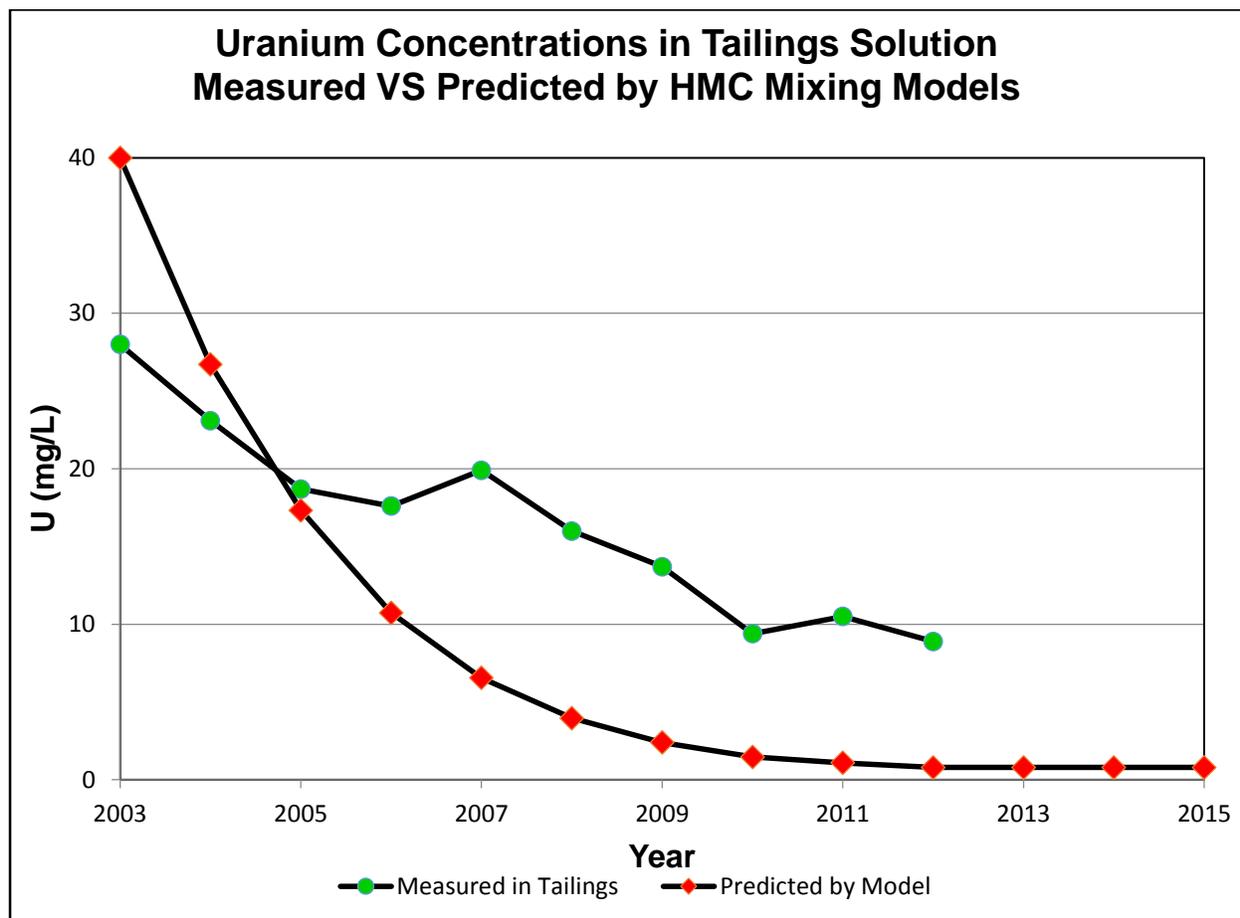


Figure 2
Comparison of Seepage Rate Estimates

Because both HMC's model and the model used for this report were developed without LTP-specific SWC data, the reliability of the seepage estimates produced by these models is suspect.

5) Concentration of uranium in tailings solution

HMC used mixing models (OMM and RMM)²³ to estimate the concentration of uranium in the tailings solution seeping from the LTP. However, the mixing models have significantly underestimated uranium concentrations (figure 3). For example, for 2012 the models predicted a uranium concentration 0.79 mg/L, while the measured concentration was 8.9 mg/L²⁴.



