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Interpretation of Vadose Zone Monitoring System Data near Engineered Trench 1

G. P. Flach

T. S. Whiteside

December 12, 2016

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EXECUTIVE SUMMARY

The E-Area Vadose Zone Monitoring System (VZMS) includes lysimeter sampling points at many locations alongside and angling beneath the Engineered Trench #1 (ET1) disposal unit footprint. The sampling points for ET1 were selected for this study because collectively they showed consistently higher tritium (H-3) concentrations than lysimeters associated with other trench units. The VZMS tritium dataset for ET1 from 2001 through 2015 comprises concentrations at or near background levels at approximately half of locations through time, concentrations up to about 600 pCi/mL at a few locations, and concentrations at two locations that have exceeded 1000 pCi/mL. The highest three values through 2015 were 6472 pCi/mL in 2014 and 4533 pCi/mL in 2013 at location VL-17, and 3152 pCi/mL in 2007 at location VL-15. As a point of reference, the drinking water standard for tritium and a DOE Order 435.1 performance objective in the saturated zone at the distant 100-meter facility perimeter is 20 pCi/mL. The purpose of this study is to assess whether these elevated concentrations are indicative of a general trend that could challenge 2008 E-Area Performance Assessment (PA) conclusions, or are isolated perturbations that when considered in the context of an entire disposal unit would support PA conclusions.

To this end multiple statistical analyses of ET1 VZMS data were performed herein to estimate the most likely average tritium concentration at shallow depths in the vadose zone (just beneath the trench excavation), and uncertainty in these best-estimates. Median values of VZMS data were then compared to simulated vadose concentrations from the 2008 PA model, a revised model accounting for B-25 box disposal in ET1, and a second revised model that accounted for B-25 boxes and removed a potential model bias in predicted soil moisture content. The 2008 PA model appears to underpredict tritium concentrations observed in the shallow vadose zone. However, data to model comparisons produced little evidence to support a hypothesis that the simulated concentrations from the revised B-25 box models are significantly different from the actual plume concentrations. That is, the revised models appear to be reasonably consistent with the field observations at ET1.

The model revised to account for B-25 box disposal predicts a sum-of-fractions (SOF) less than 1.0 based on the as-disposed-of conditions of ET1 and ET2, which were analyzed together in the 2008 PA and here as a disposal unit group. The model revised to account for B-25 box disposal and to remove a potential model bias in predicted water content forecasts an SOF of 1.05 based on 2008 PA assumptions for plume overlap with disposal unit groups adjoining ET1 and 2 (i.e. east and center Slit Trench groups). However, the phased operation of E-Area disposal units will minimize the potential for any inter-disposal unit group plume interaction. With consideration of this as-disposed-of condition, ET1 is deemed unlikely to exceed performance objectives.

Considering the model improvements developed herein and continued acquisition of tritium data from the VZMS, the following actions are recommended:

1) In the upcoming PA revision, the E-Area vadose model should be revised to account for B-25 box and similar containerized waste disposals. Furthermore, the hydraulic properties assigned to the vadose zone should be reassessed and revised if found to produce a significant bias in simulated moisture content.
2) Upon approval of the next PA, tritium administrative limits for action level lysimeters should be revised to reflect concentrations predicted by the revised PA vadose zone model.
3) Solid Waste should consider incorporating existing groundwater monitoring information as part of the PA monitoring program (specific actions to be developed). It is important to keep in mind that compliance with the DOE Order 435.1 performance objectives is assessed in groundwater rather than the vadose zone.

4) Vadose zone monitoring should continue to be maintained and expanded for trench units because it provides an early indication of trench disposal unit performance relative to PA assumptions and modeling forecasts, and addresses GW monitoring limitations due to the existing Mixed Waste Management Facility tritium plume beneath E-Area.

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LIST OF ABBREVIATIONS

CI	Confidence Interval
H-3	Tritium
ET	Engineered Trench
OSC	Operational Soil Cover
PA	Performance Assessment
SOF	Sum-of-fractions
SRNL	Savannah River National Laboratory
VZMS	Vadose Zone Monitoring System
WITS	Waste Information Tracking System
WSRC	Washington Savannah River Company LLC
WT	Water Table

1.0 Introduction

Solid low-level waste, primarily contained in B-25 boxes, was disposed of in E-Area Engineered Trench (ET) 1 from February 2001 through July 2015 based on Waste Information Tracking System (WITS) records. The radionuclides contributing at least one percentage point (0.01) to the Beta-Gamma 0-12 year (most limiting PA pathway) sum-of-fractions (SOF; WSRC 2008, NRC 2016) in order of decreasing fraction are C-14, I-129, H-3, Tc-99 and Nb-94. As of 9/30/2015 the SOF for these radionuclides of interest was 0.854 compared to a total SOF of 0.868 per WITS.

The E-Area Vadose Zone Monitoring System (VZMS) includes lysimeter sampling points at many locations alongside the ET1 disposal unit footprint. Considering the relative mobility of H-3 compared to other nuclides, VZMS sampling events have focused on tritium analyses, although other species have also been analyzed on occasion. The VZMS tritium dataset for ET1 from 2001 through 2015 comprises concentrations at or near background levels at approximately half of locations through time, concentrations up to about 600 pCi/mL at a few locations, and concentrations at two locations that have exceeded 1000 pCi/mL. The maximum values through 2015 were 6472 pCi/mL in 2014 and 4533 pCi/mL in 2013 at location VL-17, and 3152 pCi/mL in 2007 at location VL-15. As a point of reference, the drinking water standard for tritium and a performance objective at the 100-meter facility perimeter is 20 pCi/mL. The purpose of this study is to assess whether these elevated concentrations are indicative of a general trend that could challenge 2008 E-Area Performance Assessment (PA) conclusions, or are isolated perturbations that when considered in the context of a complete disposal unit would not dispute PA conclusions.

ET1 disposal limits are designed to satisfy the performance objectives of DOE Order 435.1 based on a 2008 E-Area Performance Assessment (PA) analysis (WSRC 2008). The E-Area PA predicted the radionuclide flux crossing the water table (WT) and the peak radionuclide concentration in the aquifer underlying E-Area along the facility 100 meter perimeter. Simulated radionuclide concentrations in the vadose zone soil column are not reported in the PA document, precluding direct comparison of VZMS data to published model predictions. Furthermore, the PA analysis assumed that

- a uniform distribution of radionuclide activity occurred within the ET1 footprint,
- that disposals filling ET1 occurred at a single instant,
- the equivalent of backfill soil would fill the entire trench volume at closure, and
- waste containers would not hinder (e.g. delay) waste release.

The as-disposed-of ET1 condition comprises a non-uniform waste distribution, disposals occurring over a nearly 15 year period, significant void space within the waste zone due to disposal of low-density boxed waste, and waste containers that likely affect radionuclide release. These differences constitute a mixture of conservative and non-conservative conditions relative to the 2008 PA.

To enable comparison of VZMS data to model predictions, 2008 E-Area PA models were retrieved from the archives and modified in this study to: 1) capture vadose zone concentrations at locations representative of VZMS lysimeters, and 2) more closely reflect the as-disposed-of condition of ET1 now that the disposal unit has reached 99.5% volume capacity. The study also includes a statistical analysis of VZMS tritium data to determine a representative (e.g. average) concentration for comparison to model predictions, and assess whether the field observations are consistent with the tritium inventory reported in WITS and PA-based model predictions. Inferences concerning the overarching question of whether ET1 will meet performance objectives are then drawn.

1.1 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in Manual E7 Procedure 2.60. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

2.0 Engineered Trench 1 disposal history

Figure 2-1 through Figure 2-3 contain key disposal history information provided by Solid Waste Engineering. Although the SOF for ET1 is less than one (0.868) indicating remaining radionuclide disposal capacity, the disposal unit is practically full from a volume capacity perspective (99.5%). Disposal unit closure is anticipated in FY2017. Figure 2-4 illustrates the sequence and approximate timing of ET1 waste disposals inferred from Figure 2-2 and Figure 2-3. Figure 2-5 compares disposed H-3 activity to volume consumption as percentages of their totals and indicates an overall distribution of tritium throughout the trench. The most limiting PA pathway is Beta-Gamma 12-100 years (BG2) and the disposal limit for this pathway for H-3 is 12 Ci (Swingle 2012a, Table 20, Swingle 2012b). The disposed H-3 activity is 2.21 Ci as of September 2015, which is the dataset used by this study (Figure 2-2).

ET#1 BG2 (12 - 100 yrs) SOF for Key Isotopes (Greater that 0.01)

(as of 9/30/2015)

Isotope	SOF in BG2
C14	0.262
H3	0.185
I129	0.245
NB94	0.017
TC99	0.145
Sum Total	**0.854**
Overall SOF Total	**0.868**

Figure 2-1. Sum-of-fractions summary for ET1 for the Beta-Gamma 12-100 yr (BG2) pathway.

ET#1 Volume Status and Cumulative H3 Disposed Inventory

Month	Jul-15	Jan-15	Jul-14	Jan-14	Jul-13	Jan-13	Jul-12	Jan-12	Jul-11	Jan-11	Jul-10	Jan-10	Jul-09
Vol (% full)	99.5%	99.0%	98.7%	98.7%	98.7%	98.7%	98.7%	98.7%	98.7%	98.7%	88.4%	88.4%	88.4%
H-3 Disposed (Ci) - Cumulative	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	2.21E+00	1.69E+00	1.69E+00	1.69E+00

Month	Feb-09	Jul-08	Jan-08	Jul-07	Jan-07	Jul-06	Jan-06	Jul-05	Jan-05	Jul-04	Jan-04	Jul-03	Jan-03
Vol (% full)	88.4%	88.4%	88.4%	88.4%	88.4%	87.8%	83.5%	79.2%	74.3%	73.2%	69.3%	57.6%	45.9%
H-3 Disposed (Ci) - Cumulative	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.68E+00	1.65E+00	1.30E+00	9.59E-01

Month	Jul-02	Jan-02	Jul-01	Feb-01
Vol (% full)	24.7%	18.0%	8.1%	0.0%
H-3 Disposed (Ci) - Cumulative	3.19E-01	2.64E-01	8.17E-02	0.00E+00

Figure 2-2. Tritium (H-3) disposal and volume consumption history for ET1.

