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***EVALUATION OF POTENTIAL RADIONUCLIDE RELEASE AND  
TRANSPORT FOR THE ZION NUCLEAR POWER STATION BASEMENT  
FILL END STATE: CONCEPTUAL MODEL DEVELOPMENT AND  
SENSITIVITY ANALYSIS***

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# Evaluation of Potential Radionuclide Release and Transport for the Zion Nuclear Power Station Basement Fill End State: Conceptual Model Development and Sensitivity Analysis

## 1) Introduction

ZionSolutions is in the process of decommissioning the Zion Nuclear Power Plant. The site contains two reactor Containment Buildings, a fuel building, an Auxiliary Building, and a Turbine Building that may be contaminated. The current decommissioning plan involves removing all above grade structures to a depth of 3 feet below grade. The remaining underground structures will be filled with clean concrete demolition debris (CCDD) that will not have detectable licensed radioactive material. However, the remaining structures will contain low amounts of residual licensed radioactive material. An important component of the decommissioning process is the demonstration that any remaining activity will not cause a hypothetical individual to receive a dose in excess of 25 mrem/y as specified in 10CFR 20 Subpart E.

To demonstrate compliance with 10CFR 20 Subpart E requires modeling of the release and transport of radioactive material to a receptor. This involves characterization of the buildings on site to quantify the amount of residual radioactivity, modeling the release of radioactivity from the concrete and transport through the groundwater to a receptor well or nearby water body. At this point, exposure scenarios are postulated that have a future resident inhale, ingest, or be externally exposed to radiation resulting from the residual contamination. This typically involves using well water for drinking, irrigation, and growing crops.

This report addresses the release and transport of contamination to locations where a well could be installed for domestic use. ZionSolutions is in the process of collecting the characterization data from the below grade structures to define the residual contamination (source term). Calculation of the transport of radioactive material requires site-specific information on the hydrogeologic transport properties (effective porosity, bulk density, hydraulic gradient and hydraulic conductivity to specify water flow rate and direction) and chemical transport properties (sorption). Conestoga-Rovers & Associates (CRA) has collected a substantial amount of site-specific hydrogeologic data (CRA, 2013). Brookhaven National Laboratory has collected sorption data for five nuclides and four soil types and two CCDD materials that will be used in the fill (BNL, 2012).

Based on the characterization and transport data a simplified conceptual site model (CSM) will be developed and the DUST-MS computer code will be used to predict groundwater concentrations at various receptor locations.

The objectives of this report are:

- a) Develop a simplified CSM that can be used to provide an upper bound on contaminant concentrations at a receptor well.
- b) Establish a base case transport scenario that reflects the CSM and site-specific transport properties.

- c) Perform a sensitivity analysis on key transport parameters and the spatial distribution of the source term to identify how the changes in these parameters impact the predicted concentration.
- d) Provide time-dependent water concentrations at various receptor locations for use in dose assessment calculations.

The set of model evaluations will estimate the peak groundwater concentrations that could be collected from wells drilled on-site as well as the time dependent concentrations. These concentrations may be used directly with RESRAD OFFSITE to evaluate the dose from all pathways that a hypothetical person could receive. The recently released version 3.1 contains provisions for direct input of water concentrations into a contaminated zone located in the saturated zone. This approach is under evaluation. Alternatively, the groundwater concentrations may be compared to the values generated by RESRAD OFFSITE or other models if they are used to perform the entire analysis.. .

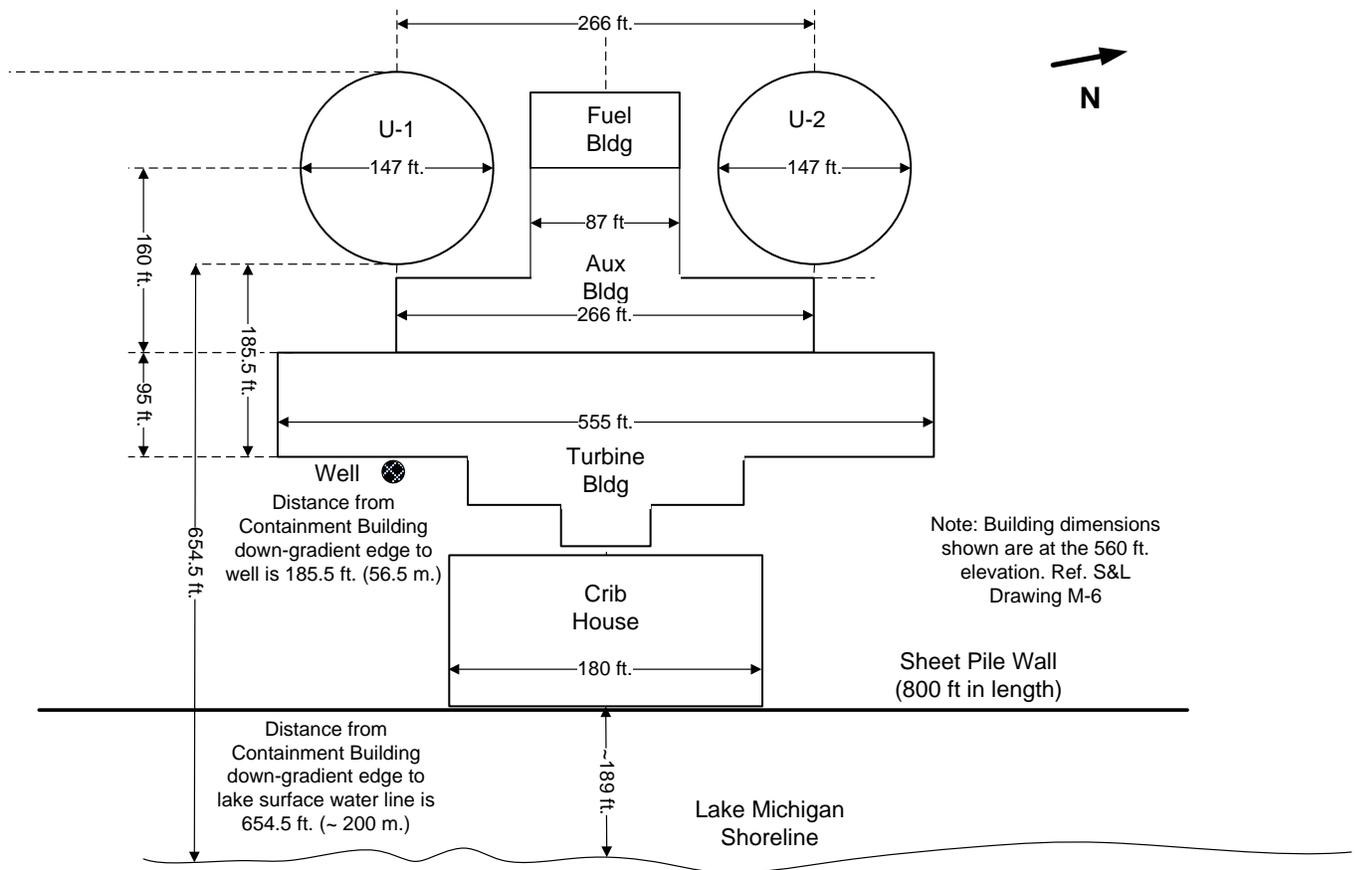
## **2) Conceptual Model**

Figure 1 provides the site layout at the Zion Nuclear Power Station located on the shores of Lake Michigan. Major features include two reactor Containment Buildings (U-1 and U-2 in Figure 1), a Fuel Building, Auxiliary Building, Turbine Building, Crib House, and a sheet pile wall to isolate the groundwater flow from beneath the plant and the Lake.

The proposed plan involves characterization of the residual contamination in the below grade structures at Zion. High-levels of contamination will be removed through a remediation process. There will be surface contamination and volumetric contamination left in place. This contamination will provide a potential source of radioactivity to the groundwater. These structures will be filled with non-contaminated concrete demolition debris blended with sand to improve flow ability and filling of the void space. The total capacity of the underground structures (basements) for placement of CCDD fill is approximately 6 million cubic feet.

To prevent the filling of the subsurface structures with water and a subsequent potential for a high-release rate near the ground surface as water flows over the top of the structure (bathtub scenario), the walls of the structures will be perforated to allow mixing and flow through the structures and concrete fill.

Preliminary characterization data suggest that the reactor Containment Buildings have the highest level of contamination. Intermediate levels of contamination were found in the Auxiliary Building and the Fuel Building. Low-levels of contamination were found in the Turbine Building.