**Figure 3
Comparison of Measured and Predicted Uranium Concentrations**

²³ Original mixing model (OMM) and reformulated mixing model (RMM) (HMC, 2012a, appendix G, attachment A, pages G.A-5 and G.A-10).

²⁴ HMC, 2013a, table 2.1-1; and HMC 2012a, appendix G, attachment A, table A-3. It should be noted that the measured values in figure 3 are based on samples collected from wells in the LTP. These values are different than the uranium value given in table 1. The values in figure 3 are expressed as the mass of uranium in a liter of tailings solution (mg/L). The value in table 1 is expressed as the mass of uranium in a kilogram of tailings (mg/kg). HMC converted the original tailings solution concentration to an equivalent tailings concentration by dividing it by 3.4. This resulted in a tailings concentration of 3.63 mg/kg. The original liquid concentration of uranium was 12.35 mg/L (Arcadis, 2012, table 4).

6) Future contamination caused by seepage from LTP

The information presented above, along with estimates of groundwater flow in the alluvial aquifer, were used to estimate future groundwater contamination caused by the seepage of tailings solution from the LTP (figure 4).

The estimates shown in figure 4 are only for contamination caused by seepage after flushing ends. They did not account for groundwater contamination that existed before the end of flushing. The uranium concentrations are for alluvial groundwater at the down-gradient edge of the LTP. The calculations that produced these estimates are described in appendix 4.