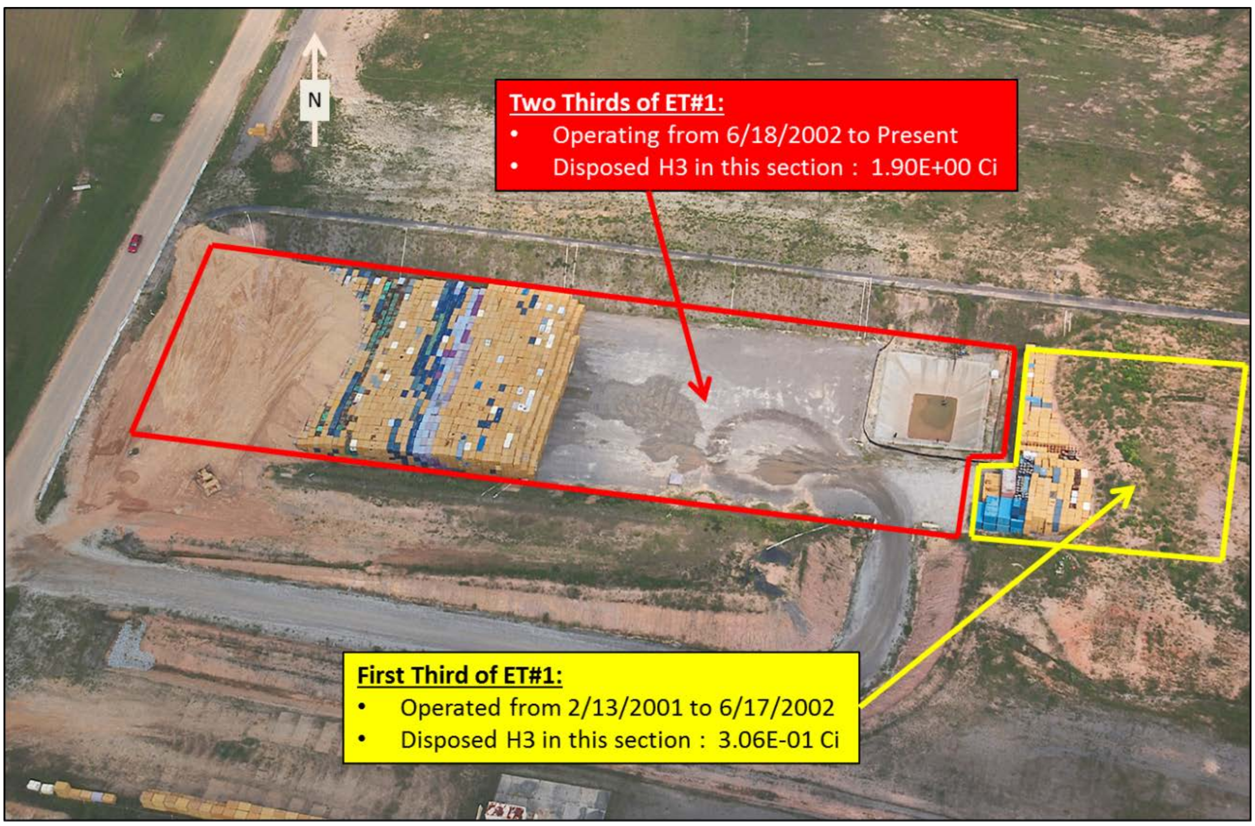
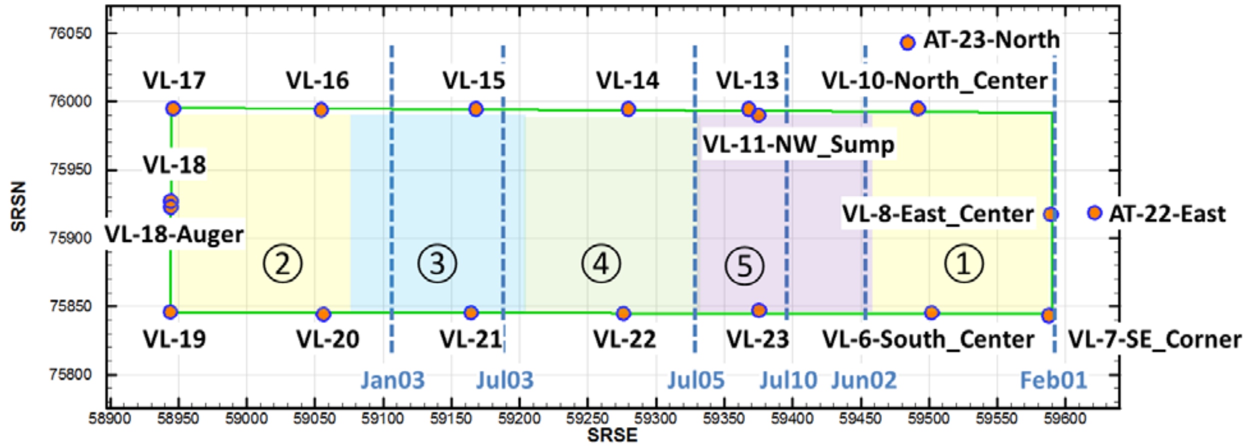


Figure 2-3. Annotated aerial photo of ET1 from August 2003.



Key:

- Shaded blocks represent 20% of disposal volume and ①→⑤ indicates sequence of disposals
- Dashed lines and month/year indicate approximate position of disposal progress
- Points represent ground surface locations of lysimeters

Figure 2-4. Sequence and approximate timing of waste disposals in ET1.

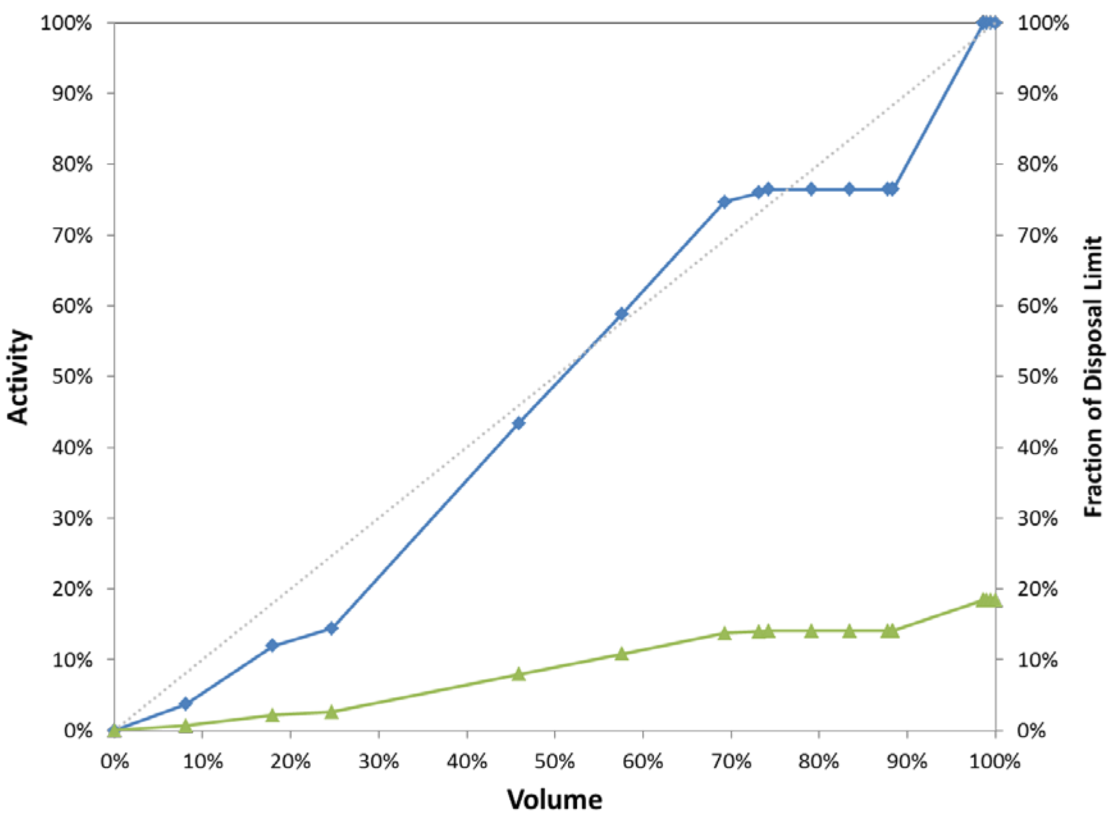
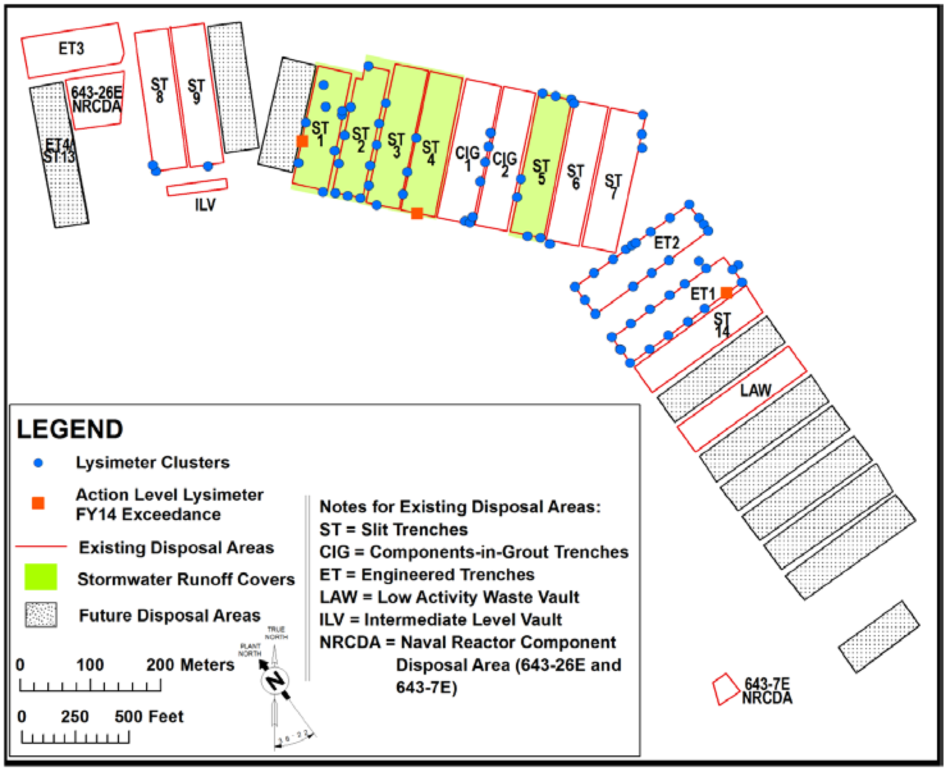


Figure 2-5. H-3 activity versus volume consumption in ET1.

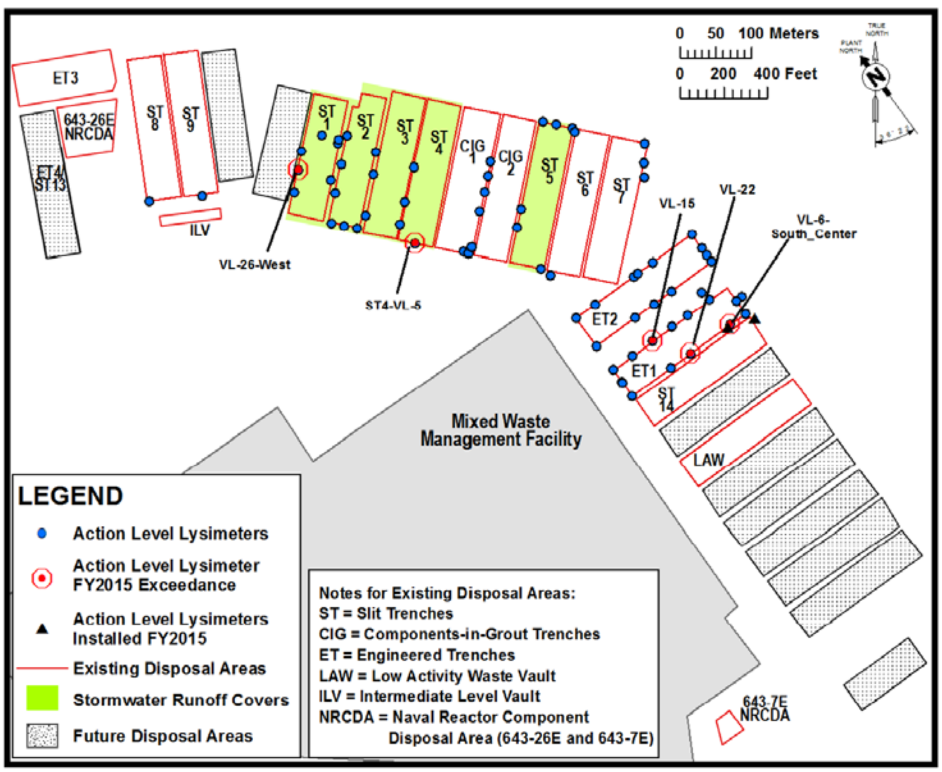
3.0 Vadose Zone Monitoring System (VZMS)

The Vadose Zone Monitoring System (WSRC 2008, Millings 2009, 2012, Hiergesell et al. 2015, 2016) is a collection of lysimeters that have been placed alongside and beneath the footprint of ET1 and other E-Area trench disposal units. Soil moisture samples are drawn from the system twice annually and analyzed for tritium. The objectives of the VZMS are to: “1) monitor trends in performance, 2) evaluate whether a facility is operating and behaving as expected and predicted by the PA, 3) evaluate the conservativeness of the PA conclusions, 4) provide input for refining the PA and building integrity in the PA analyses, and 5) provide a means to evaluate the potential for future regulatory exceedances” (Hiergesell et al. 2015).

Figure 3-1 identifies the locations of single lysimeters and multi-depth clusters, and those Action Level lysimeters that exceeded administrative limits for tritium in FY2014 and FY2015. The administrative limit is set to 25% of the average tritium concentration that would occur in the deep vadose zone for a trench operating at its radiological disposal limit for tritium. The administrative limit for Engineered Trenches is 101 pCi/mL (Hiergesell et al. 2016, Table 5-1). Exceedance of the administrative limit in a deep vadose zone lysimeter triggers further study to assess whether the disposal unit is performing as expected based on the E-Area Performance Assessment (WSRC 2008). At ET1, a single administrative limit was exceeded in FY2014 and three in FY2015. Further information is provided in Table 5-2 of both Hiergesell et al. (2015) and (2016).



(a)



(b)

Figure 3-1. VZMS lysimeter locations and Action Level Lysimeter Exceedances in (a) FY2014 (SRNL-STI-2014-00582) and (b) FY2015 (SRNL-STI-2015-00691).