**Figure 1 Zion Site building layout.**

The natural groundwater flow at the site is towards the lake and perpendicular to the lake front (Figure 1). Therefore, the releases from the two reactor units (Figure 1) will not mix. The conceptual site model is based on release from one Containment Building. This is based on the assumption that the release pathways from the two Containment Buildings are independent and that the Containment Buildings are the most contaminated buildings. The conceptual model assumes a unit source term that can be scaled to match the levels measured for characterization. The unit source level was selected as a concentration of 1 dpm/100 cm<sup>2</sup> (45.05 pCi/m<sup>2</sup>). For one Containment Building (147 ft. in diameter) this is equivalent to a total inventory of 7.1E-08 Ci. The current estimate for Cs-137 contamination in the reactor buildings is less than 10 Ci. This may change as additional characterization is performed. Thus, predicted concentrations per unit source term will be low. They can be scaled by the ratio of the measured activity to the modeled activity to estimate realistic groundwater concentrations. Note that the activity in all parts of the structure, not just the floor, should be used in determining the total activity. This assumption means that releases from building walls and sumps, which are at different elevations than the floor, are not modeled directly but are included into the floor inventory. Lumping the entire inventory into the floor is expected to provide a conservative estimate of peak concentration at the receptor locations based on current understanding of the distribution of residual contamination in the Containment Building. The ability to scale results to the total activity is a major advantage of the unit source term approach.

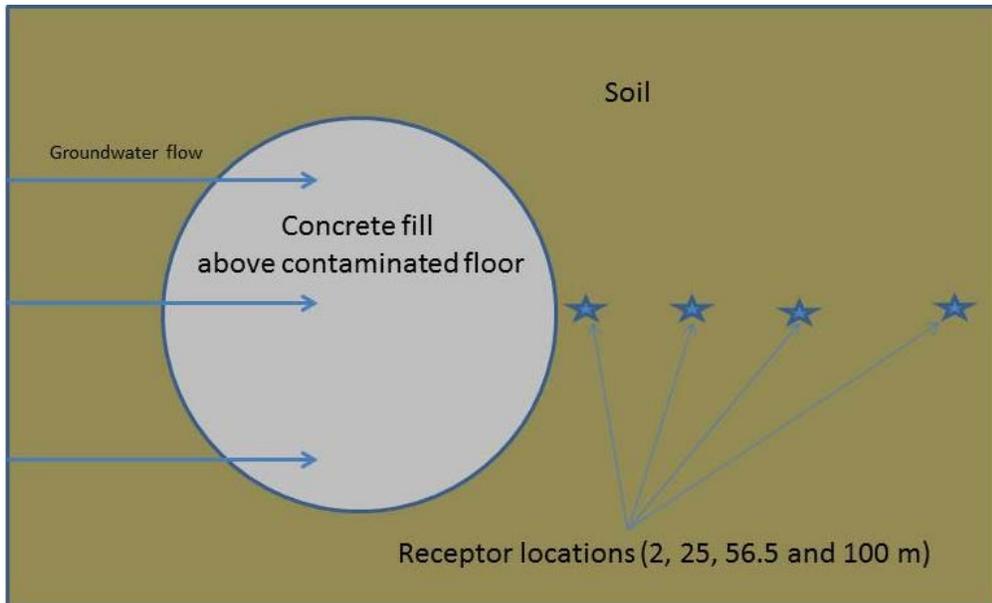
The conceptual model is portrayed in Figures 2 and 3. Figure 2 is the top view and shows the layout of the contaminated zone and downstream wells for hypothetical receptor locations. Figure 3 shows the side view and illustrates that the model assumes that mixing occurs over a five-foot thickness in the aquifer. This value was selected to be consistent with typical residential well screens. In this conceptual model the building walls are not modeled and the flow is at the rate of the regional groundwater velocity this conceptual model effectively puts the entire inventory in the Containment Building into a five-foot thick section of the aquifer without any man-made barriers to flow.

Reducing the conceptual model to release from a single building greatly simplifies the analysis. To account for the possibility of contributions from multiple buildings the unit source term approach can be used along with superposition to obtain the total groundwater concentrations. For example, groundwater concentrations from releases from the Auxiliary Building at a distance Y, where Y represents the distance from the edge of the Auxiliary Building to the receptor point could be calculated. This value, based on a unit source term, could be multiplied by the average contamination level in the Auxiliary Building. This value would be summed with the calculated concentration from the Containment Building.

The DUST-MS computer code has been selected to calculate the source term release and transport to the receptor well. DUST-MS has received wide-spread use in subsurface radionuclide release calculations (Sullivan, 1993; 2004; 2005; 2006; Hanusik 2005; Poskas, 2008) and undergone model validation studies (Sullivan, 1993; 2006). DUST-MS is a one-dimensional (1-D) model and in this simulation will be used to examine flow along the length of the Containment Building floor to downstream receptor locations.

The initial geometry considers contamination of the floor of one of the two Containment Buildings at Zion, Figure 2. Thus, the contaminated surface area is  $1.55E-05 \text{ cm}^2$ , equivalent to that of a circle with radius of 73.5 ft. The contaminated zone is covered with crushed concrete and sand mixture that was backfilled into the structure. Outside of the contaminated zone, a mixture of fill sand and native soil is simulated. The blend is consistent with the materials that form the aquifer that will be simulated to transport the radionuclides to various receptor sites. To perform the calculation it is assumed that the flow path is the longest possible (147 ft.) aligned with the groundwater flow, Figure 2. Receptor locations were set at 2, 25, 56.5, and 100 m. The distance of 56.5 m is the approximate distance from the edge of the Containment Building to the well shown in Figure 1.

Material properties were chosen to match site-specific values to the extent possible. Sorption coefficient,  $K_d$ , values were based on the measured values for Zion soils and concrete (Yim, 2012). In the test program there were two concrete samples and four soil samples. The minimum of the two concrete samples was selected for use in the transport calculations to provide a conservative estimate of groundwater concentration.

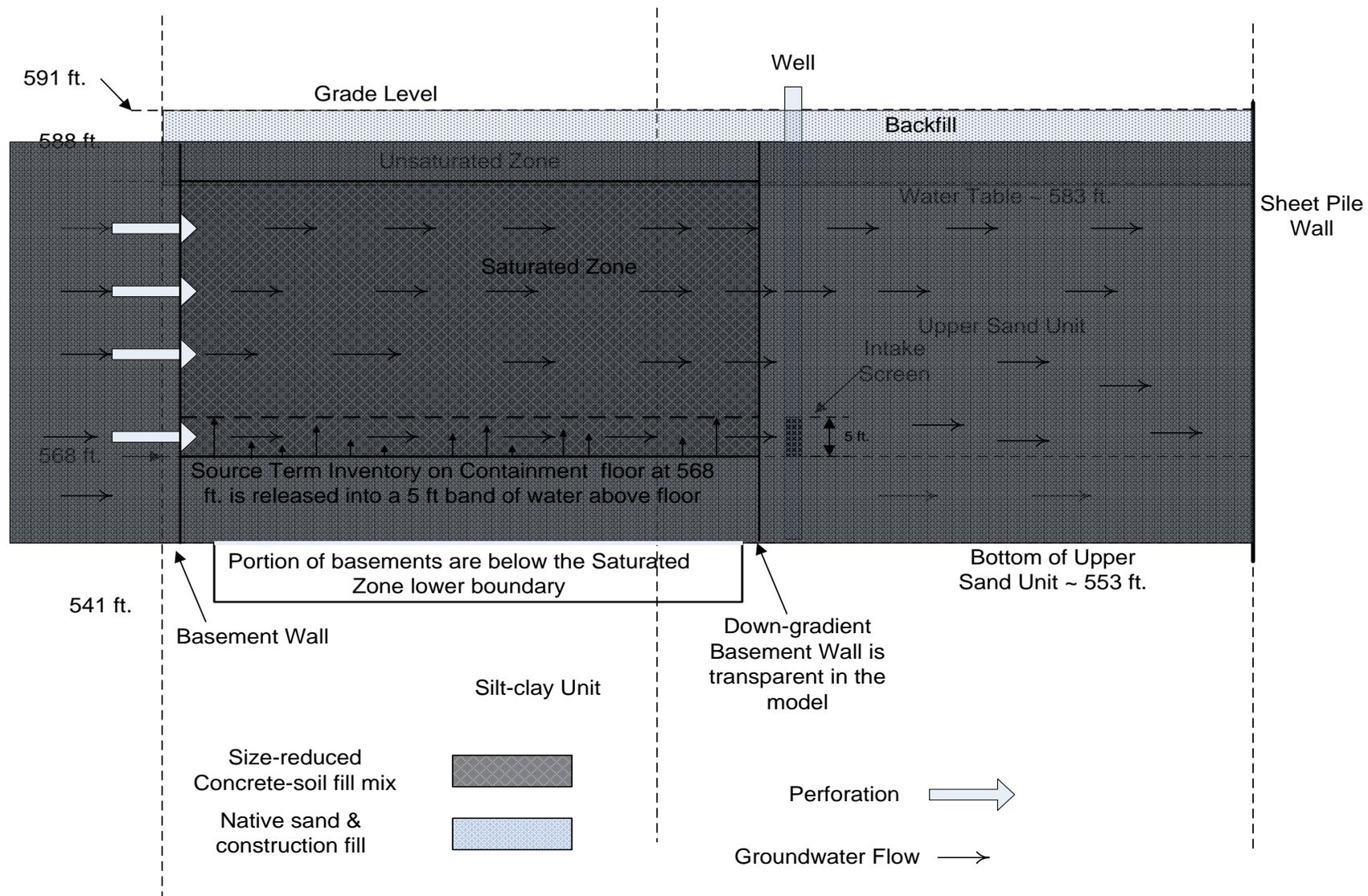


**Figure 2. Conceptual model for Zion Reactor Unit release top view.**

A key parameter in the 1-D model is the amount of water that will be allowed to mix with the released contaminants. For this set of analyses it is assumed that the releases from the floor mix with five feet of water above the floor. This value was selected as it is representative of the well screen thickness used in small residential wells (Gibbs, 1973, American Groundwater Trust, 2000).