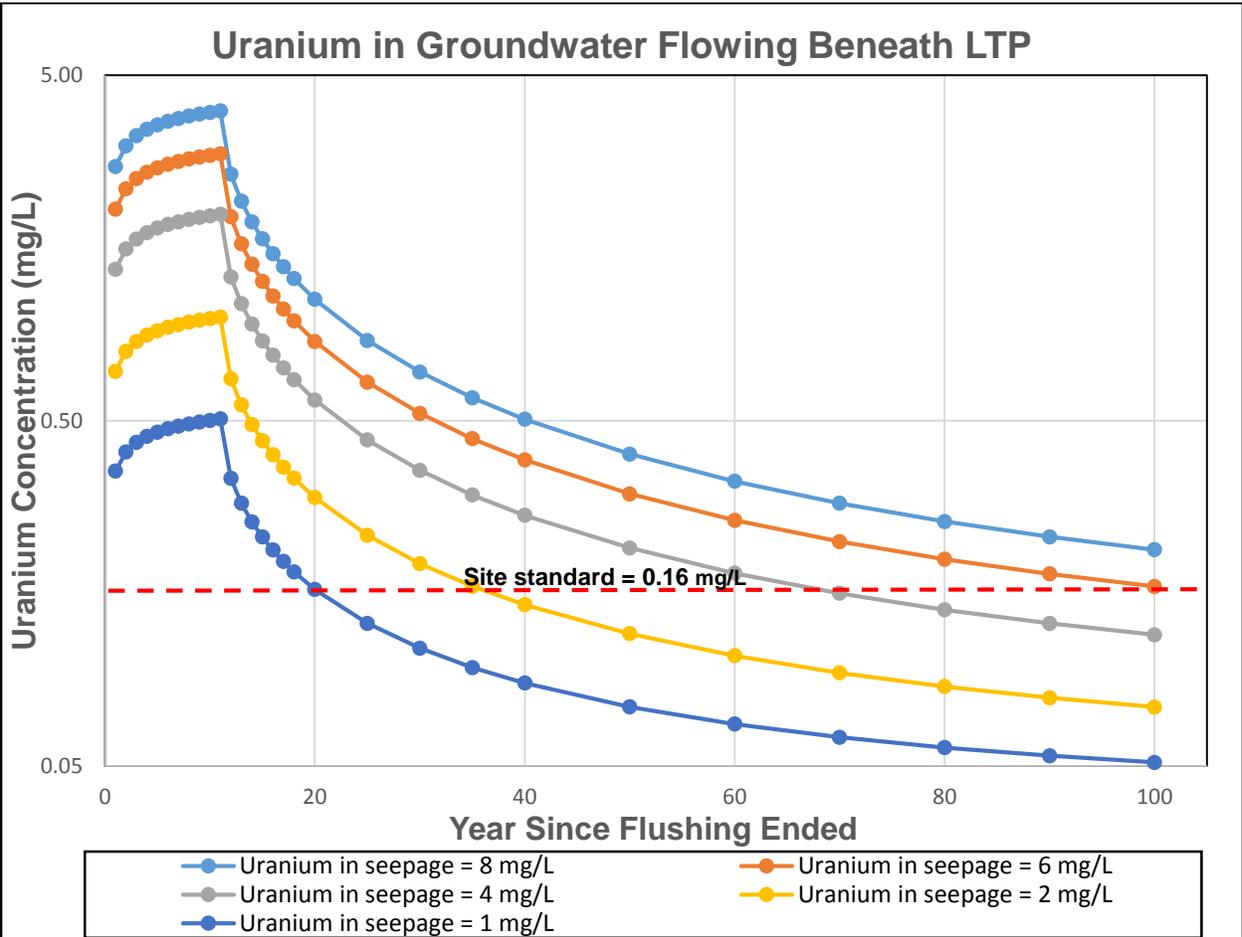


Figure 4
Uranium Concentration in Alluvial Groundwater at Down-Gradient Edge of LTP

The model predicts that the LTP will continue to contaminate groundwater in the underlying alluvial aquifer for decades after flushing ends. If the uranium concentration in the seepage is 1 mg/L, the uranium concentration in the alluvial aquifer will exceed the

site standard (0.16 mg/L)²⁵ for 20 years after flushing ends. If the uranium concentration in the seepage is 8 mg/L, the uranium concentration in the alluvial aquifer will exceed the standard for more than 100 years after flushing ends.

7) Mass of mobile uranium remaining in LTP

The mass of uranium that will seep from the LTP is small compared to the amount of mobile uranium in the LTP. Figure 5 shows the amount of mobile uranium remaining in the LTP if the seepage is assumed to contain 8 mg/L uranium²⁶. One hundred years after flushing ends, approximately 98% of the mobile uranium (7.6×10^{11} mg, 1,670,000 lbs) will remain in the LTP. The calculations performed to estimate the mass remaining in the LTP are described in appendix 5.