Shown in Figure 3-2 are tritium concentrations from the shallow-most lysimeter at each ET1 location, generally a few feet below the trench bottom, as a function of time. The shallow-most lysimeter generally produces the highest concentration at a particular location, but not always. Approximately half of the shallow lysimeters have produced tritium concentrations in vadose zone soil moisture exceeding the drinking water standard (20 pCi/mL) for at least one sampling event. The drinking water standard is used here as a point of reference and is not a performance objective for tritium in vadose zone soil moisture. Table 3-1 lists the maximum VZMS concentration for each sampling year through 2015. Lysimeters are generally sampled twice per year. For each year Table 3-1 lists the peak concentration recorded for that calendar year. A blank entry for a location indicates that no data were acquired for that calendar year, because the lysimeter was abandoned, not sampled, or insufficient sample volume was obtained for analysis.

As noted earlier, the highest three concentrations through 2015 were 6472 pCi/mL (VL-17, 2014), 4533 pCi/mL (VL-17, 2013) and 3152 pCi/mL (VL-15, 2007). The three locations exhibiting the high concentrations at any point in time are VL-17, VL-15 and VL-6-South_Center. Figure 3-3 illustrates the spatial distribution of tritium concentrations from shallow lysimeters in 2015 based on kriging interpolation of sample data across the trench footprint. No data were available from lysimeter VL-10-North_Center in 2015, and for the purpose of kriging interpolation, VL-11_NW_Sump data were omitted in favor of nearly co-located VL-13 data, and data from the AT lysimeter was repositioned to the perimeter of ET1.

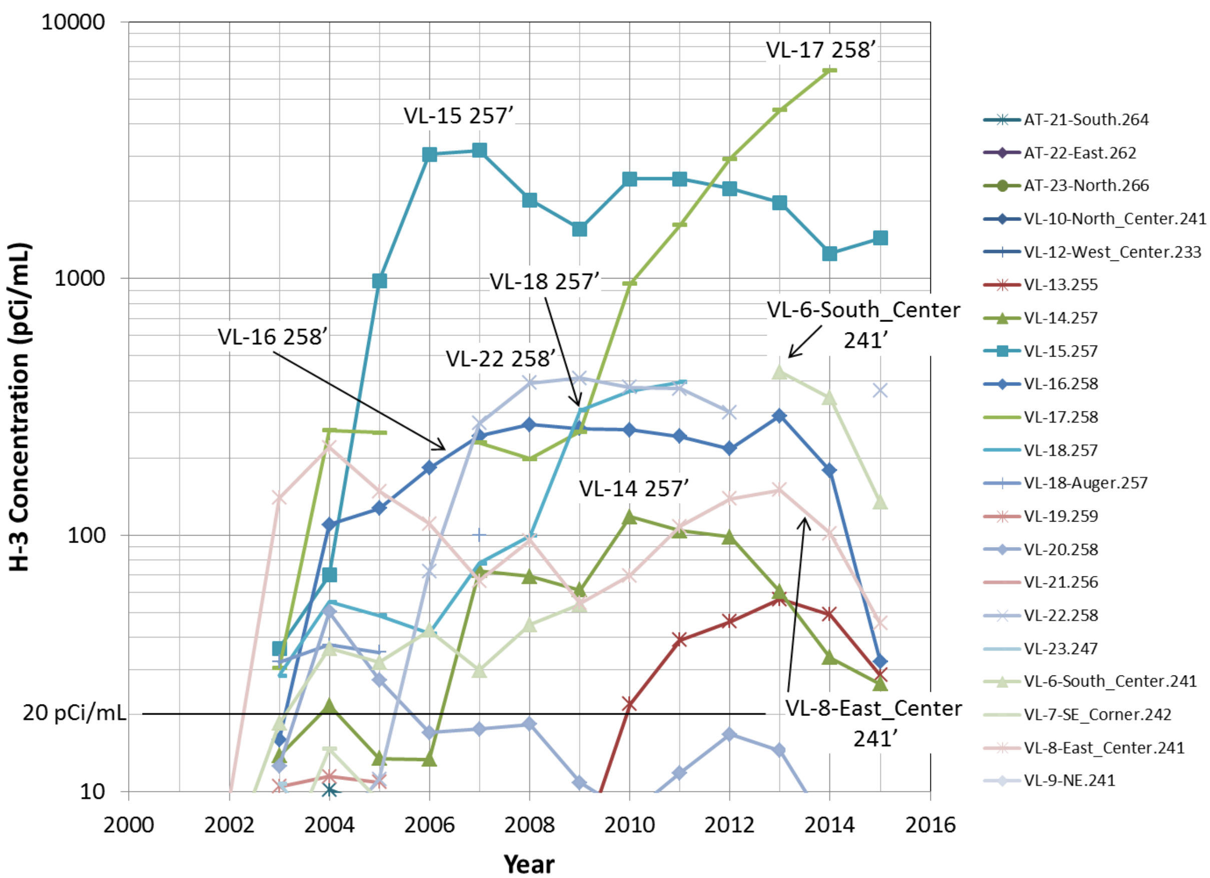


Figure 3-2. Time history of tritium concentrations in ET1 shallow vadose zone VZMS lysimeters.

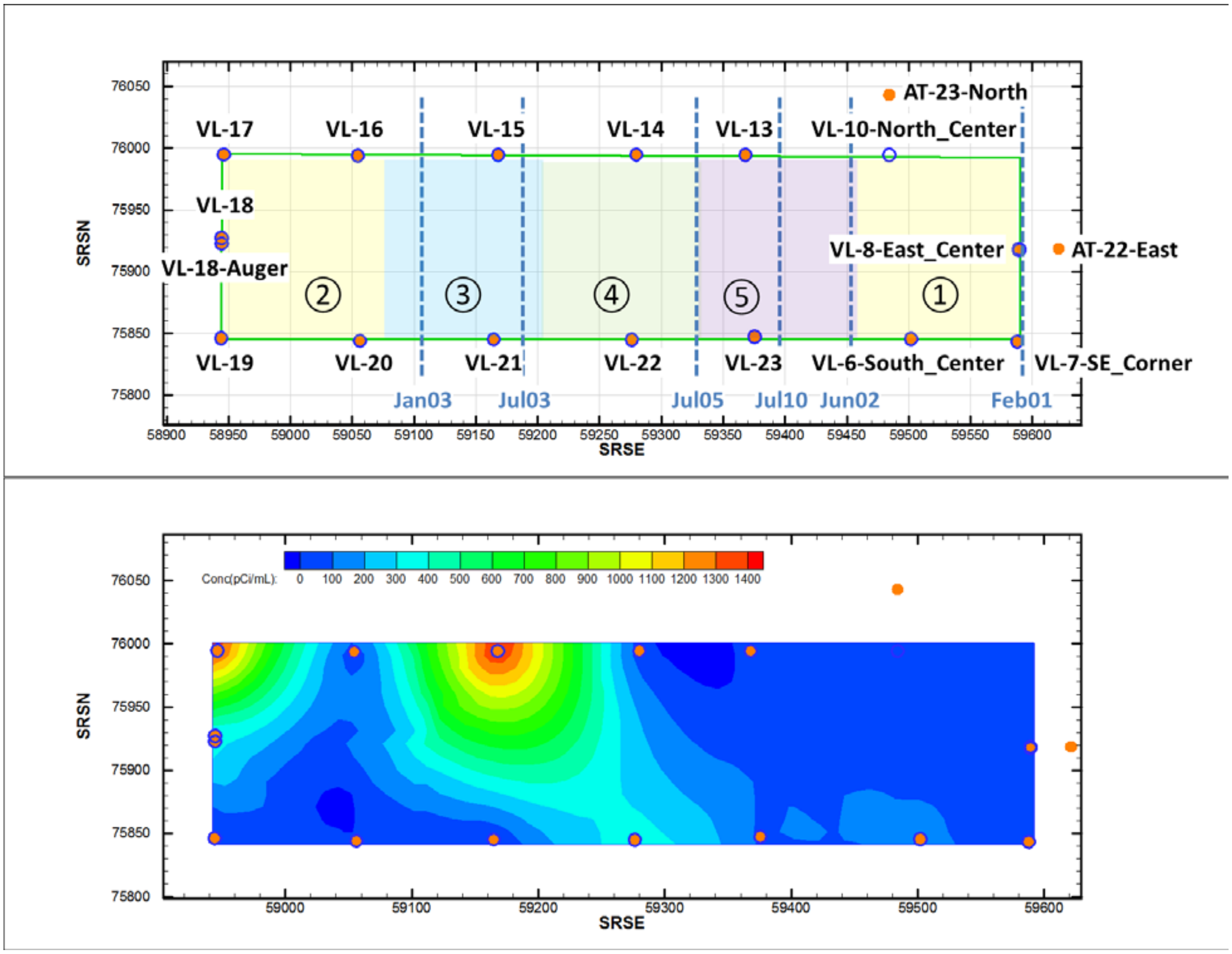


Figure 3-3. Labeled locations of ET1 lysimeters and spatial map of shallow lysimeter concentrations in 2015.

Table 3-1. VZMS tritium concentrations at ET1 through 2015.

H-3 Conc. [pCi/mL]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Max. conc.
AT-21-South	8.5	9.5	8.6	11.9	11.0	10.7	8.9	7.3	6.3		5.7	6.1				11.9
235	8.5	9.5	8.6	9.0	8.5	7.9	7.0	7.3	6.3		5.7	6.1				9.5
240				9.3	7.4											9.3
255				11.9	11.0	10.7	8.9									11.9
264				10.2	8.6	8.1										10.2
AT-22-East	10.1	11.3	9.5	10.7	7.9	8.6	6.6	6.9	6.3	6.7	6.3	6.1	6.7	5.8	4.8	11.3
233 (AL)	9.4	8.6	8.6	8.6	7.5	6.5	6.6	6.6	6.3	6.7	6.3	6.1	6.7	5.8	4.8	9.4
238	9.0	8.7	8.8	8.6	7.7	8.6	6.3	6.9	5.3	4.9	4.7	4.4	4.7	4.1	3.5	9.0
253	10.1	11.3	9.5	10.7	6.6	5.4		5.1	4.7	4.5	4.6	4.5	4.6	4.0	3.9	11.3
262	9.2	9.4	9.1	9.0	7.9	6.7	5.8	5.6								9.4
AT-23-North	6.7	6.1	5.8	10.6	7.6	7.0	5.1	4.2	3.5	3.3	3.7	3.8	3.5	3.5	3.2	10.6
237 (AL)	5.5	5.8	5.8	10.6	4.8	4.4	4.5	4.2	3.5	3.3	3.1	3.3	3.3	3.5	3.2	10.6
242	6.7	6.1	5.6	5.9	5.3	4.1	4.0	3.7	3.4	3.3	3.7	3.8	3.5	3.2	2.7	6.7
257				6.3	6.5	5.9	5.1									6.5
266				9.1	7.6	7.0										9.1
VL-10-North_Center	4.5	7.2	6.4	8.5	7.2	7.4	6.8	6.3	5.1	5.2	4.7	3.9	4.9			8.5
219				5.5			0.5									5.5
233 (AL)	4.1	7.2	6.4	6.3	7.0	7.4	6.8	6.3	5.1	5.2	4.7	3.9	4.9			7.4
241	4.5	6.2	5.9	8.5	7.2	6.7	6.7									8.5
VL-11-NW_Sump	6.5	6.5	3.6	4.7	6.0		4.5	9.3	10.3	6.7						10.3
220	6.5	6.5	3.6	4.7	6.0		4.2	9.3	10.3	6.7						10.3
241							4.5									4.5
VL-12-West_Center	8.4	6.6	4.8	11.1	4.7	4.5										11.1
219				11.1												11.1
233	8.4	6.6	4.8	3.9	4.7	4.5										8.4
VL-13			9.0	8.2	6.2	6.5	20.6	4.7	8.2	22.0	39.0	46.1	56.4	89.5	28.7	89.5
229 (AL)			9.0	8.2	4.2	2.6	2.7	3.3	3.1	3.1	3.6	4.0	5.6	7.1	7.1	9.0