The following radionuclides were selected for analysis:

- H-3,
- Fe-55,
- Co-60
- Ni-63
- Sr-90
- Cs-137



**Figure 3 Conceptual model side view.**

Tritium (H-3) was selected because it moves with the groundwater and shows the fastest arrival time and least dilution. Iron was selected because it is frequently found at nuclear power plants. Although, the long shut down period and short half-life of Fe-55 (2.7 years) have led to substantial decay and it has not been identified in characterization data at the site. Others were chosen based on preliminary characterization data.

The DUST-MS model is a one-dimensional finite-difference representation of the advective-dispersion transport in porous media. It can model time-dependent release of contamination into the groundwater and subsequent transport through various geologic regions (e.g. different transport properties) to a downstream location (receptor well). Although there is volumetric contamination that will release over time, for conservatism the conceptual model begins with the assumption that the entire inventory is released at the start of the simulation. This assumption may be relaxed to simulate time-dependent release if necessary to show that dose limits will be met.

### **3) Base Case**

The base case is established using the unit source term and grounded in conservative estimates of site-specific measured values for the model parameters where available. The base case will be used as the comparison point for the sensitivity analyses in which key parameters are varied, one at a time, to show their impact on predicted concentrations. The base case is meant to provide a conservative upper bound estimate for concentration.

#### **3.1) Parameters**

Key input parameters are provided in Appendix 1. These include the initial inventory, groundwater velocity, and transport properties for the soil and backfill (distribution coefficient, bulk density, effective porosity, dispersion coefficient, and diffusion coefficient), and the area available for flow. Soil properties were taken from measurements performed by Conestoga-Rovers and Associates for this plant (CRA, 2013). The effective porosity is derived from the site-specific total porosity and an assumption that 0.8 of the total porosity is available for transport (CRA, 2013). A few parameters that involve assumptions are discussed in detail in this section of the report.

Initial conditions assumed that the groundwater concentration of each contaminant was zero everywhere. The source term is modeled using a unit inventory approach that can be scaled to the actual inventory of the various buildings on site. For this modeling scenario, the Containment Building was modeled with the assumption of uniform contamination across the floor of the entire building. The source term was simulated as an instantaneous release of the entire modeled inventory in the floor at the start of the problem. This will provide an upper bound on predicted groundwater contamination concentrations per unit inventory.

The groundwater flow rate is  $2.55E-05$  cm/s (8.03 m/y) and the effective porosity is 0.167 based on site-specific measurements and evaluations performed by CRA, 2013).

DUST-MS is a one-dimensional model. To calculate the concentrations the cross sectional flow area is required. The area perpendicular to flow was reduced from the diameter of the Containment Building, 147 feet (44.8 m), to 35.2 m to adjust for the rectangular geometry used in DUST-MS. The product of 44.8 m (distance along the flow path) and 35.8 m (perpendicular distance) gives a flow area of 1.6E03 m<sup>2</sup>, the actual area of the Containment floor. A flow thickness of 5 feet (1.52 m) was used for the mixing height. This is a key parameter as it provides a mixing volume for dilution. In this case, it is assumed that the flow is laminar and very little mixing occurs with waters more than five feet above the floor. The aquifer is approximately 30 ft. thick. Using this thickness for flow area would lead to a reduction in peak concentrations by a factor of 6. Similarly, if the flow area was restricted to only 1 foot above the floor, peak concentrations would increase by a factor of 5.

The exact constitution of the backfill has not been decided yet. Therefore, the bulk density and porosity are unknown. A bulk density of 1.5 g/cm<sup>3</sup> and an effective porosity of 0.25 were selected for the base case. This is representative of typical sandy soils. Sensitivity analyses were performed to examine the importance of these assumptions.

The distribution coefficients ( $K_d$ ) are important parameters in controlling transport. BNL performed a set of analyses for five radionuclides (H-3 was not analyzed as it will move with the water) (BNL, 2012). Samples include two types of crushed concrete and four soil types. The values in Table 1 show the minimum  $K_d$  for the four soils and the two concretes. Although it is anticipated that the concrete will drive the pH up to above 10 and control the sorption, measurements of the blend of concrete and soil used for the backfill have not been performed. For this reason, the selected  $K_d$  for the concrete backfill region is the minimum of the value found in the soil and concrete tests. With the exception of Cs-137 this causes the soil  $K_d$  to be used in the analysis. This will have a major impact on the predicted concentrations of Ni-63 and Sr-90 and smaller impacts on other radionuclides. All measured  $K_d$  values are provided in Appendix 1.

**Table 1 Selected distribution coefficients**

	H-3	Fe-55	Co-60	Sr-90	Ni-63	Cs-137
Minimum Soil	0	2.85E+03	1.16E+03	2.3	62	527
Minimum Concrete	0	1.60E+04	1.16E+03	10.4	3440	45
Selected Backfill	0	2.85E+03	1.16E+03	2.3	62	45

### 3.2) Base Case Results

Table 2 shows the peak concentration (pCi/l) and the time (years) of the peak at the five receptor locations for an initial contamination level of 1 dpm/100 cm<sup>2</sup> in the Reactor Containment Building. The simulations were performed to cover a time period of 300 years. The predictions in this table clearly show that Fe-55 and Co-60 will never be a groundwater contamination issue. This is because both have  $K_d$  values in excess of 1000 cm<sup>3</sup>/g. Whatever is released will be sorbed onto the backfill and decay in place. Ni-63 is transported at a rate to reach the location 2 m from the source zone in appreciable quantities. However, at 25 m the Ni-63 peak

concentration has not been reached during the 300 year simulation period. The peak concentration will not be much greater than the value at 300 years due to radioactive decay. Tritium which moves with the groundwater will be flushed from the system almost immediately. The peak concentration 56.5 m from the edge of the contaminated zone occurred at the second year of the simulation. This reflects the groundwater velocity (8 m/y) which provides a pore water velocity of approximately 48 m/y. The drinking water standard for tritium and strontium are set in the U.S. Environmental Protection Agency Drinking Water Standards to 4 mrem/y. Using assumptions on ingestion, the State of California has translated this to a concentration of 20,000 pCi/l for tritium and 8 pCi/L for Sr-90 (EPA, 2009). Other States may derive different concentration values. For tritium to reach this level at 2 m outside the source zone would require an initial contamination level  $2.50E05$  dpm/100 cm<sup>2</sup>, equivalent to a total inventory of 0.18 Ci. Due to the relatively fast transport and lack of sorption, there is very little decrease in concentration with distance for H-3. The peak concentration decreases by a factor of 2 in going from 2 m to 56.5 m.

**Table 2 Peak concentration<sup>1</sup> and time of peak<sup>2,3</sup> for a uniformly distributed release from the floor of the reactor Containment Building.**

Nuclide	Peak Concentration (pCi/L)					Time of Peak (years)				
	2 m	25 m	56.5 m	100 m	200 m	2 m	25 m	56.5 m	100 m	200 m
H-3	7.9E-02	5.1E-02	4.1E-02	3.2E-02	2.1E-02	1	2	2	3	5
Fe-55	8.1E-13	1.1E-83	0	0	0	15	185	N/A	N/A	N/A
Co-60	6.2E-10	9.8E-53	0	0	0	26	> 300	N/A	N/A	N/A
Ni-63	1.5E-04	6.6E-06	2E-12	3.2E-31	0	58	> 300	> 300	> 300	N/A
Sr-90	6.e#-03	3.6E-03	1.9E-03	8.1E-04	1.4E-04	7	23	42	69	130
Cs-137	7.2E-06	4.7E-24	3.0E-70	0	0	75	> 300	> 300	N/A	N/A

Table Notes:

1. Peak Concentrations are pCi/l per unit source term concentration; 1 dpm/100-cm<sup>2</sup> or 45.05 pCi/m<sup>2</sup>.
2. > 300 means that the peak dose was not reached during the 300 year simulation period.
3. N/A applies to situations in which the calculated concentrations are reported as zero. Thus, time of peak concentration does not apply.

The other nuclide that is of concern based on concentration at the 56.5 m distance is Sr-90. To reach 8 pCi/L in the groundwater would require an initial contamination level of 4300 dpm/100 cm<sup>2</sup>, equivalent to a total inventory of 3.00E-04 Ci. A major reason that the Sr concentrations predicted at 56.5 m are high is that it is assumed that the backfill K<sub>d</sub> matches the lowest soil K<sub>d</sub>. The measured backfill K<sub>d</sub> is a factor of two higher. Due to the sorption on the concrete and soil, the times for the peak strontium concentration occur after tens to hundreds of years depending upon the receptor location. Thus, Sr is characterized by a long, broad and slowly changing plume of contamination, Figure 4.