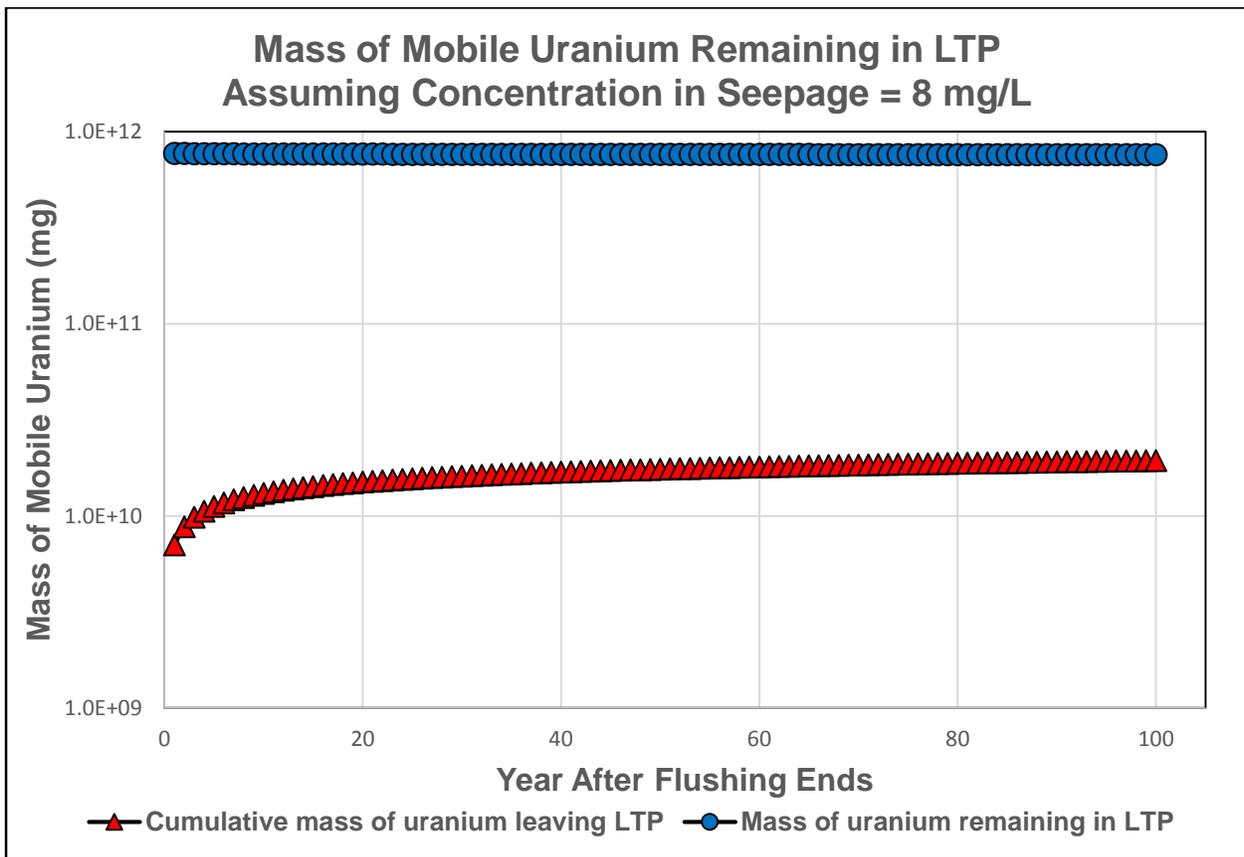


Figure 5
Mobile Uranium remaining in LTP

²⁵ HMC, 2013a, table 1.1-1.

²⁶ 8 mg/L is the highest seepage concentration that was used to estimate the groundwater concentrations in figure 4.

8) Summary, Conclusions, and Recommendations

1. HMC has underestimated the mass of uranium in the LTP. HMC estimated the mass of uranium to be 8.0×10^8 mg (1757 lbs). However, available data indicate the LTP contains 7.8×10^{11} mg of mobile uranium (1,710,000 lbs). This is more than 900 times greater than HMC's estimate. (section 2)
2. HMC has measured the mass of each form of uranium (mass in tailings solution, mass adsorbed, mass in minerals) in only one core sample. This core may not be representative of the entire LTP. HMC should collect additional core samples. Data from the cores should be used to derive a more accurate estimate of the masses of each form uranium in the LTP. (section 2)
3. The flushing program has not significantly reduced the amount of mobile uranium in the LTP. Since 2000 approximately 6.0×10^{10} mg (132,000 lbs) has been flushed from the LTP. This represents about 8% of the mobile uranium, and 1% of the total uranium in the LTP. (section 3)
4. HMC's seepage rate modeling could not be directly evaluated because much of the input data were not provided. In addition, HMC does not appear to have collected LTP-specific SWC data. Therefore, an alternate estimate of seepage, using the model VS2DTI, was performed for this report. This modeling resulted in higher estimates of seepage than HMC obtained. For example, ten years after flushing ends, HMC's model estimated a seepage rate of 9.2×10^6 L/yr. The modeling done for this report estimated a rate of 3.6×10^7 L/yr, approximately four times greater than HMC's estimate. (section 4)
5. The lack of LTP-specific SWC data casts doubt on the seepage estimates produced by HMC's model, as well as those produced by the model developed for this report. HMC should collect LTP-specific SWC data. These data should be used to develop models that will produce more reliable estimates of seepage rates. (section 4)
6. The mixing models used by HMC underestimate the concentration of uranium in the tailings solution. For 2012, the mixing models predicted a uranium concentration 0.79 mg/L. The measured concentration was 8.9 mg/L. (section 5)
7. The modeling performed for this report indicates that the LTP will continue to contaminate groundwater in the underlying alluvial aquifer for decades after flushing ends. If the uranium concentration in the seepage is 1 mg/L, the uranium concentration in the alluvial aquifer will exceed the site standard (0.16 mg/L) for 20 years after flushing ends. If the uranium concentration in the seepage is 8 mg/L, the uranium concentration in the alluvial aquifer will exceed the standard for more than 100 years after flushing ends. (section 6)

8. The LTP will contain a large amount of mobile uranium for the foreseeable future. One hundred years after flushing ends, approximately 98% of the mobile uranium will remain in the LTP.

References

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Appendix 1

LTP and the HMC Mill

Uranium milling began in 1958 and ended in 1990²⁷.

LTP covers approximately 234 acres²⁸.

Height of LTP²⁹: 70 – 90 ft.

Mass of tailings in LTP³⁰: 2.105×10^7 tons = 1.9×10^{10} kg

Tailings classification: SP to SM³¹ (sand to silty sand)³².