H-3 Conc. [pCi/mL]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Max. conc.
237			4.3	5.3	3.5	4.8	4.5	4.3	8.2		8.2	26.1	20.2	89.5	28.7	89.5
244			5.9	6.1	4.5											6.1
247			5.9	5.3	4.5	5.2	20.6	4.7	4.7	4.9	9.5	15.1	35.5	34.8	13.9	35.5
254			6.3	4.2	5.7	5.4	7.1		6.2	10.7	23.5	17.9	26.3		20.0	26.3
255			4.8	5.4	6.2	6.5	7.7	4.7	5.8	22.0	39.0	46.1	56.4	49.0	28.5	56.4
VL-14			13.8	21.7	13.5	45.6	73.1	69.1	61.1	118.0	115.1	98.3	60.2	77.4	62.7	118.0
229			6.1	5.6	5.8											6.1
239 (AL)			6.3	8.2	7.9	8.3	8.5	11.4	11.1	11.2	10.2	11.1	20.5	53.0	49.5	53.0
246			8.3	8.3	8.6	31.2	73.1	20.3	18.2	18.0	26.0	31.7	44.9	49.1	45.0	73.1
251			9.4	9.9	10.4	11.0	25.2	20.4	19.5	25.9	115.1	47.0	55.0	77.4	62.7	115.1
255			9.6	15.6	9.9	45.6	29.9	32.1	37.9	38.0	47.1	61.3	40.6	51.8	26.2	61.3
257			13.8	21.7	13.5	13.4	72.8	69.1	61.1	118.0	104.1	98.3	60.2	33.3	26.4	118.0
VL-15			36.2	69.8	1003.0	3040.0	3151.8	2051.7	1831.0	2447.7	2445.5	2387.3	2128.0	1467.9	1434.5	3151.8
228 (AL)			6.2	4.5	5.6	6.4	4.3	5.7	5.3	6.7	10.7			26.2		26.2
235			3.8	4.4	7.7	17.9	23.1	27.3		39.9	90.6	204.0		704.6	1057.9	1057.9
241			4.7	47.4	52.3	49.4	196.5	450.2	558.1	726.6	1376.2	1577.4	1454.9	993.7	722.1	1577.4
244			6.1	55.4	52.8	123.0	409.8	618.2	763.0	1098.7	1366.9	2387.3	1576.5	1467.9	446.4	2387.3
251			24.7	53.7												53.7
255			33.8	66.6	1003.0	1930.0	2594.9	2051.7	1831.0	2358.1	2370.4	2273.2	2128.0	1063.0	1174.0	2594.9
257			36.2	69.8	980.0	3040.0	3151.8	2026.0	1558.4	2447.7	2445.5	2242.8	1977.8	1252.9	1434.5	3151.8
VL-16			97.0	110.0	127.0	183.0	243.2	270.1	259.9	257.5	242.6	217.5	292.3	214.9	60.0	292.3
229			97.0	57.7	20.3	26.4	11.3									97.0
235 (AL)			8.0	13.9	8.2	8.0	8.6	8.4	8.4	8.8	8.7	9.4	8.5	8.1	8.4	13.9
241			8.9	11.0	10.9	10.7	11.5	11.1	11.3	11.4	11.4	14.8	15.3	13.4	13.9	15.3
247			12.1	15.4	16.9	17.6	15.2	14.5	16.5	23.4	19.6	14.9	17.4	14.4	10.4	23.4
251			14.0	23.4	23.1	25.6	31.8	40.7	43.6	28.1	20.4	41.9	25.0	24.5	19.1	43.6
255			15.7	49.5	95.6	140.0	144.2	148.6	152.6	149.2	146.5	144.4	146.6	214.9	60.0	214.9
258			16.0	110.0	127.0	183.0	243.2	270.1	259.9	257.5	242.6	217.5	292.3	178.1	32.2	292.3

H-3 Conc. [pCi/mL]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Max. conc.
VL-17			30.3	256.0	251.0	177.0	229.7	215.9	264.0	955.2	1618.7	2932.8	4533.0	6472.1	1387.7	6472.1
231 (AL)			8.4	17.9	10.5	10.2	11.3	9.3	9.3	9.2	8.6	10.7	10.2	14.4	11.2	17.9
238			9.7	10.9	11.6	11.4	11.7	11.2	10.7	12.2	11.2	15.1	17.8	19.5	25.3	25.3
243			9.1													9.1
247			10.0	18.9	17.7	18.3	22.9	32.0	58.9	65.6	69.8	199.6	247.1	255.7	202.4	255.7
251			11.3	25.9	42.9		82.3									82.3
256			16.3	104.0	146.0	177.0	199.9	215.9	264.0	259.0	277.3	483.1	1043.3	1232.9	1387.7	1387.7
258			30.3	256.0	251.0		229.7	198.2	253.3	955.2	1618.7	2932.8	4533.0	6472.1		6472.1
VL-18			148.0	638.0	428.0	186.0	77.8	99.5	307.1	365.0	394.3	459.2	256.9	267.9	262.7	638.0
229			148.0	638.0	428.0	186.0										638.0
234 (AL)			8.0	8.0	7.0	7.3	6.0	6.5	5.8	5.7	6.9	12.6	5.3	5.7	5.6	12.6
240			7.7	8.6	7.9	8.2	7.8	7.9	7.7	7.1	7.6	7.4	8.6	6.8	6.7	8.6
248			8.7	11.8	14.0	15.6	17.8	20.8	23.8	29.4	33.6	45.5	41.0	44.2	46.8	46.8
250			10.1	15.5	16.8	18.2	21.5	29.6	42.0	52.0	61.4	246.3	67.2	71.0	72.2	246.3
254			16.9	61.1	63.4	61.7	71.6	86.3	139.0	157.8	220.5	459.2	256.9	267.9	262.7	459.2
257			28.4	54.9	48.7	41.5	77.8	99.5	307.1	365.0	394.3					394.3
VL-18-Auger			32.1	39.1	141.0	33.6	99.8	182.3	351.6	460.6	472.6		434.6	414.6	370.5	472.6
229					141.0		8.8									141.0
234 (AL)			6.1	6.6	6.7	6.7	6.1	2.1	5.3	5.0	5.7		5.3	4.4	4.7	6.7
240			6.6	8.3	7.3	9.4	6.0	6.0	6.0	6.6	6.6		6.4	6.8		9.4
248			14.3	31.0	25.1	21.4	20.0	21.1	20.8	28.3	35.7		47.7	52.5	59.4	59.4
250				25.8	25.2			25.8	34.8	52.2	78.9		97.1	102.4	103.3	103.3
254			20.1	39.1	37.4	33.6	41.7	182.3	351.6	460.6	472.6		434.6	414.6	370.5	472.6
257			32.1	37.4	35.0		99.8									99.8
VL-19			163.0	264.0	181.0	174.0	145.8	7.4	8.4	9.0	8.4	7.9	7.7	6.7	5.6	264.0
230			163.0	264.0	181.0	174.0	145.8									264.0
238 (AL)			7.9	8.4	7.4	7.2	6.9	7.4	8.4	8.5	8.4	7.9	7.7	6.7	5.6	8.5
245			7.4	14.8												14.8

H-3 Conc. [pCi/mL]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Max. conc.
252			7.9	8.4	7.6											8.4
255				9.2	8.7	9.6	10.6									10.6
259			10.5	11.5	10.9					9.0						11.5
VL-20			12.6	50.2	27.3	17.0	17.6	18.3	10.9	161.7	11.9	16.7	14.5	7.0	7.3	161.7
230			7.5													7.5
240 (AL)						6.6										6.6
243			9.6	8.8	8.2	7.5	7.1	6.5	5.8	161.7	5.9	6.0	6.2	5.8		161.7
258			12.6	50.2	27.3	17.0	17.6	18.3	10.9	8.2	11.9	16.7	14.5	7.0	7.3	50.2
VL-21			8.7	9.3	9.8	6.7	5.9	15.7	4.0	4.6	88.2	6.1			5.7	88.2
228			5.6	6.8	6.7	6.7	5.9									6.8
235							3.7									3.7
239			6.2	7.2	5.4	5.2	4.3	4.6	4.0	4.6	88.2	6.1			5.7	88.2
246			6.6	8.8	9.8			15.7								15.7
254			5.4													5.4
256			8.7	9.3												9.3
VL-22			6.6	6.6	11.2	72.5	272.9	391.7	409.6	376.7	380.5	356.9			404.8	409.6
230 (AL)			6.6	6.5	5.7	5.6	5.2	5.0	4.3	4.0	4.1	4.5			48.6	48.6
241			5.6	6.3	5.2	4.9	4.5	5.3	8.6	27.4	165.1	191.5			245.8	245.8
251			5.5	5.9	6.0	13.8	55.0	121.7	263.1	373.1	380.5	356.9			404.8	404.8
258			5.1	6.6	11.2	72.5	272.9	391.7	409.6	376.7	373.0	300.7			364.9	409.6
VL-23			10.8	8.3	6.2	6.4	5.2	5.6	5.2	5.5	4.7	5.2		11.8	121.2	121.2
230 (AL)				6.8	6.2	6.3	5.2	5.6	4.6	4.7	4.7	5.2		11.8	121.2	121.2
241			6.2	8.3	6.1	6.4		5.6	5.2	5.5						8.3
247			10.8	6.3												10.8
VL-6-South_Center	11.4	11.9	18.5	36.2	32.0	42.6	39.4	44.8	53.8		41.5	49.4	502.1	342.8	389.0	502.1
219	11.4			10.7	9.3	7.7										11.4
233 (AL)		11.9	10.8	8.7	26.2	36.3	39.4		34.6		41.5	49.4	502.1		389.0	502.1
241		5.4	18.5	36.2	32.0	42.6	29.7	44.8	53.8				432.9	342.8	134.6	432.9

H-3 Conc. [pCi/mL]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Max. conc.
VL-7-SE_Corner	10.8	10.5	5.1	14.7	9.2	9.1	9.1	9.2	5.8	5.4	5.3	5.7	6.5	9.3	9.2	14.7
214						7.4										7.4
219	10.8	10.5														10.8
233		9.5														9.5
235.7 (AL)									5.2	5.1	5.0	5.1	5.5	9.3	9.2	9.3
242		5.6	5.1	14.7	9.2	9.1	9.1	9.2	5.8	5.4	5.3	5.7	6.5	5.9	5.4	14.7
VL-8-East_Center	8.3	9.3	140.0	220.0	148.0	111.0	66.5	95.5	54.3	69.7	108.4	138.6	149.8	101.6	63.0	220.0
220	5.6			6.7												6.7
233	7.0															7.0
234.9 (AL)									9.8	16.4	29.4	41.1	48.9	64.0	63.0	64.0
241	8.3	9.3	140.0	220.0	148.0	111.0	66.5	95.5	54.3	69.7	108.4	138.6	149.8	101.6	45.3	220.0
VL-9-NE	5.1	6.5	6.0	6.7	4.3	4.4	4.2				4.1	3.8	4.4			6.7
213						4.4	4.2									4.4
219	5.0	6.5														6.5
233		6.3	6.0	6.7	4.3	4.4										6.7
241	5.1										4.1	3.8	4.4			5.1
Max. conc.	11.4	11.9	163.0	638.0	1003.0	3040.0	3151.8	2051.7	1831.0	2447.7	2445.5	2932.8	4533.0	6472.1	1434.5	6472.1

The *average* concentration of tritium expected in the waste zone can be estimated from the WITS inventory (2.21 Ci) and estimated material properties and saturation state. Table 3-2 summarizes a calculation assuming boxed waste (Phifer and Wilhite 2001) and waste zone soil saturation based on three assumptions: gravity equilibrium (no infiltration), 100% saturation, and field measurements (Phifer et al. 2006). Initial H-3 concentrations range from 742 to 1348 pCi/mL depending on the saturation assumption. Although dispersion and decay will attenuate tritium as it migrates from the waste zone into the shallow vadose zone, this calculation suggests that concentrations averaging several hundred pCi/mL can be expected from shallow lysimeters.

Because the VZMS tritium data vary widely, spanning approximately three orders of magnitude, average concentrations observed in the field just beneath the ET1 waste zone are not obvious from simple visual inspection of the spatial-temporal data. However, statistical techniques can be applied to subsets of the overall database to estimate representative concentrations (e.g. mean, median) and uncertainty ranges. In the statistical analysis that follows, concentrations acquired from lysimeters positioned around the perimeter of the disposal unit are assumed to be representative of the entire disposal area.

Going forward, two data subsets are considered to characterize tritium release to the shallow vadose zone. The first data population is composed of the peak H-3 concentration observed at any point in time for the shallow-most lysimeter at each plan-view location. For brevity these concentrations are identified using labels such as “Max_high” or “MaxAtHighElev”. The intent of this dataset is to include the peak concentrations leaving the ET1 waste zone and entering undisturbed native soil regardless of timing, recognizing that varying disposal times and container integrity likely resulted in varying plume arrival times at the various lysimeters. The second data population is a snapshot of H-3 concentrations observed in the shallow-most lysimeters in FY2015. The intent of this dataset is to consider near current conditions directly beneath the waste zone. This dataset is identified with abbreviated labels such as “2015_high” and “2015AtHighElev”.

A random process is described most completely through a detailed *statistical distribution* relating values to probability of occurrence, for example, a normal distribution $\mathbb{N}$ with mean μ and variance σ^2, $\mathbb{N}(\mu, \sigma^2)$. Figure 3-4 illustrates normal probability plots for (a) untransformed concentration and (b) the base 10 logarithm of concentration, based on the “Max_high” dataset. The observed degrees of fit indicate that VZMS concentrations are much better approximated by a *log-normal* distribution than a *normal* distribution.