Table 3 shows the peak concentration of each nuclide normalized to the peak concentration of the nuclide measured 2 m outside the waste zone. The objective of this table is to illustrate the

difference in fall off with distance due to radioactive decay. Tritium ( $K_d = 0$ ) falls off very slowly with 52% of its value at a distance of 56.5 m downstream. Others, with non-zero  $K_d$  values, fall off much more rapidly. It is unlikely that Fe-55 or Co-60 could be measured in the groundwater 2 m outside of the waste zone. Their high  $K_d$  values in soil cause a substantial drop in peak concentration with distance. Cs-137, depending on the source strength, may be measurable at 2 m from the contaminated zone but would not be measurable at 25 m.

**Table 3 Peak nuclide concentrations at three receptor locations normalized to maximum concentration at 2 m.**

Nuclide	Normalized Concentration			
	2 m	25 m	56.5 m	100 m
H-3	1	0.64	0.52	0.40
Fe-55	1	1.41E-71	N/A	N/A
Co-60	1	1.59E-43	N/A	N/A
Ni-63	1	0.044	1.32E-08	2.15E-27
Sr-90	1	0.57	0.29	0.128
Cs-137	1	6.47E-19	4.15E-65	N/A

At the Zion site, the tritium contamination level is low based on current characterization data. This makes Sr-90 the most likely contaminant to exceed drinking water standards. For this reason attention is focused on Sr-90.

Figure 4 shows the Sr-90 concentration in pCi/L as a function of distance on a semi-log scale. In this figure, the source zone extends from 10.2 to 55 m. Times depicted in Figure 3 range from 10 to 160 years. The distances of a potential receptor from the downgradient edge of the source zone are labeled with vertical bars. The maximum distance is slightly more than 200 meters from the source zone. The figure shows a broad region of contamination moving through the system. Peak concentrations are less than 0.01 pCi/L based on a unit source term of 1 dpm/100 cm<sup>2</sup>. These values will have to be scaled to the actual contamination level.

Figure 5 shows the Sr-90 concentration in pCi/L as a function of time for distances of 2, 25, 56.5, 100 and 200 m from the source zone over 200 years. The peak concentration decreases slowly with distance and is less than an order of magnitude in going from 2 m to 100 m from the source zone (Table 2). The time to reach the peak at 100 m from the source zone is 69 years (Table 2) and reflects the substantial retardation in transport compared to the groundwater which has a pore velocity of approximately 48 m/y. The Sr-90 distribution coefficient in this simulation was 2.3 cm<sup>3</sup>/g leading to a transport rate of less than 2 m/y.

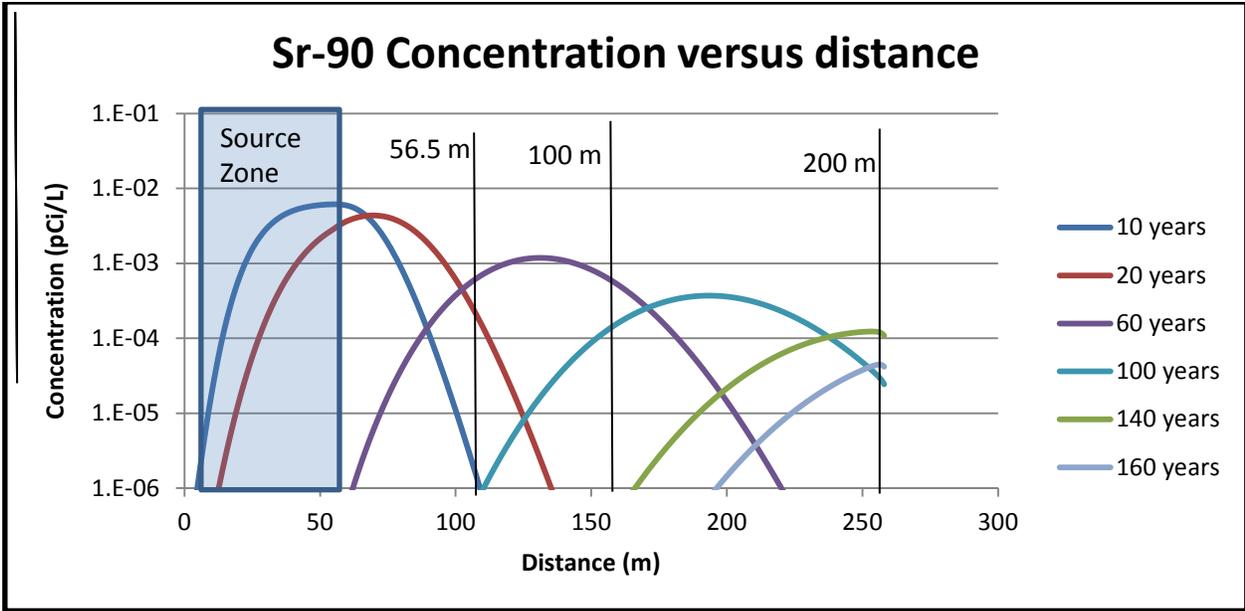


Figure 4 Base Case Sr-90 concentration (pCi/L) versus distance at times up to 160 years.

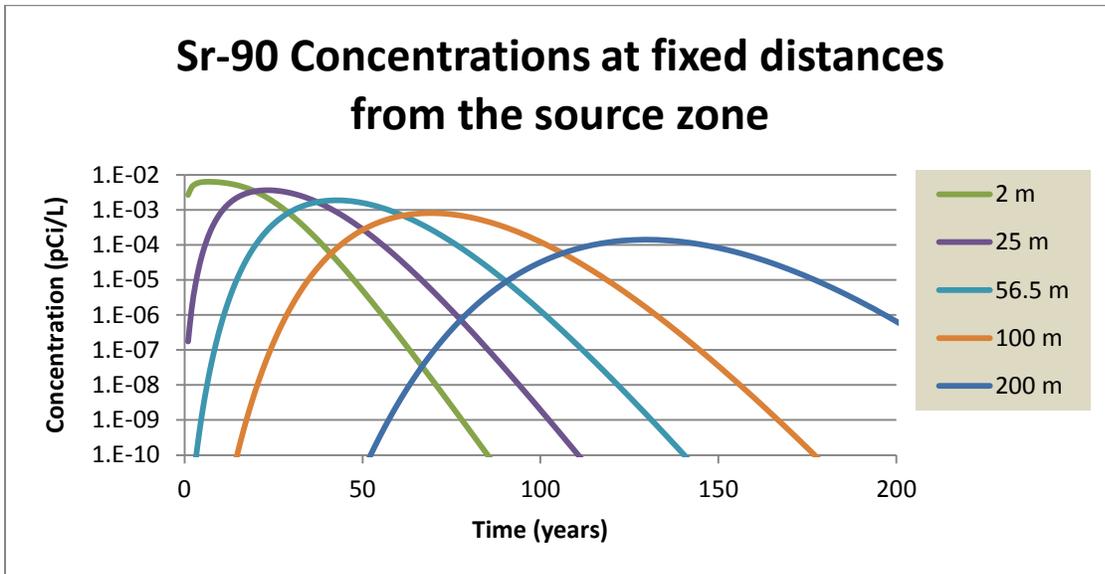


Figure 5 Base Case Sr-90 concentration (pCi/L) at fixed distances from the source zone as a function of time.

#### 4) Sensitivity Analyses

Although site-specific values are available, there is natural variability in the soil system and in the backfill material. To address this variability a sensitivity analysis was performed. The sensitivity analysis varied the parameters (e.g. flow rate, distribution coefficient, etc.) individually and examine the impact on peak groundwater contamination and the time to reach the peak. The sensitivity will be determined by evaluating the relative change in peak

concentration or time to reach the peak concentration. The relative change is defined as a percentage using the following equation:

$$R_i = 100 * (V_i - V_b) / V_b$$

Where  $R_i$  = percentage relative change for sensitivity parameter  $i$ .

$V_i$  = value of the sensitivity measure (time or peak concentration)

$V_b$  = value of the sensitivity measure in the base case.

The sensitivity analysis will help to identify key parameters that impact the groundwater concentration.

#### **4.1) Sensitivity Analyses Parameters**

Table 4 shows the selected sensitivity parameters. The selections are based on having a reasonable range of values to bracket the actual value for the parameter. The source distribution sensitivity case places 90% of the activity in the last 10% of the source area. This is performed as a worst case analysis due to the high concentration of contamination being nearer to the receptors. A similar distribution located in the interior would be retained by sorption on the fill material and provide lower concentration estimates. The maximum groundwater velocity (16.9 m/y) was obtained by taking the maximum measured conductivity multiplied by the maximum estimated hydraulic gradient.

#### **4.2) Sensitivity Analyses Results**

The sensitivity analysis covers seventeen separate cases for each nuclide. These will be discussed on a nuclide specific basis at four locations, 2, 25, 56.5, and 100 m from the source zone. A positive value for the percentage change represents an increase over the baseline. Appendix 2 contains the tables of results for all seventeen cases. A summary of the results follows.