Permeability of tailings³³: geometric mean = 120 ft/yr (1.16×10^{-4} cm/s), range = 52 ft/yr – 362 ft/yr (5.0×10^{-5} cm/s – 3.5×10^{-4} cm/s).

Tailings flushing program began in 2000³⁴ and is expected to continue through 2014³⁵. The extraction wells and toe drains are scheduled to operate through 2016³⁶.

Tailings flushing rate has ranged from 61 gpm to 302 gpm, and the average has been 234 gpm³⁷.

Principle uranium minerals in the ore: coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) uraninite (UO_2), tyuyamunite ($Ca(UO_2)_2(VO_4)_2 \cdot 5-8 H_2O$), and carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3 H_2O$).³⁸

Ore grade 0.05 to 0.30 percent U_3O_8 ³⁹.

²⁷ HMC, 2012a, page 2-2.

²⁸ HMC, 2012a, page 2-3.

²⁹ HMC, 2012a, page 2-3.

³⁰ HMC, 2012a, page 2-3. Note: the text states that 11.41 million tons of tailings were generated under AEC contracts and 10.89 million tons were generated under commercial contracts. This adds up to 22.3 million tons, not 21.05 million tons.

³¹ HMC, 2012a, appendix B, attachment B-1, page 3-2. Note: all of the tailings samples were collected near the perimeter of the LTP (HMC, 2012a, appendix B, attachment B-1, tables 2 and 3, and figures 2 through 10). Thus, the slime portion of the tailings, which tend to be deposited away from the perimeter, may not be well represented by the samples (HMC, 2012a, appendix B, attachment B-1, page 1-1).

³² USGS, 2008, page 9.

³³ HMC, 2012a, appendix B, attachment B-1, table 2. Note: only data from the falling head tests in piezometers are used. Constant head laboratory tests were performed on remolded samples that probably do not represent undisturbed conditions in the LTP (HMC, 2012a, appendix B, attachment B-1, page 3-4).

³⁴ HMC, 2012a, page 2-7.

³⁵ HMC, 2013b, page 9-33.

³⁶ HMC, 2013b, page 9-33.

³⁷ For years 2000 through 2010 (HMC, 2012a, appendix F, table F-3).

³⁸ HMC, 2012a, appendix B, page B-1.

³⁹ HMC, 2012a, page 2-2.

Appendix 2

Calculation of Contaminant Masses

Mobile contaminants

The mass of mobile contaminants in the LTP is:

$$M_m = M_{ltp} \times C_m$$

Where:

M_m = mass of mobile contaminant in LTP

M_{ltp} = mass of tailings in LTP: 2.1×10^7 tons⁴⁰ = 1.9×10^{10} kg

C_m = concentration of mobile contaminant in LTP (table A2-1⁴¹)

Molybdenum: $M_m = 1.9 \times 10^{10}$ kg x 23.60 mg/kg = 4.5×10^{11} mg

Selenium: $M_m = 1.9 \times 10^{10}$ kg x 50.00 mg/kg = 9.5×10^{11} mg

Uranium: $M_m = 1.9 \times 10^{10}$ kg x 40.96 mg/kg = 7.8×10^{11} mg

Table A2-1
Concentrations of Mobile Contaminants
Remaining in the LTP after Flushing⁴²

Contaminant	Dissolved in tailings solution (mg/kg) ⁴³	Weakly adsorbed to tailings solids (mg/kg) ⁴⁴	Total dissolved plus weakly adsorbed (mg/kg)
Molybdenum	16.83	6.77	23.60
Selenium	0.08	49.92	50.00
Uranium	3.63	37.33	40.96

⁴⁰ HMC, 2012a, page 2-3.

⁴¹ Same as table 1 in body of report.

⁴² Data for core #1, Arcadis, 2012, table 4.

⁴³ HMC converted the original liquid (pore water) concentration (mg/L) to an equivalent solid concentration (mg/kg) by dividing liquid concentration by 3.4. The original liquid concentrations of molybdenum, selenium, and uranium were 57.22 mg/L, 0.28 mg/L, and 12.35 mg/L, respectively.

⁴⁴ Concentration of weakly adsorbed contaminant calculated by subtracting pore solution concentration from extraction 1 concentration.