Key characteristics of a distribution can be identified through various statistical measures, or *statistics*. Common statistics are the *mean* and *median* which define a representative central value, and the *variance* (or equivalently *standard deviation*) which measures the spread of the population. The statistical mean is the arithmetic average of the random variable or population. The median is the value for which half of the population values are below and the other half are above (50% cumulative probability).

The means of the “Max_high” and “2015_high” data are $m = (1/N)\sum_{i=1}^{N} c_i$= 536 and 247 pCi/mL, respectively, where N is the number of samples and c is concentration. These simple arithmetic averages do not account for data location or potential clustering. The spatial average of the interpolated “2015_high” data in Figure 3-3 is 228 pCi/mL. Thus accounting for data location slightly lowers the estimated mean (-8%). Because this difference is small, further statistical analyses ignore data locations and give equal weight to each lysimeter location.

Table 3-2. Estimated initial concentration of tritium in the ET1 waste zone.

Parameter	Value	Units	Comments
Trench length, L	650	ft	
	198.1	m	
Trench width, W	160	ft	
	48.8	m	
Cover thickness, D	4	ft	
	1.22	m	
Waste zone thickness, D	17.3	ft	B-25 boxes, stacked four high
	5.27	m	
Equiv. soil thick. in waste layer, D	2.2	ft	Based on WSRC-RP-2001-00613
	0.67	m	
Fraction of waste zone thickness	13%		
Vadose zone thickness, D	35	ft	
	10.67	m	
Waste volume, V	6479	m^3	
Porosity, n	0.46	cm^3 void / cm^3	Operational soil cover prior to compaction
H-3 inventory, I	2.21	Ci	As-disposed-of through 9/30/2015
Gravity equilbrium:			Expected average concentration - high estimate
Mean waste height above WT	13.30	m	Vadose zone + half of waste zone thickness
	1330	cm	Use to estimate saturation
Saturation, S	0.73	cm^3 water/cm^3 void	Manual lookup: Table 5-21, WSRC-STI-2006-00198
Water content, θ	0.33	cm^3 water / cm^3	
Water volume, V_w	2161	m^3	2160711 L
H-3 concentration, C	1022811	pCi/L	
	1023	pCi/mL	
Full saturation:			Expected average concentration - low estimate
Saturation, S	1.00	cm^3 water / cm^3 void	
Water content, θ	0.46	cm^3 water / cm^3	
Water volume, V_w	2980	m^3	2980291 L
H-3 concentration, C	741538	pCi/L	
	742	pCi/mL	
Field observations:			Expected average concentration - field observations
Saturation, S	0.55	cm^3 water / cm^3 void	Average of Sec. 5.8, WSRC-STI-2006-00198 range
Water content, θ	0.25	cm^3 water / cm^3	
Water volume, V_w	1639	m^3	1639160 L
H-3 concentration, C	1348251	pCi/L	
	1348	pCi/mL	

The standard deviations of the “Max_high” and “2015_high” sample means (standard error) are $s_m = s/\sqrt{N} = 316$ and 110 pCi/mL, where s is the sample standard deviation:

$$\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(c_i - m)^2}$$

Unless a set of samples exhibits a normal distribution, the distribution of the sample mean only approaches a normal distribution in the limit $N \to \infty$ (Central Limit Theorem; Box et al. 1978). The sample counts are $N = 22$ and 17 for the “Max_high” and “2015_high” datasets, respectively. Because the VZMS data exhibit a highly-skewed, approximately log-normal, population distribution (Figure 3-4), a substantially larger sample count N is almost certainly required to achieve an approximately normally distributed sample mean m. This expectation is supported by a calculation of the 95% confidence interval for the “Max_high” sample mean, naïvely assuming a normal distribution: $m - 1.96s_m < \mu < m + 1.96s_m$ where μ is the true mean of the population. The result is $-83 < \mu < 1156$ pCi/mL. The negative concentration defining the lower end of the interval is nonsensical and clear indication of non-normality. Thus uncertainty in the “Max_high” and “2015_high” sample means can only be crudely estimated assuming normality (e.g. $\pm 1.96s_m \approx \pm 2s_m$ or “2-sigma” uncertainty range).

A statistical *bootstrapping* technique (Efron, 1982) can be used to estimate the distribution of VZMS sample means, from which more accurate confidence intervals can be computed. In the bootstrap approach, the sample data are used as a surrogate for the true underlying population. Each bootstrapping realization is generated by randomly re-sampling the actual set of sample results (with replacement) to produce a new sample of the same size (e.g. a set of 15 samples would be randomly sampled 15 times for each realization). A sample mean is computed for each of many realizations. The distribution of realization sample means approximates the true distribution. Figure 3-5 summarizes bootstrapping results for the “Max_high” and “2015_high” datasets. Both sample mean distributions are skewed, but far less than the underlying sample data. The “Max_high” distribution displays several peaks, which apparently result from a small sample size ($N = 22$) and sample variability over three orders of magnitude. The “2015_high” distribution is much smoother, and probably a better approximation of its true population distribution. The median (50% cumulative probability) and 95% confidence interval results (2.5% and 97.5% cumulative probability) based on bootstrapping are $80 < 510 < 1156$ pCi/mL for the “Max_high” data and $65 < 237 < 485$ pCi/mL for the “2015_high” concentrations as shown in Table 3-3 (a).

Because the “Max_high” bootstrapping distribution exhibits clear artifacts of small sample size, the confidence interval for the “Max_high” sample mean is also estimated assuming the sample data are log-normally distributed, based on Figure 3-4(b). The mean and standard deviation of $log10(c)$ are taken as the sample mean and sample standard deviation. The resulting median and 95% confidence intervals are $84 < 315 < 1914$ pCi/mL, which is similar to the bootstrapping result (Table 3-3 (b)).

An alternative approach for analyzing VZMS sample data is to generate samples of $log10(c)$, compute the sample mean (m) and standard deviation (s_m) of $log10(c)$ for each realization, and estimate the sample mean of c by assuming a log-normal distribution and using the back transformation (Appendix D in Flach 2002):

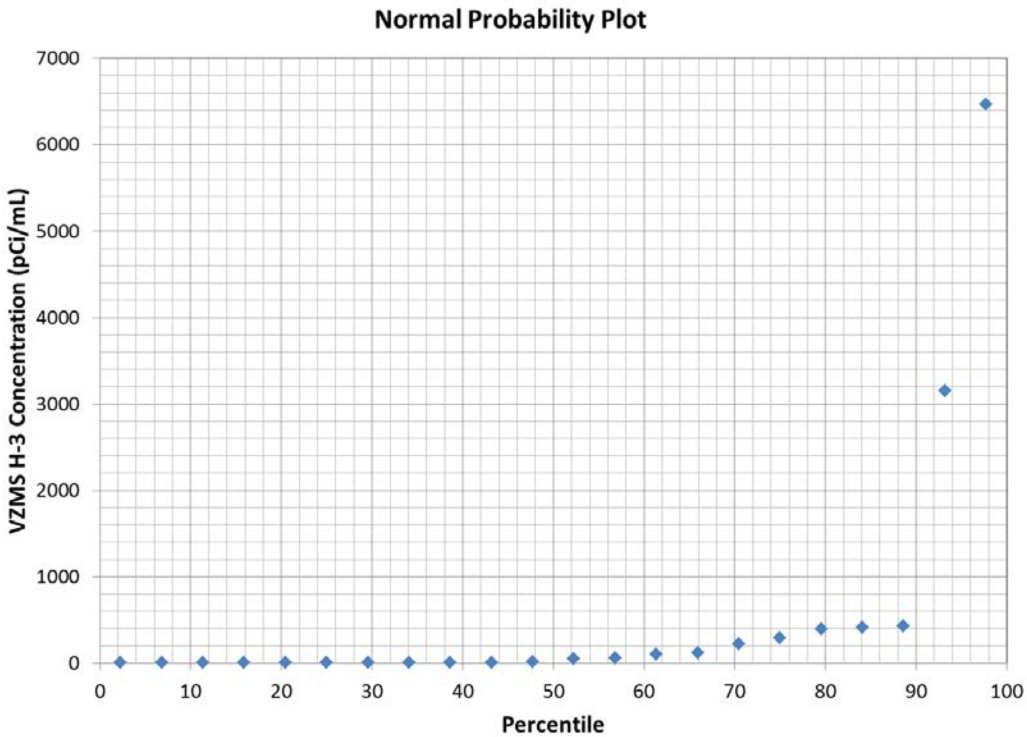
$$10^{m+s_m^2\ln(10)/2}$$

This approach can be applied to bootstrapping samples or samples drawn from an assumed log-normal distribution following Table 3-3 (a) and (b), respectively. The results of the alternative approach applied to the “Max_high” data set are summarized in Table 3-3 (c) and (d). The results from the four analyses of “Max_high” are similar.

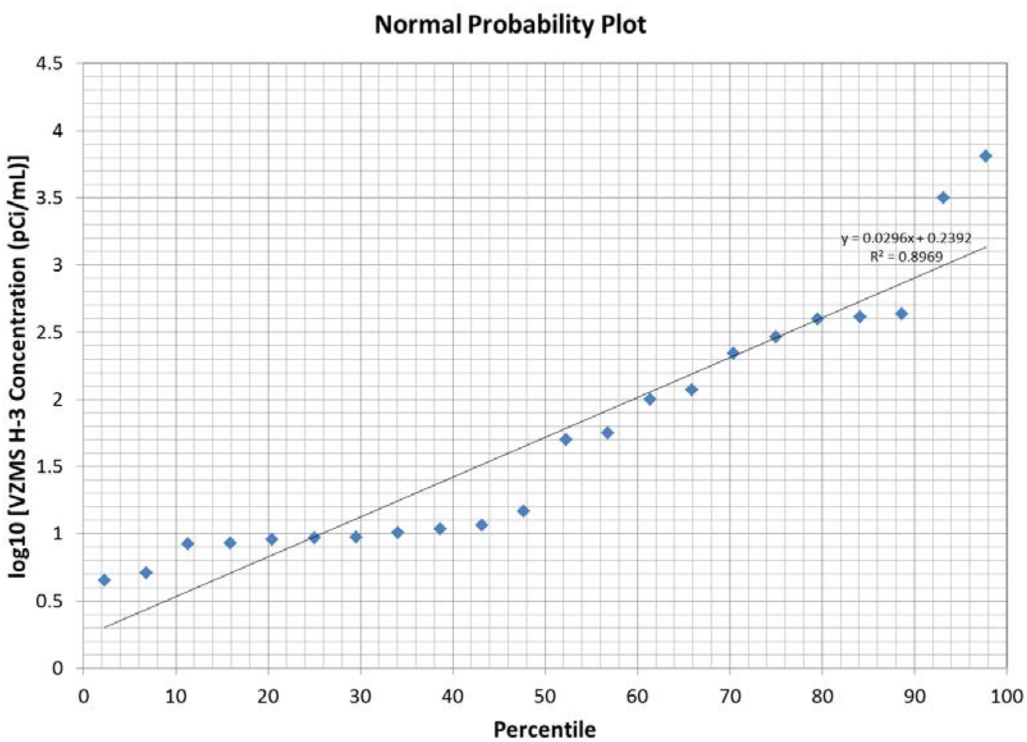
While Figure 3-4 indicates that a log-normal distribution better represents the sample data distribution than a normal distribution, the data distribution can be refined by optimizing a Box-Cox transformation of the sample set (Box et al. 1978, Section 7.9). For the “Max_high” data set the optimal power λ is -0.2, which is close to a log-normal distribution ($\lambda = 0$) and supports the log-normal approximations discussed above.

Qualitatively, the average sample concentrations appear to be consistent with the range of H-3 average concentrations estimated to initially reside in the ET1 waste zone (Table 3-2). However, decay and dispersion will attenuate the waste zone concentration as the plume migrates toward shallow lysimeter locations, precluding direct comparison of Table 3-2 and Table 3-3. To remedy this disconnect, subsurface flow and solute transport modeling is used in the next section to estimate H-3 concentrations in the undisturbed vadose zone beneath ET1.

Also of interest are tritium concentrations in the deep vadose zone from ET1 Action Level lysimeters, where lower concentrations are expected due to further decay and dispersion. Table 5-2 of Hiergesell et al. (2016) presents these data for FY2015. Statistical results for this dataset are presented in Figure 3-6 and Table 3-3.