**Table 4 Sensitivity Analysis Parameters**

Parameter	Baseline	Range
Source Distribution	Uniform (1 dpm/100 cm <sup>2</sup> )	Same total activity with 90% of the activity within the last 10% of the source area.
Groundwater Velocity	8.03 m/y	4 – 16.9 m/y
Distance to Receptor Well	100 m	2, 25, and 56.5 m from the edge of the source zone
<b>Soil Parameters</b>		
Soil Effective Porosity	16.74%	6% - 25%
Soil Bulk Density	2.12 g/cm <sup>3</sup>	1.5 – 2.3 g/cm <sup>3</sup>
Distribution Coefficient - Soil	Measured Value	½ - 2 times measured value
<b>Backfill Parameters</b>		
Backfill Effective Porosity	25%	15 – 35%
Backfill Bulk Density	1.5 g/cm <sup>3</sup>	1.2 – 1.8 g/cm <sup>3</sup>
Distribution Coefficient – Concrete backfill	Minimum value measured in sand or concrete	½ - 2 times selected value.

***Tritium H-3***

H-3 was most sensitive to the non-uniform inventory parameter for peak concentration. The non-uniform inventory caused a 66% increase in peak concentration 2 m away from the contaminated zone decreasing to an 11% increase 200 m from the contaminated zone. This decrease is attributed to dispersion during transport which spreads the contaminant out spatially leading to lower peak values. As expected, H-3 exhibited no sensitivity to the density or the  $K_d$  (however, the  $K_d$  is assumed to be zero with no variability) in the soil or backfill. It was sensitive to groundwater velocity with a factor of 2 increase in velocity leading to 20% lower peak concentrations and a factor of 2 decrease in velocity leading to a 20% higher concentration. This is also due to dispersion. In the transport equation, the dispersion coefficient is multiplied by the pore velocity. Thus, higher flow rates lead to higher dispersion for the same value of the dispersion coefficient. The peak concentration was sensitive to soil porosity with lower porosity leading to higher peak concentrations and the opposite was true for higher porosity. This can be attributed to lower porosity having less water to dilute the source.

The sensitivity to time was difficult to assess in this study because tritium moves so fast that the peak concentration 100 meters away occurred in year 3. This simulation used 1 year time steps so any change in the timing is subject to high estimation errors. To obtain a better understanding of the change in peak times the simulation should be repeated with 0.1 year time steps.

***Fe-55***

The peak concentration of Fe-55 was most sensitive to the soil  $K_d$  showing orders of magnitude change in the predicted soil concentrations. This was caused by the high value for  $K_d$  and the short half-life (2.7 years) of Fe-55. The sorption in the backfill and soil effectively contained the Fe-55 and it decayed in place. In the source region filled with backfill the peak concentration was linearly proportional to  $K_d$ . Doubling the  $K_d$  in the source zone reduced the peak

concentration by a factor of 2. The density which multiplies the  $K_d$  term in the transport equation also showed a similar effect. Increasing the density or the  $K_d$  value both lead to increases in the retardation coefficient ( $R = 1 + \rho K_d / \theta$ , where  $\rho$  is the bulk density,  $K_d$  is the distribution coefficient, and  $\theta$  is the effective porosity). The porosity does not impact the peak concentrations because the retardation coefficient is multiplied by the effective porosity. This leaves a term that is the sum of the effective porosity and the product of density and distribution coefficient. The effective porosity is less than 1, therefore it is insignificant compared to the second term if  $K_d$  is larger than 5. For Fe-55 the  $K_d$  value is over 1000.

The sensitivity of the peak time was difficult to determine because in most cases the peak time was either in excess of 300 years or the contamination never arrived at the receptor location. There was some sensitivity to soil  $K_d$  and density with higher values having longer transport times.

### ***Co-60***

Co-60 also has a  $K_d$  value in excess of 1000 similar to Fe-55. The sensitivity behavior was similar to Fe-55.

### ***Ni-63***

The peak concentration for Ni-63 was most sensitive to soil  $K_d$  and soil density. Peak concentration increased by several orders of magnitude when decreasing  $K_d$  by a factor of two. However, the value for the peak concentrations were extremely low ( $< 10^{-6}$  pCi/L at the 56. m distance from the source zone). The peak concentration also displayed some sensitivity to the non-uniform source distribution with peak concentrations increasing by several hundred percent. Although Ni-63 has a relatively high value for  $K_d$  ( $62 \text{ cm}^3/\text{g}$ ) in these simulations, the half-life of 100 years prevents the complete decay of Ni-63 over the 300 year simulation period. Therefore, it does reach the receptor wells. The peak concentrations were also sensitive to groundwater velocity due to the limited amount of decay.

The sensitivity of the peak time was difficult to determine because in most places the peak time was over 300 years. At the 2 m distance the non-uniform inventory, high groundwater velocity, low backfill and soil density and low  $K_d$  test cases all showed an earlier arrival. In contrast, the higher  $K_d$  case in the soil led to a later arrival.

### ***Sr-90***

Strontium 90 was the most interesting sensitivity analysis case. The low  $K_d$  ( $2.3 \text{ cm}^3/\text{g}$ ) and the half-life (29 years) allowed a well-developed concentration profile which exhibited the full range of impacts of the different parameters on predicted concentrations. The peak concentration for Sr-90 was sensitive to the  $K_d$  in the soil and backfill, groundwater velocity, non-uniform source inventory and density of the soil and backfill. The peak concentration was increased by a factor of 9 in a localized zone in the source region. This increase was reduced to a factor of 3 within 2 m of the source zone and was only 50% higher than the base case after 56.5 m. The peak concentration was linearly proportional to changes in  $K_d$  in the source zone. Changes in  $K_d$  in the soil showed a non-linear response with the peak concentrations being more sensitive to changes away from the source zone. This reflects the impact of decay on the predicted concentrations. For a lower  $K_d$  the travel time to the receptor location is less and therefore there is less time for decay. A similar effect was observed with groundwater velocity with higher peak

concentrations compared to the baseline with distance for high groundwater flow. There was very little change in predicted concentrations with change in the porosity or the backfill.

The time to reach the peak concentration is much less sensitive than the value of the peak concentration as compared to baseline values, with the exception of changes in the soil  $K_d$  or the groundwater velocity. Doubling the groundwater velocity leads to reducing the time to reach the peak by close to a factor of 2, as expected.

#### ***Cs-137***

Cs-137 has a high  $K_d$  in the soil (527 cm<sup>3</sup>/g) and a relatively low  $K_d$  in the backfill (45 cm<sup>3</sup>/g). The high soil  $K_d$  makes transport beyond 2 m almost negligible. While the sensitivity to  $K_d$  and other parameters is quite high (several orders of magnitude above the base case) at distances beyond 2 m, the value for the peak concentration remains extremely low (< 10<sup>-10</sup> pCi/L). At the 2 m receptor location the peak concentration is sensitive to  $K_d$  in the backfill or the soil and to the density of the soil. At 2 m a decrease in soil  $K_d$  by a factor of 2 leads to a factor of 2 increase in peak concentration.

The sensitivity of the peak time was difficult to determine because beyond the 2 m point the peak time was over 300 years. At 2 m the time to reach the peak is sensitive to the soil  $K_d$ , groundwater velocity, and non-uniform inventory.

### **4.3) Discussion**

A detailed sensitivity analysis was performed for the six nuclides and several key transport parameters. Tritium and Sr-90 provide the most interesting results. Tritium because it does not sorb shows the importance of groundwater flow velocity and porosity. Sr-90 which sorbs slightly shows the importance of  $K_d$  and bulk density on predicted concentrations. For sorbing nuclides, the porosity is not an important parameter. All contaminants were sensitive to the source distribution, but the sensitivity dissipates with distance. For Sr-90 placing 90% of the inventory with 10% of the source zone led to a 900% increase in peak concentration in the source zone. However, due to dispersion this caused only a 50% increase in peak concentration as compared to the base case at a distance of 56.5 m from the source. For H-3 the high mobility reduced the peak concentration to a 66% increase over the baseline at a distance of 2 m from the source. The other nuclides, Fe-55, Co-60, Ni-63, and Cs-137, had sufficiently high  $K_d$  values that peak concentrations were extremely low. Although the peak concentrations for these nuclides were sometimes extremely sensitive to parameter values exhibiting several orders of magnitude increase in peak concentration over the baseline the resulting concentrations were so low that they are not of concern.

### **5.0) Conclusions**

A baseline model for predicting groundwater concentrations at the Zion Nuclear Power Station after decommissioning has been developed. The model uses the DUST-MS simulation model which calculates the release and transport of radioactive contamination in a groundwater system. The analysis is based on a unit source term of 1 dpm/100 cm<sup>2</sup> on the entire floor of one

Containment Building. This inventory is assumed to be instantly released into the groundwater. Conservative assumptions based on existing site data were used in the base case for the transport parameters needed to assess groundwater concentrations as a function of distance. A sensitivity analysis was performed covering nine key parameters and seventeen different cases.

The baseline and sensitivity analyses are based on a unit source term and must be scaled to actual contamination levels. Nevertheless the analysis shows that groundwater concentrations for Fe-55, Ni-63, Co-60, and Cs-137 will not be a concern for any potential contamination level. Sr-90 and H-3 could reach levels of concern if contamination levels averaged a few thousand dpm/100 cm<sup>2</sup>. More detailed analysis may be warranted once characterization is complete.