The masses of dissolved and adsorbed contaminants may also be calculated as above:

Dissolved

$$\text{Molybdenum (dissolved)} = 1.9 \times 10^{10} \text{ kg} \times 16.83 \text{ mg/kg} = 3.2 \times 10^{11} \text{ mg}$$

$$\text{Selenium: (dissolved)} = 1.9 \times 10^{10} \text{ kg} \times 0.08 \text{ mg/kg} = 1.5 \times 10^9 \text{ mg}$$

$$\text{Uranium: (dissolved)} = 1.9 \times 10^{10} \text{ kg} \times 3.63 \text{ mg/kg} = 6.9 \times 10^{10} \text{ mg}$$

Weakly adsorbed

$$\text{Molybdenum (adsorbed)} = 1.9 \times 10^{10} \text{ kg} \times 6.77 \text{ mg/kg} = 1.3 \times 10^{11} \text{ mg}$$

$$\text{Selenium: (adsorbed)} = 1.9 \times 10^{10} \text{ kg} \times 49.92 \text{ mg/kg} = 9.5 \times 10^{11} \text{ mg}$$

$$\text{Uranium: (adsorbed)} = 1.9 \times 10^{10} \text{ kg} \times 37.33 \text{ mg/kg} = 7.1 \times 10^{11} \text{ mg}$$

Total contaminants

The total mass of contaminants in the LTP is:

$$M_m = M_{ltp} \times C_t$$

Where:

M_m = total mass of contaminant in LTP

M_{ltp} = mass of tailings in LTP: $2.1 \times 10^7 \text{ tons}^{45} = 1.9 \times 10^{10} \text{ kg}$

C_t = concentration of contaminant in LTP⁴⁶

$$\text{Molybdenum: } M_m = 1.9 \times 10^{10} \text{ kg} \times 50 \text{ mg/kg} = 9.5 \times 10^{11} \text{ mg}$$

$$\text{Selenium}^{47}: M_m = 1.9 \times 10^{10} \text{ kg} \times 96 \text{ mg/kg} = 1.8 \times 10^{12} \text{ mg}$$

$$\text{Uranium: } M_m = 1.9 \times 10^{10} \text{ kg} \times 235 \text{ mg/kg} = 4.5 \times 10^{12} \text{ mg}$$

⁴⁵ HMC, 2012a, page 2-3.

⁴⁶ Data for core #1, Arcadis, 2012, table 4.

⁴⁷ Does not include mass of selenium in silicate minerals. Value not reported for selenium (Arcadis, 2012, table 4).

Appendix 3

Calculation of Seepage Rates

The model VS2DTI was used to estimate seepage rates from the LTP. VS2DTI simulates flow in variably saturated porous media. A description on the model can be found in Hsieh, et al., 2000.

Seepage was simulated through two material types, sand tailings and slime tailings. The sands were represented by a silty clay and the slimes by a clay. The properties of these materials are shown in table A3-1.

Table A3-1
Properties of Materials used to Model Seepage Rates from LTP⁴⁸

Material	Saturated Hydraulic Conductivity (ft/yr)	Porosity	Residual moisture content	Van Genuchten α (1/ft)	Van Genuchten β
Silty clay	100 ⁴⁹	0.47	0.163	0.701	1.39
Clay	10 ⁵⁰	0.51	0.102	0.640	1.20

Each material was simulated as a column 70 feet thick. The column was represented by 35 cells, each one foot wide and two feet thick.

At the beginning of the simulation, the upper ten feet of the column was unsaturated and the lower 60 feet was saturated.

The recharge rate through the top of the column was 0.01 feet per year⁵¹.

The model output (ft³/ft²-yr) was converted to a volumetric rate by assuming the area of the LTP to be 200 acres.

The simulation time was 100 years, beginning with the year after flushing ends.

⁴⁸ All properties, except hydraulic conductivities, were taken from Tuller and Or, 2003, table 1.

⁴⁹ HMC, 2012a, appendix B, attachment B-1, table 2.

⁵⁰ Assumed to be an order of magnitude lower than sand tailings.

⁵¹ This is approximately 1% of the average annual precipitation (10.48 in/yr, HMC, 2012a, page 2-1 and figure 2.1-2). According to HMC, the areal recharge rate is 0.5 in/yr, or about 5% of annual precipitation (HMC 2012a, Appendix A, page A-3, and appendix D, page D-1, and table D-1). According to Stothoff, natural recharge in this climate is typically no more than a few percent of annual precipitation (Stothoff, 2012, section 7.3.7 Site 7—Grants).