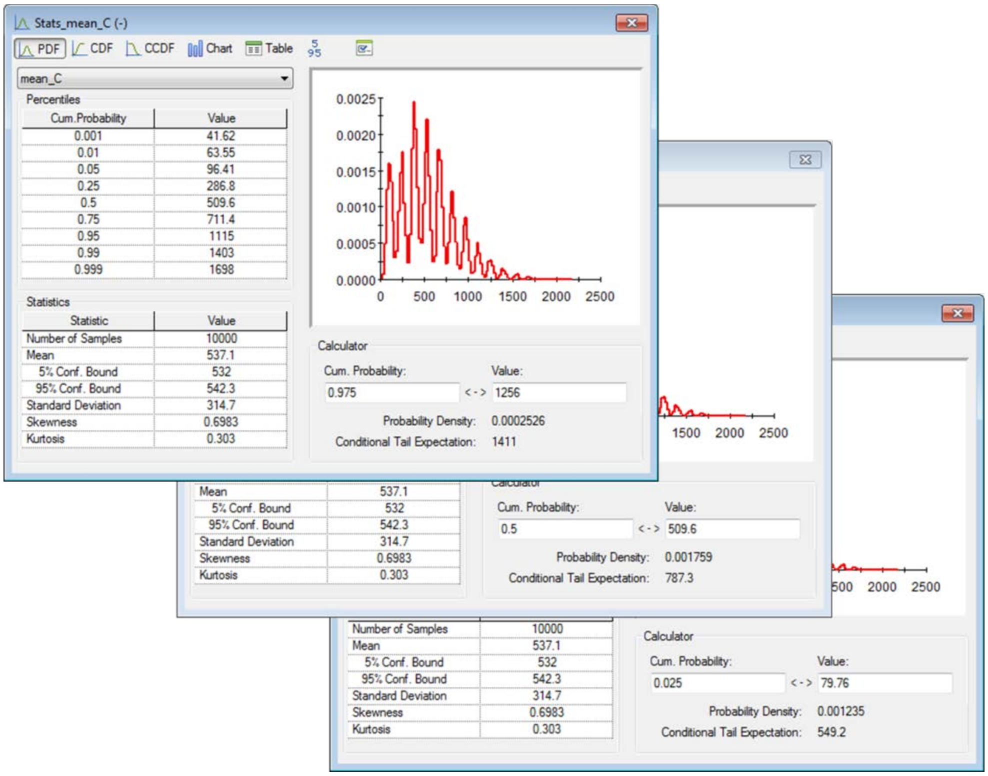


(a)

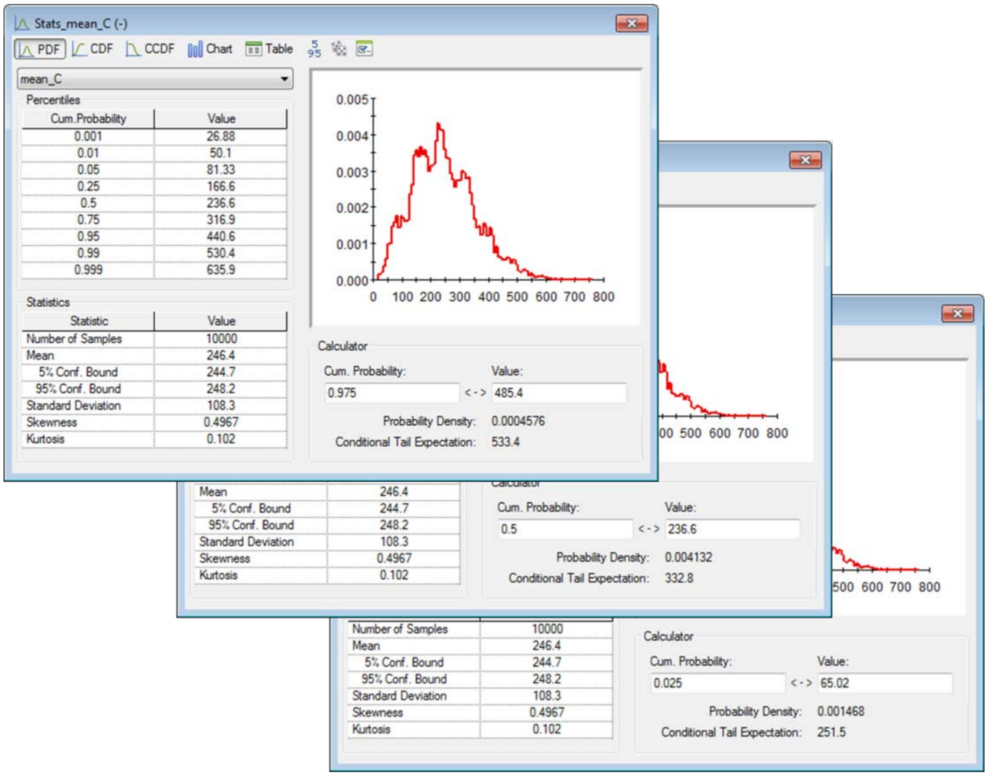


(b)

Figure 3-4. Normal probability plots for concentration and log10[concentration] using “Max_high” dataset.



(a)



(b)

Figure 3-5. Bootstrapping results for the (a) "Max_high" and (b) "2015_high" datasets.

Table 3-3. Summary of statistical analysis of VZMS data.

Dataset:	"Max_high"	"2015_high"	2015 Action Level
Standard sample statistics			
Sample count	22	17	16
Sample mean	536	247	121
Spatial average based on kriging interpolation	—	228	—
Standard deviation of the mean (Standard error)	316	110	68
Statistics on the Sample Mean			
(a) Bootstrapping technique w/ Sampling concentration			
2.5% cumulative probability, Lower limit of 95% CI*	80	65	22
25% cumulative probability	287	167	72
50% cumulative probability, Median	510	237	112
75% cumulative probability	711	317	161
97.5% cumulative probability, Upper limit of 95% CI	1156	485	267
(b) Log-normal distribution assumption w/ Sampling concentration			
2.5% cumulative probability, Lower limit of 95% CI	84	—	—
25% cumulative probability	193	—	—
50% cumulative probability, Median	315	—	—
75% cumulative probability	541	—	—
97.5% cumulative probability, Upper limit of 95% CI	1914	—	—
(c) Bootstrapping technique w/ Sampling log10(concentration)			
2.5% cumulative probability, Lower limit of 95% CI	75	—	—
25% cumulative probability	238	—	—
50% cumulative probability, Median	453	—	—
75% cumulative probability	862	—	—
97.5% cumulative probability, Upper limit of 95% CI	2873	—	—
(d) Log-normal distribution assumption w/ Sampling log10(concentration)			
2.5% cumulative probability, Lower limit of 95% CI	109	—	—
25% cumulative probability	279	—	—
50% cumulative probability, Median	480	—	—
75% cumulative probability	858	—	—
97.5% cumulative probability, Upper limit of 95% CI	3081	—	—

*CI = Confidence Interval

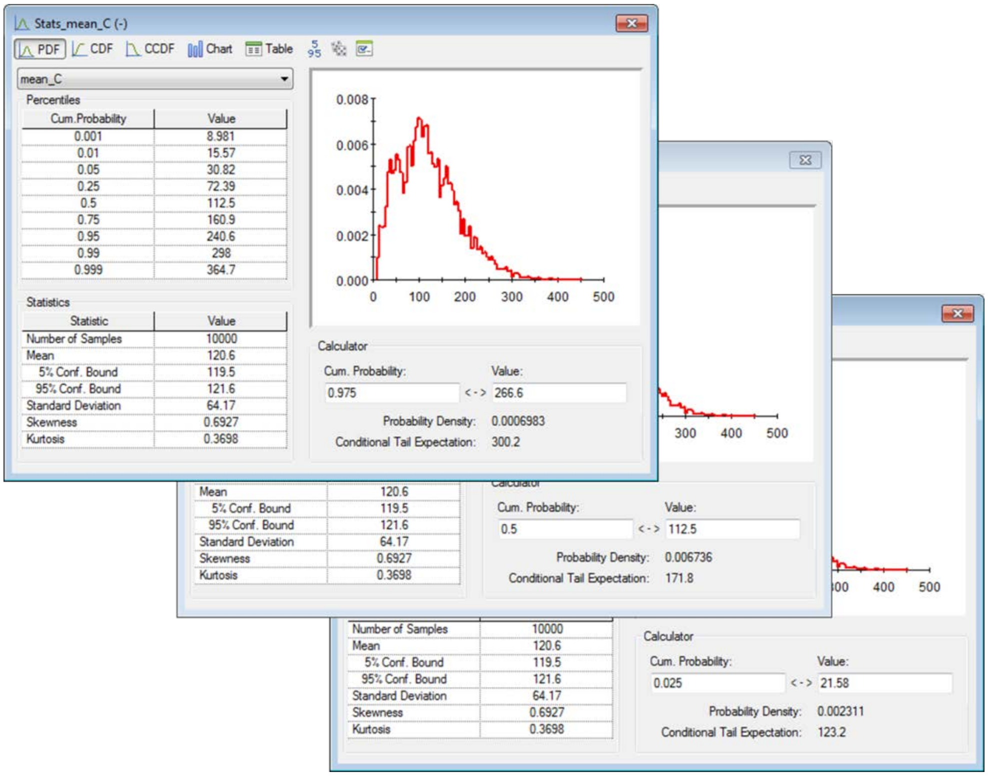


Figure 3-6. Bootstrapping results for FY2015 ET1 Action Level lysimeter dataset.

4.0 Radionuclide transport simulations

Performance Assessment simulations of radionuclide transport from disposal units to the 100-meter perimeter are composed of two-dimensional vadose zone flow and transport simulations and a three-dimensional aquifer transport simulation using a flow field extracted from the GSA/PORFLOW model (Flach 2004).

4.1 Vadose zone model simulations

A vadose zone flow and solute transport model for Engineered Trenches was developed for the 2008 E-Area Performance Assessment (WSRC 2008). Because model development occurred while disposal operations were underway for ET1 and predated ET2 operation, hypothetical conditions were assumed regarding waste disposal timing and distribution. Specifically, the 2008 PA assumed: (a) uniform waste disposal within the entire excavated volume (including side slopes), (b) the disposal unit was filled to capacity in a single instant, and (c) soil backfilled the entire excavated volume (no consideration of waste containers).

The as-disposed-of conditions of ET1 are: (a) non-uniform waste distribution excluding use of side-slope volume, (b) disposal operations occurring over several years, and (c) most waste disposals taking the form of B-25 and similar containers with low-density contents. To better reflect as-disposed-of condition (a), the 2008 PA vadose zone model was modified in this study by confining waste inventory to the full-depth portion of the trench excavation. Secondly, the model grid was refined to reduce numerical dispersion and enable more accurate monitoring of simulated concentrations at lysimeter elevations, as shown in Figure 4-1. This initial modification to the 2008 PA model is labeled Case01.

Figure 4-2 illustrates simulated concentration for Case01 at 1.0 year. The initial waste zone concentration is only 123 pCi/mL compared to much higher values in Table 3-3, because the waste zone is assumed to be completely filled with backfilled soil. Thus downstream plume concentrations cannot exceed 123 pCi/mL.

Figure 4-3 plots simulated H-3 concentrations at Edge and Center lysimeters at four depths: Upper, Middle, Lower and Water table elevations. VZMS data statistics from Table 3-3 are also shown for comparison, and those individual "Max_high" concentrations greater than 10 pCi/mL. The elapsed times for the sample data are the difference between the sample acquisition date and the estimated date of burial of nearby waste. The Upper_Edge and Upper_Center locations correspond most closely to the selected shallow VZMS data. Several VZMS data peaks occur after the time window predicted by the model. This discrepancy may be due to delays in waste release due to waste containment in B-25 boxes.

Although the magnitudes of the simulated Upper_Edge and Upper_Center concentrations are within the 95% confidence intervals for VZMS data, they fall close to the lower bound of the interval. This observation suggests a systemic model bias. The most likely cause of model bias in Case01 is the assumption of 100% backfill soil in the waste zone, which leads to a low initial concentration as discussed earlier. Table 3-2 indicates that a substantial increase in concentration can be realized by accounting for the low-density of uncompacted boxed waste. Figure 4-3through Figure 4-8 illustrate the results from five additional modeling cases that account for the B-25 box disposals in ET1.