Although Fe-55, Ni-63, Co-60, and Cs-137 did exhibit sensitivity to  $K_d$  values and groundwater velocity, for the range of values tested in the sensitivity analysis the concentrations at the receptor well locations was so low that the dose from these nuclides will be negligible with respect to the 25 mrem/yr standard. Tritium which does not sorb,  $K_d = 0$ , showed sensitivity to groundwater velocity and soil porosity (Appendix 2 provides the detailed results). At the 2 m distance, the peak H-3 was sensitive to the non-uniform distribution of contamination. Predicted concentrations of Sr-90 are sensitive to  $K_d$ , density, and groundwater velocity. The time to reach the peak concentration is much less sensitive than the value of the peak concentration as compared to baseline values. The time to reach the peak concentration is sensitive to the soil  $K_d$  and the groundwater velocity.

The values in this report provide a groundwater concentration at various distances from the source zone. This data may be used as input to RESRAD-OFFSITE to perform dose assessment. A methodology has been developed to place the DUST-MS predicted concentrations into a file that can be used to specify the groundwater concentrations as a function of time for RESRAD-OFFSITE.

### **Additional Studies**

This assessment of groundwater concentrations is the initial attempt. There are several studies being conducted now that may lead to changes in parameter values or even in the conceptual model for release. A final assessment will be performed to address any changes that occur as a result of ongoing studies. The conditions that may trigger the requirement for additional work are described in the following paragraphs.

The conceptual site model does not account for contamination in buildings other than the Containment Building where contamination levels are expected to be the highest based on the initial characterization data and process knowledge. If the Auxiliary Building or Turbine Building exhibit significant contamination they may need to be modeled. The decision to perform this modeling will be based on the amount of contamination and the distance to potential receptors. In any event, the concentration estimates in this report at a distance of 2 m outside the Containment Building (Table 2) will provide an upper bound on groundwater concentration in the case of uniform contamination. At this location only H-3, Sr-90, and possibly Ni-63 could be of concern from a groundwater concentration perspective.

Additional model assessments may be required to examine the impact of localized regions of high contamination (e.g. hot spots) which may occur in a number of regions due to previous spills, activated concrete in the sub-pile area of the Containment Building, or the presence of embedded piping. While the sensitivity test case which placed 90% of the inventory in the 10% of the modeled domain closest to the nearest receptor was meant to bound the worst case distribution of hot spots, this will need to be reviewed once characterization is completed.

At present the, final facility end state is not known. The current conceptual model assumes crushed concrete will be used to fill the subsurface structures that will remain in place. This material will be blended with soil to improve the flow to enhance the backfilling process. Alternatives under consideration are:

- Including crushed cinder block in the CCDD fill material
- Leaving most of the walls and floors in the building basements in place (as opposed to a configuration where each building basement is a single compartment)
- Filling the basement compartments with a grout mixture – under this alternative two options are possible:
  - Grout mixture with CCDD included
  - Grout without CCDD.

Backfilling with soils and cinder block will most likely not lead to a change in the conceptual model, but may change the transport parameters ( $K_d$ , porosity, density). Changing the basement fill end state configuration to either a single grout-filled compartment (monolith) or a series of grout-filled compartments could require a change in the conceptual site model and key dose modeling assumptions. Modeling either the grout-filled monolith or grout-filled individual compartment end states will be challenging as there are likely to be void pockets (creating potential conduits) due to difficulties in assuring 100% filling. Additionally, there will be cracks in the grout due to cooling and settling effects (Savannah River Remediation, 2009) reference for this]. It is likely that water could flow through these cracks and impact release rates. If an end state is selected with grout fill, a decision will have to be made to use either the existing conceptual model or to develop a new conceptual model based on fracture flow. Use of the existing conceptual model would require a demonstration that it is conservative compared to end states with grout fill.

## 6.0) References

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# Appendix 1 Key DUST-MS input parameters.

Material 1 is the backfill and material 2 is the native soil.

DUST-MS VERSION 3 8/97

Spherical and finite difference release models  
Capability to read upstream mass flow rate from  
An auxiliary file as a boundary condition

TITLE: Zion Preliminary model run

NUMBER OF ISOTOPES. . . . . 6  
ACTIVITY FLAG (0=Gm, 1=Ci, 2=Bq). . . . . 1  
NUMBER OF NODAL POINTS/MIXING CELLS . . . . . 200  
TRANSPRT FLAG (FIN DIFF=1) . . . . . 1

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . H-3  
HALF-LIFE (YRS) . . . . . 1.23E+01  
SATURATION CONCENTRATION. . . . . 1.00E+03\*  
ATOMIC WEIGHT . . . . . 3.0

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . FE-55  
HALF-LIFE (YRS) . . . . . 2.70E+00  
SATURATION CONCENTRATION. . . . . 1.00E+03  
ATOMIC WEIGHT . . . . . 55.0

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . CO-60  
HALF-LIFE (YRS) . . . . . 5.27E+00  
SATURATION CONCENTRATION. . . . . 1.00E+03  
ATOMIC WEIGHT . . . . . 60.0

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . NI-63  
HALF-LIFE (YRS) . . . . . 1.00E+02  
SATURATION CONCENTRATION. . . . . 1.00E+03  
ATOMIC WEIGHT . . . . . 63.0

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . SR-90  
HALF-LIFE (YRS) . . . . . 2.90E+01  
SATURATION CONCENTRATION. . . . . 1.00E+03  
ATOMIC WEIGHT . . . . . 90.0

\*\*\*\* CONTAMINANT PROPERTIES \*\*\*\*

RADIONUCLIDE. . . . . CS-137  
HALF-LIFE (YRS) . . . . . 3.02E+01  
SATURATION CONCENTRATION. . . . . 1.00E+03  
ATOMIC WEIGHT . . . . . 137.0

\*\*\*\* DECAY CHAINS \*\*\*\*

NUMBER OF DECAY CHAINS(0=NO, > 1=YES) . . . . . 0

\*\*\*\* TIME PARAMETERS \*\*\*\*

NUMBER OF TIME INCREMENTS . . . . . 1000  
NO. OF DISCRETE TIME CHANGES. . . . . 1  
TIME INCREMENT (DELT - YEARS) . . . . . 1.00E+00  
MULTIPLIER FOR INCREASING DELT. . . . . 0.00E+00  
MAXIMUM VALUE OF DELT (YEARS) . . . . . 1.00E+00  
MAXIMUM VALUE OF TIME (YEARS) . . . . . 1.00E+03

LIST OF TIMES AT WHICH 'DELT' CHANGES:

NO.	TIME (YRS)	NO.	TIME (YRS)	NO.	TIME (YRS)	NO.	TIME
(YRS)							
1	0.00E+00						

\*\*\*\* MATERIAL PROPERTIES \*\*\*\*

NUMBER OF MATERIALS . . . . . 2  
 NUMBER OF MATERIAL PROPERTIES . . . . . 4  
 NUMBER OF REDEFINED MATERIALS . . . . . 107

MAT. NO.	DISTR. COEFF.	DENSITY	DISPERS.	DIFFUSION	Contaminant
1	0.00E+00	1.50E+00	1.00E+02	1.00E-06	H-3
2	0.00E+00	2.12E+00	1.00E+02	1.00E-06	H-3
1	1.60E+04	1.50E+00	1.00E+02	1.00E-06	FE-55
2	2.85E+03	2.12E+00	1.00E+02	1.00E-06	FE-55
1	5.00E+03	1.50E+00	1.00E+02	1.00E-06	CO-60
2	5.00E+03	2.12E+00	1.00E+02	1.00E-06	CO-60
1	3.44E+03	1.50E+00	1.00E+02	1.00E-06	NI-63
2	6.20E+01	2.12E+00	1.00E+02	1.00E-06	NI-63
1	1.04E+01	1.50E+00	1.00E+02	1.00E-06	SR-90
2	3.00E+01	2.12E+00	1.00E+02	1.00E-06	SR-90
1	4.50E+01	1.50E+00	1.00E+02	1.00E-06	CS-137
2	5.27E+02	2.12E+00	1.00E+02	1.00E-06	CS-137

- Saturation concentration is the solubility limit of the nuclide in solution. It can be used to limit release from a wastefrom. In this study the values is set to 10 g/cm<sup>3</sup> a value so high that it cannot impact the release calculations and all the inventory is released immediately.

## Material Properties

The transport material properties include the bulk density, distribution coefficient, dispersion coefficient and diffusion coefficient for each material (backfill and native soil).

The diffusion and dispersion coefficients play a minor role on the predicted concentrations. The diffusion coefficient was set to 1.0E-06 cm<sup>2</sup>/s. This is a large value for most nuclides in porous media and is representative for tritium (H-3). The longitudinal dispersion coefficient is dependent on the length of travel and generally ranges from 1/10 to 1/100 of the total travel distance. For this study, the maximum travel distance was 200 m and a value of 0.1 m (100 cm) was used. This will overpredict spreading at distances less than 100 m but it is not a major contributor to the overall transport.

The density for the backfill is unknown as a final decision on the size of the backfill and the fraction of sand mixed in has not been determined. A value of 1.5 g/cm<sup>3</sup>, typical for soils, was used. The density for the native soils was chosen at 2.12 g/cm<sup>3</sup> the average value from the sampling performed by CRA (CRA, 2013).