Each material was modeled separately⁵² and the seepage rates combined by assuming that the LTP was composed of 50% sand tailings and 50% slime tailings. This is illustrated by the following example:

For year 20:

$$\text{Seepage rate for sand tailings} = 7.3 \times 10^{-2} \text{ ft}^3/\text{ft}^2.$$

$$\text{Seepage rate for slime tailings} = 7.0 \times 10^{-2} \text{ ft}^3/\text{ft}^2.$$

Then, assuming the LTP is composed of 50% sands and 50% slimes, the combined seepage rate is:

$$0.5 \times (7.3 \times 10^{-2} \text{ ft}^3/\text{ft}^2) + 0.5 \times (7.0 \times 10^{-2} \text{ ft}^3/\text{ft}^2) = 7.2 \times 10^{-2} \text{ ft}^3/\text{ft}^2.$$

Then the volumetric seepage rate in year 20, assuming the area of the LTP is 200 acres, is:

$$\begin{aligned} 7.2 \times 10^{-2} \text{ ft}^3/\text{ft}^2 \times 200 \text{ ac} \times 43,560 \text{ ft}^2/\text{ac} &= 6.3 \times 10^5 \text{ ft}^3 \\ \times 28.32 \text{ L}/\text{ft}^3 &= 1.8 \times 10^7 \text{ L}. \end{aligned}$$

⁵² The mass balance errors for the sand and slime simulations were 0.04% and 0.11%, respectively.

Appendix 4

Calculation of Future Groundwater Contamination Caused by Seepage from the LTP

This appendix shows the calculations performed to estimate the concentrations of uranium in the alluvial aquifer caused by seepage of tailings solution from the LTP. The estimates are only for contamination caused by seepage after flushing ends. The calculations do not account for groundwater contamination that existed before the end of flushing.

The concentration of uranium in the alluvial groundwater will depend on:

1. The concentration of uranium in the tailings solution.
2. The background concentration of uranium in alluvial groundwater flowing beneath the LTP.
3. The rate at which tailings solution seeps from the LTP.
4. The rate at which groundwater in the alluvial aquifer flows beneath the LTP.

The following assumptions are made:

1. All the seepage from the LTP enters the alluvial groundwater.
2. The seepage from the LTP completely mixes with the underlying groundwater. No other attenuation occurs.⁵³

Concentration of uranium

The measured concentrations of uranium in the tailings solution are shown in the body of this report (figure 3). The most recent concentration is about 8 mg/L. Estimates were performed for uranium concentrations of 8 mg/L, 6 mg/L, 4 mg/L, 2 mg/L, and 1 mg/L.

The background concentration of uranium in alluvial groundwater flowing beneath the LTP⁵⁴ = 0.029 mg/L.

Rate of seepage from LTP

The seepage rate is shown in the body of the report (figure 2). It ranges from 8.8×10^8 L/yr in year 1 (440 gpm), to 3.5×10^6 L/yr in year 100 (1.8 gpm).

⁵³ The uranium is expected to remain mobile because it will probably exist as a uranium-carbonate complex (HMC 2010a, page 7 and figure 2).

⁵⁴ Average concentration in background well P, 2001 – 2012 (HMC 2013b, table 12.2-13).

Groundwater flow beneath LTP

The rate of groundwater flow beneath the LTP is:

$$q = K \times \Delta h/n$$

Where:

q = flow rate

K = hydraulic conductivity⁵⁵ = 30 ft/day

Δh = hydraulic gradient⁵⁶ = 3.3×10^{-3}

n = porosity⁵⁷ = 0.2

Then:

$$q = 30 \text{ ft/day} \times (3.3 \times 10^{-3})/0.2 = 0.495 \text{ ft/day} = 181 \text{ ft/yr}$$

The volume of groundwater per square foot beneath the LTP is:

$$V = 1 \text{ ft}^2 \times d \times n$$

Where:

V = volume

d = saturated thickness of alluvium beneath of LTP⁵⁸ = 35 ft

n = porosity⁵⁹ = 0.2

Then:

$$V = 1 \text{ ft}^2 \times 35 \text{ ft} \times 0.2 = 7 \text{ ft}^3 = 198 \text{ L}$$

⁵⁵ HMC, 2012a, page 3-7.

⁵⁶ HMC, 2012a, page 3-7.

⁵⁷ HMC, 2012a, page 3-7.