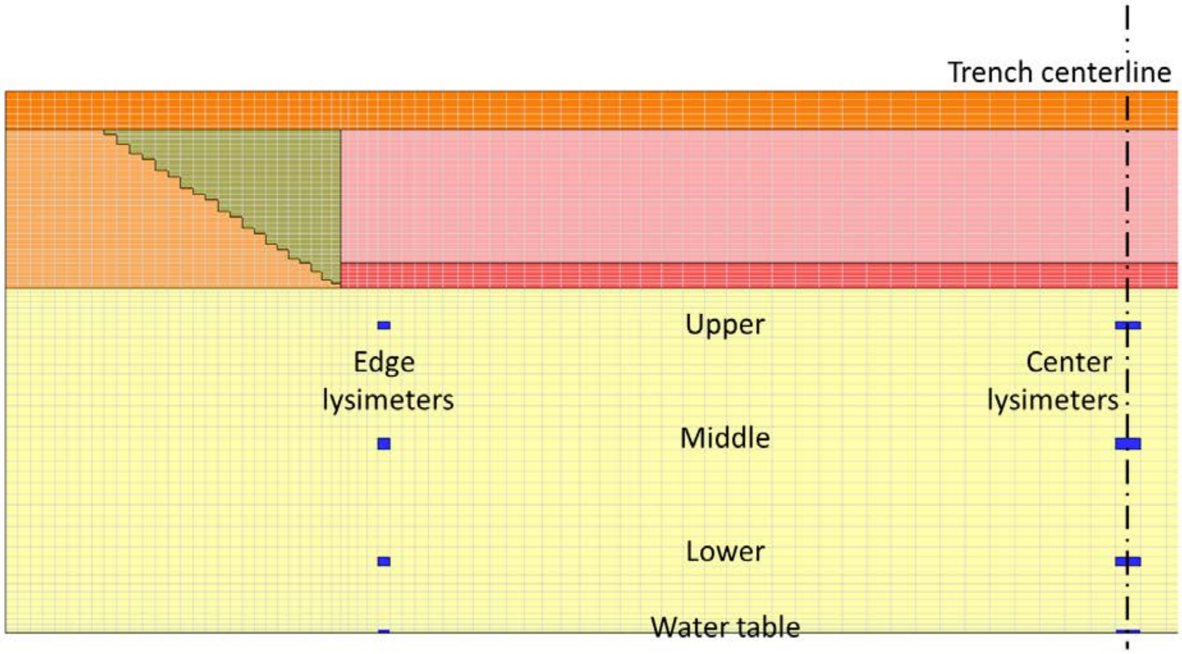


Figure 4-1. Refined vadose zone grid and added edge and center lysimeter observation points.

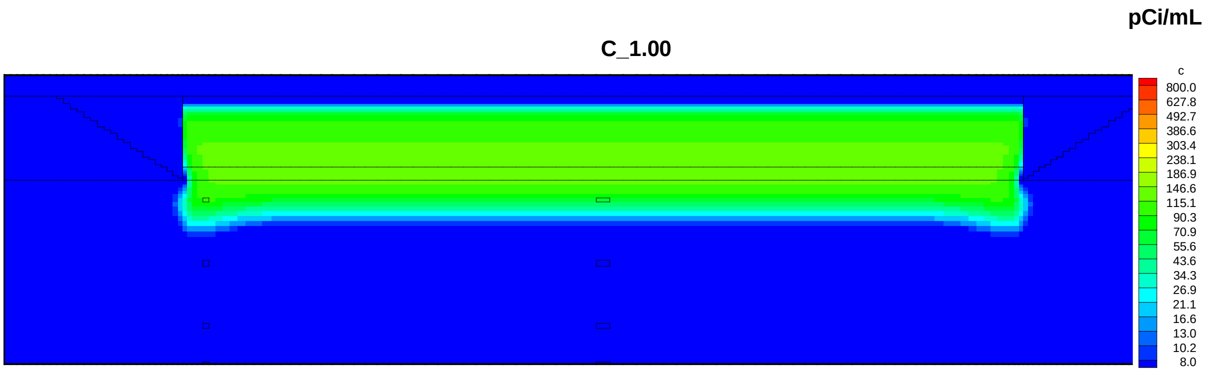


Figure 4-2. Simulated H-3 plume for Case01 at an elapsed time of 1.0 yr.

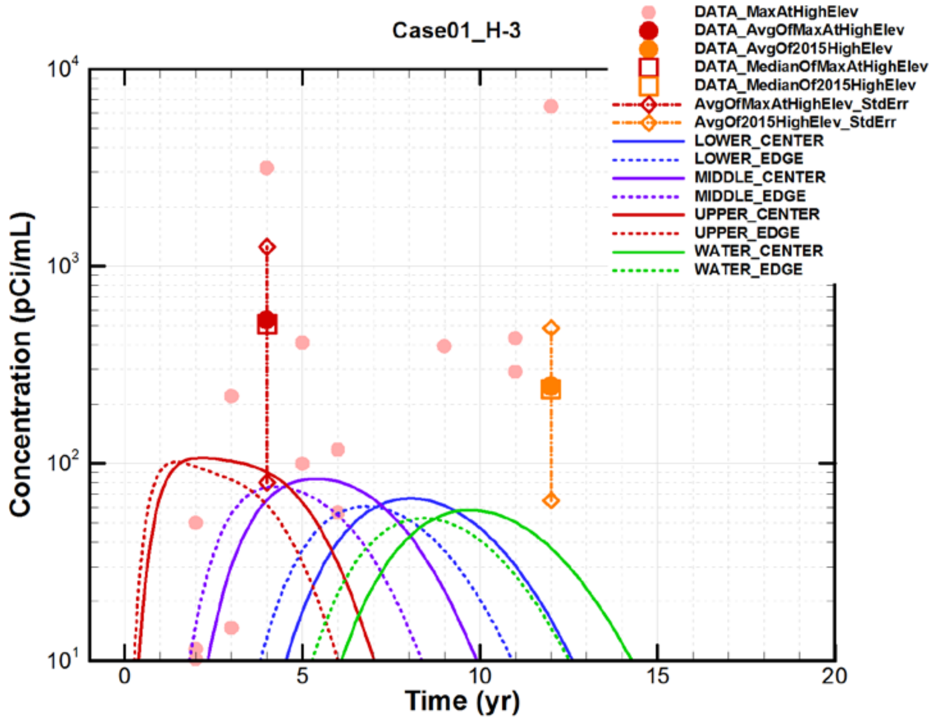


Figure 4-3. Simulated vadose zone concentrations for modeling Case01 -- PA + grid refinement + no side slope usage.

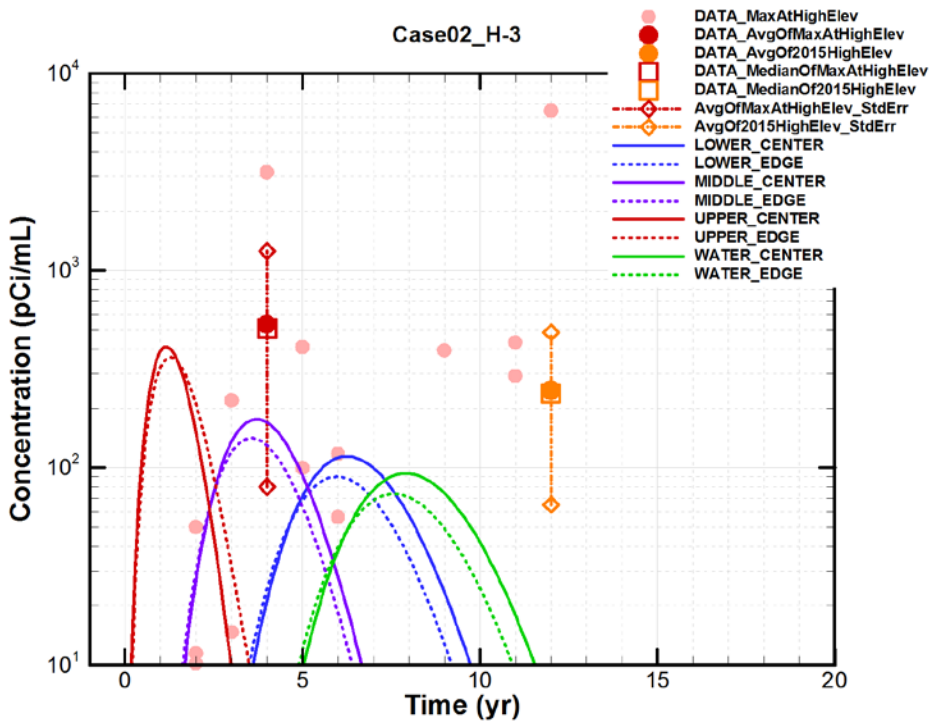


Figure 4-4. Simulated vadose zone concentrations for modeling Case02 -- B-25 boxes + no dispersion.

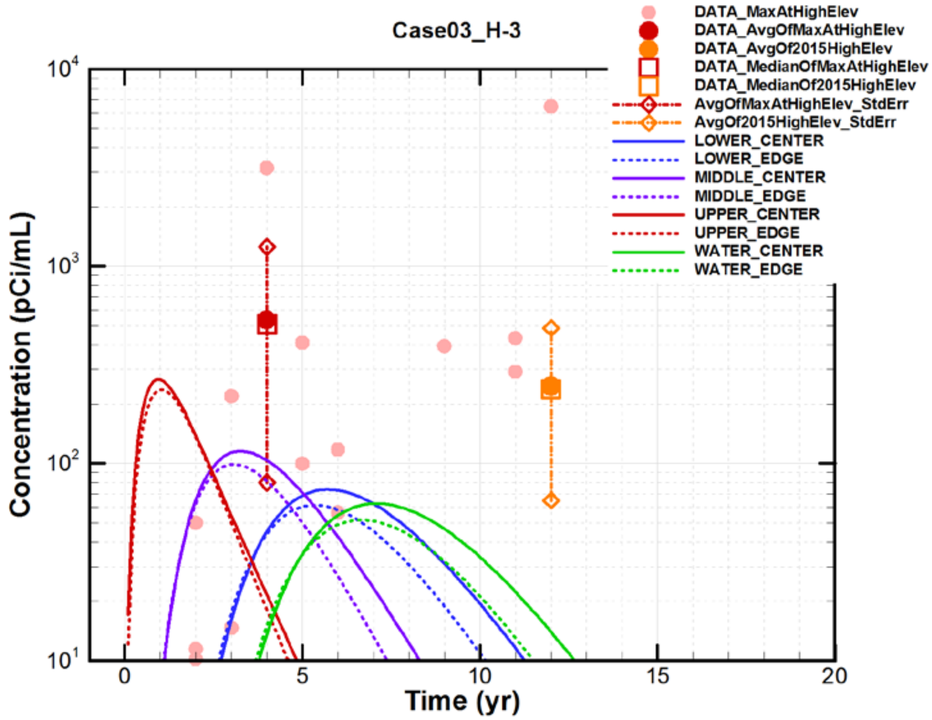


Figure 4-5. Simulated vadose zone concentrations for modeling Case03 -- B-25 boxes + 5% dispersivity.

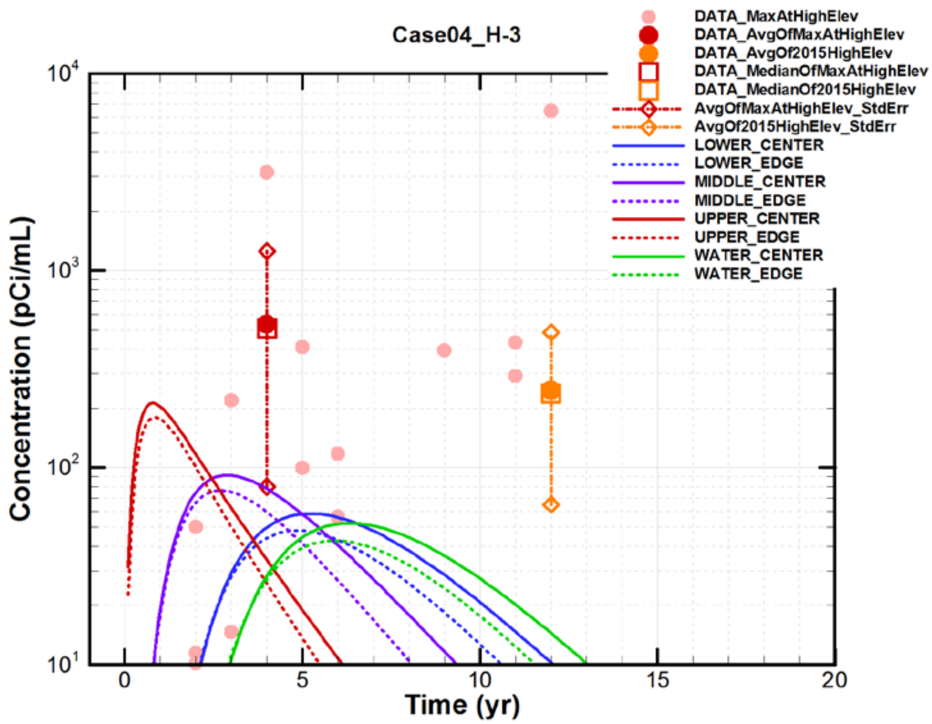


Figure 4-6. Simulated vadose zone concentrations for modeling Case04 -- B-25 boxes + 10% dispersivity.