The distribution coefficients (K<sub>d</sub>) are important parameters in controlling transport. BNL performed a set of analyses for five radionuclides (H-3 was not analyzed as it will move with the water) (BNL, 2012). Samples include two types of crushed concrete and four soil types. The values in Table 5 are the best estimates based on the measured K<sub>d</sub> for the four soils and the two concretes. Although it is anticipated that the concrete will drive the pH up to above 10 and control the sorption, measurements of the blend of concrete and soil used for the backfill have

not been performed. For this reason, the selected  $K_d$  for the concrete region is the minimum of the value found in the soil and concrete tests. With the exception of Cs-137 this causes the soil  $K_d$  to be used in the analysis. This will have a major impact on the predicted concentrations of Ni-63 and Sr-90. The minimum values selected to be used in the analysis are presented in Table 6.

**Table 5 Best estimate for Zion site  $K_d$  (ml/g) for each soil or concrete media.**

Media ID	Description	$K_d$ (ml/g)				
		Fe-55	Ni-63	Sr-85	Cs-137	Co-60
CJGSSB001B	Disturbed Sand	2857±481	331±99	3.4±0.3	635±96	> 1161
CJGSSB001C	Native Sand	5579±2306	62±2.5	2.3±0.2	615±60	> 1161
CJGSSB002C	Silt/Clay	> 17288	136±10	5.7±0.2	3011±306	> 1161
CJGSSB001D	Silt	8061±3483	75±4.9	2.3±0.5	527±17	> 1161
B1-01107-CJFCCV-001	U-1 Containment Concrete	16546±7859	3438±915	10.4±1.3	85±3.8	> 1161
B2-08101-BJFCCV-A016	Crib House Lower Floor Concrete	> 17288	8361±1168	18.5±4.2	45±2.4	> 1161

**Table 6 Selected distribution coefficients**

	H-3	Fe-55	Co-60	Sr-90	Ni-63	Cs-137
Minimum Soil	0	2.85E+03	1.16E+03	2.3	62	527
Minimum Concrete	0	1.60E+04	1.16E+03	10.4	3440	45
Selected Backfill	0	2.85E+03	1.16E+03	2.3	62	45

### Groundwater flow

Groundwater flow was based on the geometric mean hydraulic conductivity as measured by CRA (5.00E-03 cm/s) and regional hydraulic gradient (0.0051) to provide a flow rate estimate of 2.55E-05 cm/s (8.03 m/y).

### Cross Sectional Area

DUST-MS is a one-dimensional model. To calculate the concentrations the cross sectional flow area is required. The area perpendicular to flow was reduced from 147 feet (44.8 m) to 35.2 m to adjust for the rectangular geometry used in DUST-MS. The product of 44.8 m (distance along the flow path) and 35.8 m (perpendicular distance) gives a flow area of  $1.6 \times 10^3 \text{ m}^2$ , the actual area of the Containment floor. A flow thickness of 5 feet (1.52 m) was used for the mixing height. This is a key parameter as it provides a mixing volume for dilution. In this case, it is assumed that the flow is laminar and very little mixing occurs with waters more than five feet above the floor. The aquifer is approximately 30 ft. Using this value for flow area would lead to

a reduction in peak concentrations by a factor of 6. Similarly, if the flow area was restricted to only 1 foot above the floor, peak concentrations would increase by a factor of 5.

### **Porosity**

The porosity value for the soil was set to the effective porosity (0.1674) based on the measured total porosity (0.209) and recommendations of CRA (CRA, 2103) to assume that 80% of the porosity is available to transmit flow.

The effective porosity of the backfill region is not known. A value of 0.25, typical for soils, was used.

### **Boundary Conditions for all contaminants:**

- Zero flux at the upstream boundary (no mass entering or leaving the system). The upstream boundary is the starting point of the calculation and using a zero flux boundary condition prohibits mass from traveling out of the system upstream from the source zone.
- Zero concentration at the downstream boundary (maximizes flux leaving the system). The downstream boundary is the end of the modeling domain. Forcing the concentration at this boundary to be zero maximizes the transport of contaminants through the modeled domain.

### **Initial Conditions for all contaminants:**

- Zero concentration at all locations.

### **Source Term Release:**

The modeled domain is treated by dividing the region into a series of computational cells to represent the system. Within each computational cell a mass balance is performed based on the flux of contaminants into and out of the cell accounting for the modeled transport processes and losses within the cell (radioactive decay) and production within the cell due to release from the wasteform. In this simulation the wasteform contains the inventory and a release mechanism is specified to be instantaneous. To simulate the contaminated region, the Containment Building is divided into a number of computational cells. The choice of the number is arbitrary but should be based on the groundwater flow rate, retardation effects, and computational time step. In this study, the source term was represented using 80 containers each 56 cm (1.84 feet) in length to represent the 147 foot diameter of the floor of the reactor Containment Building. The source was uniformly divided among the containers with a unit inventory of 1 dpm/100 cm<sup>2</sup> for each nuclide. Multiplying by the area of the Containment Building floor (1.58E03 m<sup>2</sup>) provides an initial total inventory of 7.1E-08 Ci. Therefore each container has 8.88E-10 Ci. Release was assumed to occur instantly at the start of the simulation. This is an extremely small amount of contamination. However, the results of these simulations can be scaled to the actual inventory when it is determined. The actual inventory should include the entire inventory of the Containment Building which will include contributions from the walls.

## Appendix 2: Sensitivity Analyses Results

The following tables summarize the results of the 17 sensitivity studies listed in Table 3 (reproduced below). They include the following simulations:

- Soil  $K_d$  low and high values
- Soil Porosity low and high values
- Soil Density low and high values
- Non-uniform inventory (high concentrations at the downstream edge of the source zone)
- Backfill  $K_d$  low and high values
- Backfill Porosity low and high values
- Backfill Density low and high values
- Groundwater velocity low and high values.

The following tables examine the sensitivity of the peak concentration and the time of the peak concentration at five receptor locations. For reference the peak concentration and the time of the peak concentration in the base case are provided. The table presents the percentage change defined as the change from the base case value (sensitivity case – base case) divided by the base case value and multiplied by 100 to provide percent. Values are presented for each sensitivity case (e.g. ‘high’ and ‘low’ porosity, etc.) as the response is generally slightly different. A negative value for the response indicates that changing the parameter leads to a decrease in response (peak concentration or time) Examining the base case values is important in understanding the sensitivity results. In some cases the results are quite sensitive, e.g. orders of magnitude change in predicted concentration, but they are meaningless in terms of dose. For example, for Cs-137 at 100 m from the source zone there is a 2.50E26% change in concentration for the low soil  $K_d$  case. However, the base case concentration is predicted to be essentially 0 (1.00e-70 pCi/L) thus, even with this large percentage change, the actual concentration is still effectively 0 (< 1.00e-50 pCi/L). Both predicted concentrations are so small that they are meaningless in a practical sense.

Parameter	Baseline	Range
Source Distribution	Uniform (1 dpm/100 cm <sup>2</sup> )	Same total activity with 90% of the activity within the last 10% of the source area.
Groundwater Velocity	8.03 m/y	4 – 16.9 m/y
Distance to Receptor Well	100 m	2, 25, and 56.5 m from the edge of the source zone
<b>Soil Parameters</b>		
Soil Effective Porosity	16.74%	6% - 25%
Soil Bulk Density	2.12 g/cm <sup>3</sup>	1.5 – 2.3 g/cm <sup>3</sup>
Distribution Coefficient - Soil	Measured Value	½ - 2 times measured value
<b>Backfill Parameters</b>		
Backfill Effective Porosity	25%	15 – 35%
Backfill Bulk Density	1.5 g/cm <sup>3</sup>	1.2 – 1.8 g/cm <sup>3</sup>
Distribution Coefficient – Concrete backfill	Minimum value measured in sand or concrete	½ - 2 times selected value.