⁵⁸ HMC, 2012a, page 3-5 and figure 3.2.2-3.

⁵⁹ HMC, 2012a, page 3-7.

The length of time required for groundwater to traverse the LTP (flow from up-gradient to down-gradient boundary) is:

$$t = L/q$$

Where:

t = time

L = length of typical flow path beneath LTP⁶⁰ = 2000 ft

q = groundwater flow rate = 181 ft/yr

Then:

$$t = 2000 \text{ ft} \times 181 \text{ ft/yr} = 11 \text{ yrs}$$

Because the seepage rate from the LTP varies with time, the volume of seepage that mixes with water passing beneath the LTP also varies with time.

For example, a 1 ft² column of groundwater that passes under the up-gradient edge of the LTP in year 20 will traverse the LTP in 11 years and pass under the down-gradient edge in year 31. As it traverses the LTP it will mix with seepage coming in from above. The addition of seepage to the groundwater column as it passes underneath the LTP is illustrated in table A4-1.

⁶⁰ HMC, 2012a, figure 3.2.2-6.

Table A4-1
Calculation of Seepage and Groundwater Fractions in
Groundwater-Seepage Mixture

Year	Volume of ground-water column (L)	Volume of seepage added to ground-water column (L) ⁶¹	Cumulative volume of seepage added to ground-water column (L)	Volume of cumulative seepage and ground-water in mixture (L)	Fraction of seepage in mixture	Fraction of ground-water in mixture
20	198	2.02	2.02	200.0	0.010	0.990
21	198	1.92	3.95	201.9	0.020	0.980
22	198	1.83	5.78	203.8	0.028	0.972
23	198	1.75	7.53	205.5	0.037	0.963
24	198	1.67	9.21	207.2	0.044	0.956
25	198	1.61	10.81	208.8	0.052	0.948
26	198	1.54	12.35	210.4	0.059	0.941
27	198	1.48	13.84	211.8	0.065	0.935
28	198	1.43	15.26	213.3	0.072	0.928
29	198	1.38	16.64	214.6	0.078	0.922
30	198	1.33	17.97	216.0	0.083	0.917

The concentration of uranium in the groundwater after it traverses the LTP (year 30) will be:

$$C_t = C_s \times f_s + C_g \times f_g$$

Where:

C_t = concentration of uranium in groundwater-seepage mixture

C_s = concentration of uranium in seepage

f_s = fraction of seepage in groundwater-seepage mixture = 0.083 (see above)

C_g = concentration of uranium in groundwater = 0.029 mg/L

f_g = fraction of groundwater in groundwater-seepage mixture = 0.917 (see above)

Then, if the seepage contains 4 mg/L, the concentration of uranium in the groundwater-seepage mixture will be:

$$C_t = 4 \text{ mg/L} \times 0.083 + 0.029 \text{ mg/L} \times 0.917 = 0.359 \text{ mg/L.}$$

⁶¹ Model output.

Appendix 5

Calculation of Mass of Mobile Uranium Remaining in LTP

The mass of uranium leaving the LTP in any year is equal to the product of the seepage rate and the concentration of uranium in the seepage.

$$M_{ln} = S_n \times C$$

Where:

M_{ln} = mass leaving LTP in year n
 S_n = seepage rate in year n
 C = uranium concentration

Then, for year 20 after flushing ends, assuming uranium concentration = 8 mg/L:

$$M_{l20} = 1.9 \times 10^7 \text{ L} \times 8 \text{ mg/L} = 1.5 \times 10^8 \text{ mg}$$

The mass of mobile uranium remaining in the LTP in any year is equal to the initial mobile mass minus the cumulative mass that has left the LTP in the preceding years:

$$M_{rn} = M_i - \sum (M_{l1} + M_{l2} \dots + M_{ln})$$

Where:

M_{rn} = mass remaining in LTP in year n
 M_i = initial mobile mass = 7.8×10^{11} mg
 M_{ln} = mass leaving LTP in year n

Then, for year 20 after flushing ends:

$$\begin{aligned} M_{r20} &= 7.8 \times 10^{11} \text{ mg} - \sum (7.1 \times 10^9 \text{ mg} + 1.7 \times 10^9 \text{ mg} \dots + 1.5 \times 10^8 \text{ mg}) \\ &= 7.651 \times 10^{11} \text{ mg} \end{aligned}$$