### H-3

#### Sensitivity of Peak Concentration

Peak Conc (pCi/L)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
0.0795	2 m	0.0	0.0	4.2	-3.0	0.0	0.0	66.0
0.0508	25 m	0.0	0.0	36.2	-6.1	0.0	0.0	58.7
0.0413	56.5 m	0.0	0.0	31.0	-15.5	0.0	0.0	25.4
0.0324	100 m	0.0	0.0	51.2	-20.1	0.0	0.0	15.4
0.0214	200 m	0.0	0.0	70.6	-25.7	0.0	0.0	11.2

Peak Conc (pCi/L)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
0.0795	2 m	0.0	0.0	27.0	-19.0	0.0	0.0	16.5	-32.3
0.0508	25 m	0.0	0.0	21.7	-9.6	0.0	0.0	25.6	-16.3
0.0413	56.5 m	0.0	0.0	14.3	-13.1	0.0	0.0	20.3	-25.7
0.0324	100 m	0.0	0.0	9.6	-9.9	0.0	0.0	14.8	-22.8
0.0214	200 m	0.0	0.0	6.5	-6.5	0.0	0.0	4.2	-18.2

#### Sensitivity of Peak Time

Peak time (years)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
1	2 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	25 m	0.0	0.0	-50.0	0.0	0.0	0.0	-50.0
2	56.5 m	0.0	0.0	-50.0	50.0	0.0	0.0	0.0
3	100 m	0.0	0.0	-33.3	33.3	0.0	0.0	0.0
5	200 m	0.0	0.0	-40.0	40.0	0.0	0.0	0.0

Peak Time (years)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
1	2 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	25 m	0.0	0.0	-50.0	0.0	0.0	0.0	50.0	-50.0
2	56.5 m	0.0	0.0	0.0	0.0	0.0	0.0	100.0	-50.0
3	100 m	0.0	0.0	0.0	0.0	0.0	0.0	100.0	-33.3
5	200 m	0.0	0.0	0.0	20.0	0.0	0.0	100.0	-40.0

**Fe-55**

**Sensitivity of Peak Concentration**

Peak Conc (pCi/L)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
8.13E-13	2 m	1277.6	-93.2	0.0	0.0	275.2	-26.9	800.4
1.15E-83	25 m	1.14E+16	-100.0	0.0	0.0	1.2E+9	-100.0	795.7
	56.5 m							
	100 m							
	200 m							

Peak Conc (pCi/L)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
8.13E-13	2 m	96.8	-49.6	0.0	0.0	24.2	-16.4	-93.2	1535.9
1.15E-83	25 m	95.7	-49.7	0.0	0.0	24.3	-16.6	-100.0	1..2E+17
	56.5 m								
	100 m								
	200 m								

**Sensitivity of Peak Time**

Peak Time (years)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
15	2 m	0.0	6.7	0.0	0.0	0.0	0.0	-1.1
185	25 m	-4.9	>67	0.0	0.0	-2.7	115	0.0
>300	56.5 m							
>300	100 m							
>300	200 m							

Peak Time (years)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
15	2 m	0.0	0.0	0.0	0.0	0.0	0.0	6.7	-6.7
185	25 m	0.0	0.0	0.0	0.0	0.0	0.5	-99.5	-5.4
>300	56.5 m								
>300	100 m								
>300	200 m								

## Co-60

### Sensitivity of Peak Concentration

Peak Conc (pCi/L)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
6.23E-10	2 m	831.0	-91.4	0.0	0.0	214.6	-24.4	799.8
9.88E-53	25 m	3.71E+13	-100.0	0.0	-0.1	9.69E+07	-96.6	799.8
	56.5 m							
	100 m							
	200 m							

Peak Conc (pCi/L)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
6.23E-10	2 m	89.4	-48.3	0.0	0.0	23.1	-15.9	-91.1	928.9
9.88E-53	25 m	88.3	-48.2	0.0	0.0	22.5	-15.7	-100.0	2.2E+14
	56.5 m								
	100 m								
	200 m								

### Sensitivity of Peak Time

Peak Time (years)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
26	2 m	-11.5	7.7	0.0	0.0	-7.7	0.0	0.0
300	25 m	-10.7	0.0	0.0	0.0	-3.0	0.0	0.0
>300	56.5 m							
>300	100 m							
>300	200 m							

Peak Time (years)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
26	2 m	-3.8	0.0	0.0	0.0	0.0	0.0	7.7	-11.5
300	25 m	0.0	0.0	0.0	0.0	-0.3	0.0	0.0	-12.0
>300	56.5 m								
>300	100 m								
>300	200 m								

**Ni-63**

**Sensitivity of Peak Concentration**

Peak Conc (pCi/L)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
1.51E-04	2 m	29.1	-30.5	0.0	0.0	14.6	-3.3	575.5
6.61E-06	25 m	527.8	-99.6	0.5	-0.3	226.8	-33.9	408.3
2.00E-12	56.5 m	4.45E+07	-100.0	2.5	-1.5	266900.0	-90.3	740.0
3.24E-31	100 m	5.74E+18	-100.0	6.2	-4.3	4.01E+11	-99.8	788.9
	200 m							

Peak Conc (pCi/L)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
0.000151	2 m	98.0	-49.1	0.0	0.0	24.5	-16.6	-29.1	30.5
6.61E-06	25 m	96.7	-48.9	0.2	0.0	24.2	-16.2	-99.6	583.8
2.00E-12	56.5 m	88.0	-46.5	0.5	0.0	22.5	-15.0	-100.0	7.60E+07
3.24E-31	100 m	83.0	-46.0	0.3	0.0	21.6	-14.8	-100.0	4.17E+19
	200 m								

**Sensitivity of Peak Time**

Peak Time (years)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
58	2 m	-27.6	41.4	-1.7	0.0	-20.7	10.3	-43.1
300	25 m	-22.7	0.0	0.0	0.0	-1.3	0.0	0.0
> 300	56.5 m							
>300	100 m							
>300	200 m							

Peak Time (years)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
58	2 m	5.2	0	-1.7	1.7	1.7	-5.2	27.6	-29.3
300	25 m	0.0	0	0.0	0.0	0.0	0.0	0.0	-24.3
> 300	56.5 m								
> 300	100 m								
>300	200 m								

**Sr-90**

**Sensitivity of Peak Concentration**

Peak Conc (pCi/L)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
0.00635	2 m	7.4	-11.0	0.3	-0.2	4.1	-1.1	292.1
0.00363	25 m	39.4	-46.3	1.7	-1.1	21.5	-5.2	78.2
0.00187	56.5 m	89.8	-68.5	3.2	-1.6	44.9	-9.6	48.7
0.000817	100 m	175.4	-83.7	4.5	-3.1	78.7	-15.1	37.1
0.000141	200 m	493.6	-96.1	7.8	-5.7	177.3	-25.5	28.4

Peak Conc (pCi/L)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
0.00635	2 m	81.1	-48.3	2.8	-2.7	22.4	-15.7	-11.0	6.0
0.00363	25 m	46.0	-44.9	2.2	-1.9	16.0	-12.7	-37.5	20.7
0.00187	56.5 m	31.6	-39.6	1.6	-1.1	11.8	-10.2	-59.6	49.7
0.000817	100 m	23.6	-35.1	1.5	-1.2	9.3	-8.4	-78.1	105.6
0.000141	200 m	17.7	-29.7	0.7	-1.4	7.1	-7.1	-94.7	336.2

**Sensitivity of Peak Time**

Peak Time (years)	Location	Soil Low $K_d$	Soil High $K_d$	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
7	2 m	-28.6	28.6	0.0	0.0	-14.3	0.0	-71.4
23.5	25 m	-36.2	57.4	-2.1	0.0	-19.1	4.3	-31.9
43	56.5 m	-39.5	69.8	-2.3	0.0	-23.3	5.8	-18.6
69	100 m	-42.0	78.3	-1.4	1.4	-23.9	7.2	-10.1
130	200 m	-43.8	83.1	-2.3	1.5	-25.8	6.9	-5.8

Peak Time (years)	Location	Backfill Low $K_d$	Backfill High $K_d$	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
7	2 m	-14.3	0.0	0.0	0.0	-7.1	0.0	42.9	-42.9
23.5	25 m	-14.9	8.5	-2.1	0.0	-6.4	2.1	80.9	-48.9
43	56.5 m	-9.3	9.3	-1.2	0.0	-3.5	2.3	87.2	-51.2
69	100 m	-5.8	8.0	0.0	0.7	-1.4	2.2	90.6	-50.7
130	200 m	-3.1	4.2	-0.4	0.0	-1.2	1.2	91.2	-51.5

**Cs-137**

**Sensitivity of Peak Concentration**

Peak Conc (pCi/L)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
7.25E-06	2 m	206.2	-76.1	0.0	0.0	82.1	-13.9	519.3
4.69E-24	25 m	1.60E+10	-100.0	0.2	-0.2	2.92E+06	-93.0	712.4
3.01E-70	56.5 m	2.54E+26	-100.0	0.3	-0.7	6.51E+14	-99.9	783.7
0	100 m							
0	200 m							

Peak Conc (pCi/L)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
7.25E-06	2 m	89.0	-45.8	0.1	-0.1	22.5	-15.0	-73.9	213.1
4.69E-24	25 m	79.7	-43.7	0.2	0.0	20.7	-14.1	-100.0	4.54E+10
3.01E-70	56.5 m	75.4	-43.5	0.0	-0.3	19.6	-14.0	-100.0	9.04E+27
0	100 m								0
0	200 m								

**Sensitivity of Peak Time**

Peak Time (years)	Location	Soil Low K <sub>d</sub>	Soil High K <sub>d</sub>	Soil Low Porosity	Soil High Porosity	Soil Low Density	Soil High Density	Non uniform inventory
75	2 m	-23.5	26.8	-0.7	0.0	-69.3	2.6	-20.3
300	25 m	0.0	0.0	0.0	0.0	-42.7	0.0	0.0
300	56.5 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	100 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Peak Time (years)	Location	Backfill Low K <sub>d</sub>	Backfill High K <sub>d</sub>	Backfill Low Porosity	Backfill High Porosity	Backfill Low Density	Backfill High Density	Low GW Vel	High GW Vel
75	2 m	2.6	-2.6	0.0	-0.7	0.7	-1.3	23.5	-22.2
300	25 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	56.5 m	0.0	0.0	0.0	0.0	0.0	0.0	-99.7	0.0
300	100 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0