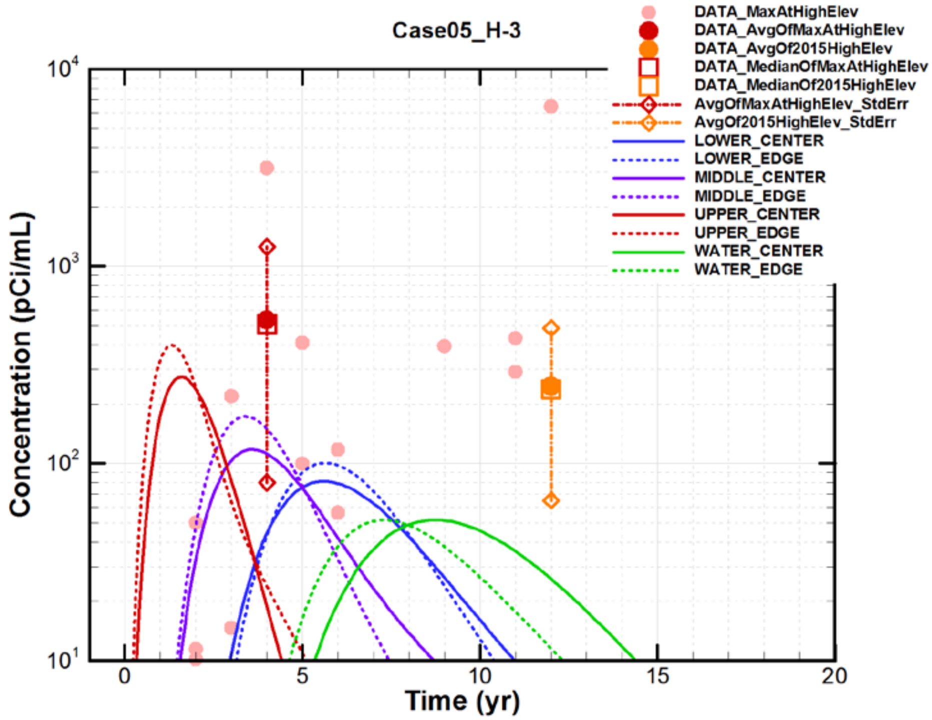


Figure 4-7. Simulated vadose zone concentrations for modeling Case05 -- B25 boxes + 25% low permeability in undisturbed soil.

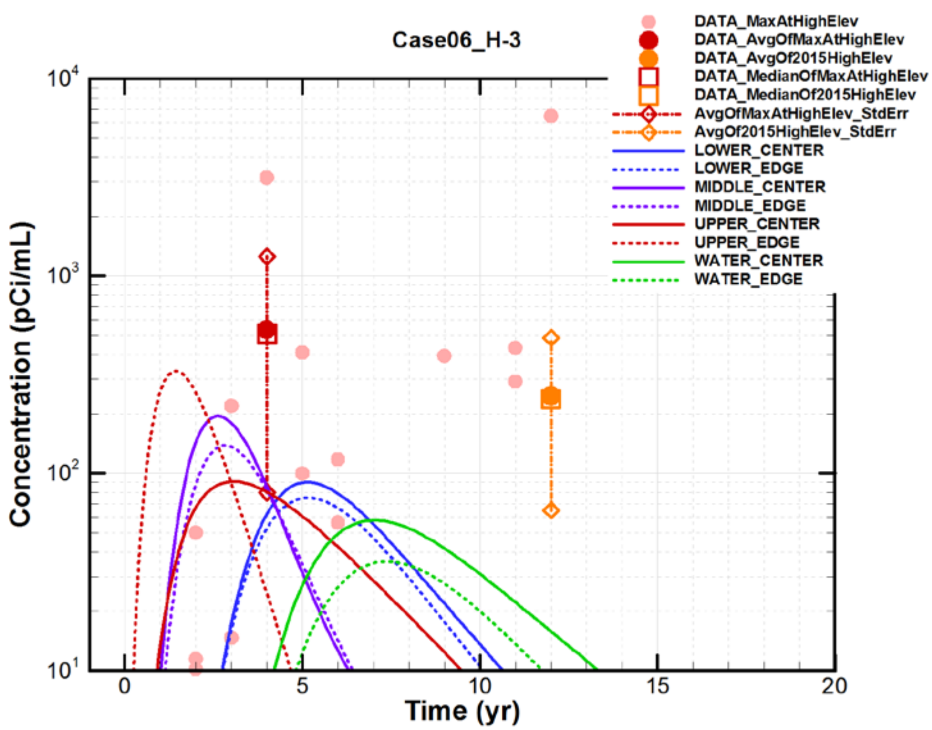


Figure 4-8. Simulated vadose zone concentrations for modeling Case06 -- B25 boxes + 35% low permeability in undisturbed soil.

For B-25 boxes stacked four high, typical of ET1 disposal operations (Figure 2-3), Phifer and Wilhite (2001, Section 6.0) estimated a subsidence potential of 15.1 ft out of a 17.3 ft stack height. This subsidence potential implies 87% void space in containers not counting material porosity. Appendix A presents a derivation of equations for blending the porous-medium properties of two distinct materials to achieve the equivalent properties of the composite material. Table 4-1 and Figure 4-9 summarize the properties of the composite material. The presence of significant void space in uncompacted boxed waste disposal results in significantly lower water content (and hydraulic conductivity). The lower water content significantly raises the initial waste zone concentration, along the lines of the concentrations shown in Table 3-2.

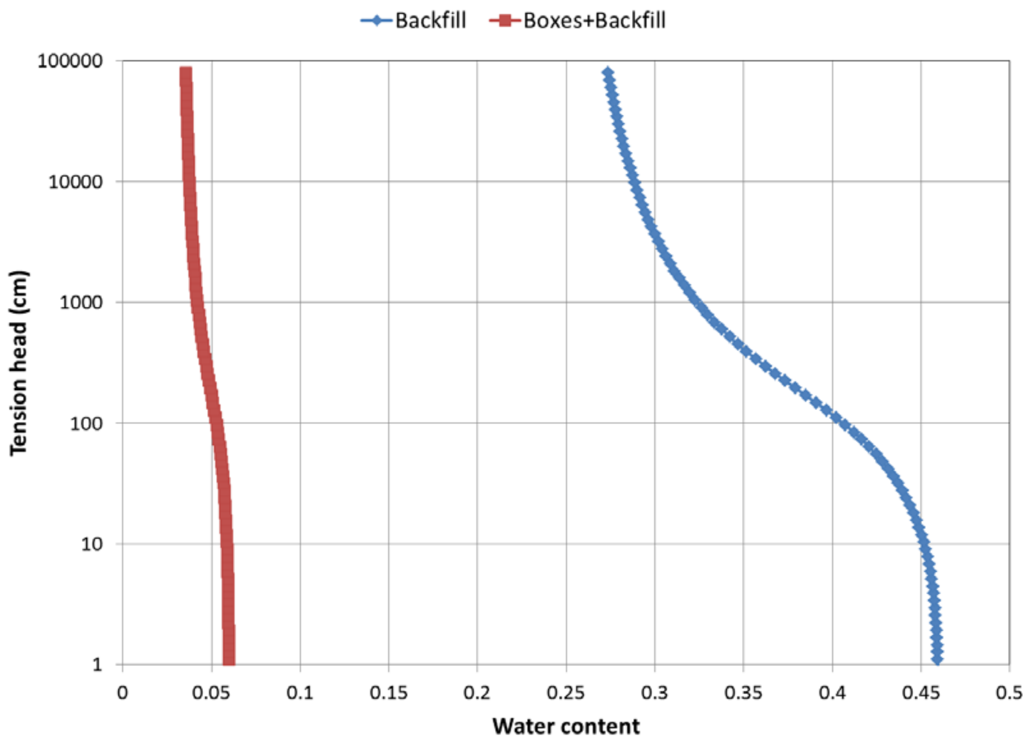
Table 4-1. Material properties of blended backfill soil and low-density boxes.

Parameter	Material 1	Material 2	Blend	Units	Comments
	OSC				Operational soil cover (OSC) before dynamic compaction
		Box			Box minus contents (void space)
			ET waste		Effective properties of ET waste zone, prior to compaction
Volume fraction	0.13	0.87	1		WSRC-RP-2001-00613, Section 6.0 -- 15.1 ft subsidence potential out of 17.3 ft stack height for B-25 boxes
Porosity	0.46	1	0.9298		
Solid density	2.65	2.65	2.65	g/mL	
Bulk density	1.431	0	0.18603	g/mL	
Saturated hydraulic conductivity	3.8E+03 1.2E-04	0 0.0E+00	4.94E+02 1.6E-05	cm/yr cm/s	Box void space assumed to be impermeable

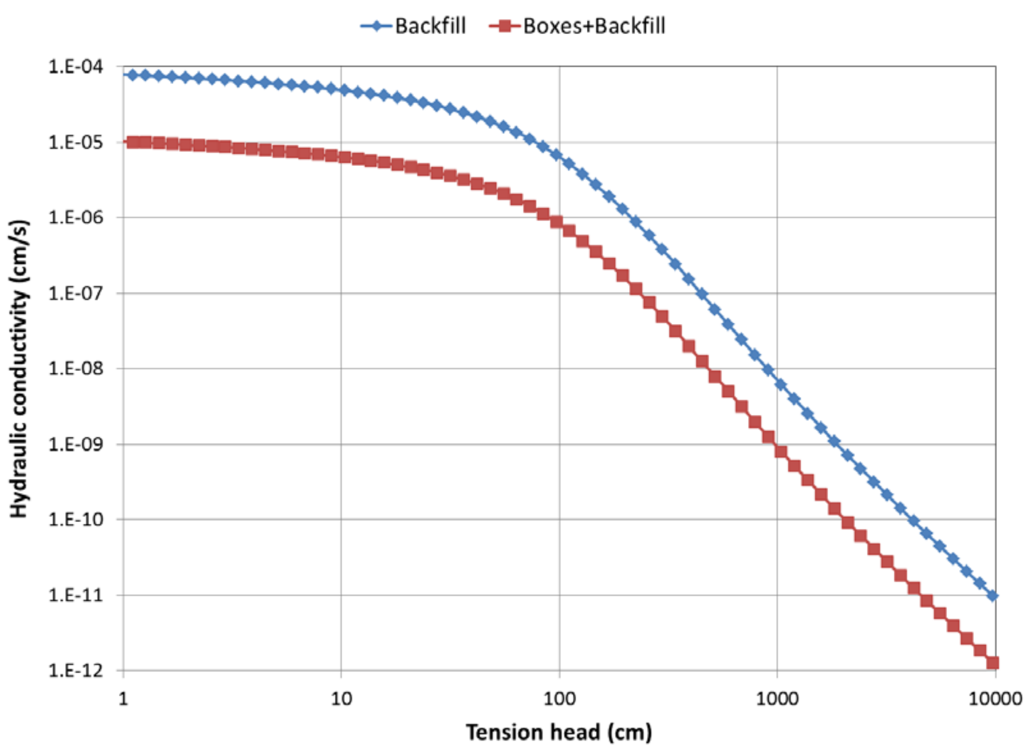
The five additional modeling cases using the waste zone properties shown in Table 4-1 and Figure 4-9 are summarized as follows:

- Case02: B-25 box + dispersivity = 0% of plume travel distance
- Case03: B-25 box + dispersivity = 5% of plume travel distance
- Case04: B-25 box + dispersivity = 10% of plume travel distance
- Case05: B-25 box + 25% low-permeability soil beneath waste zone
- Case06: B-25 box + 35% low-permeability soil beneath waste zone

All five cases have an initial concentration in the waste zone of 873 pCi/mL for an ET1 tritium inventory of 2.21 Ci. Case02 maximizes the peak concentration at downstream lysimeter locations by minimizing plume dispersion. The peak simulated concentrations at the shallow Upper lysimeters are around 400 pCi/mL, which is similar to the mean and median values given in Table 3-3 and well within the 95% confidence bounds, unlike Case01. However, the Case02 plume has a short duration, approximately three years, whereas the VZMS data suggest a broader plume (Figure 3-2). Figure 4-10 provides snapshots of the plume at elapsed times of 0.4, 1.0 and 1.6 years.



(a)



(b)

Figure 4-9. Soil characteristics curves for mixed backfill soil and uncompacted boxed waste.

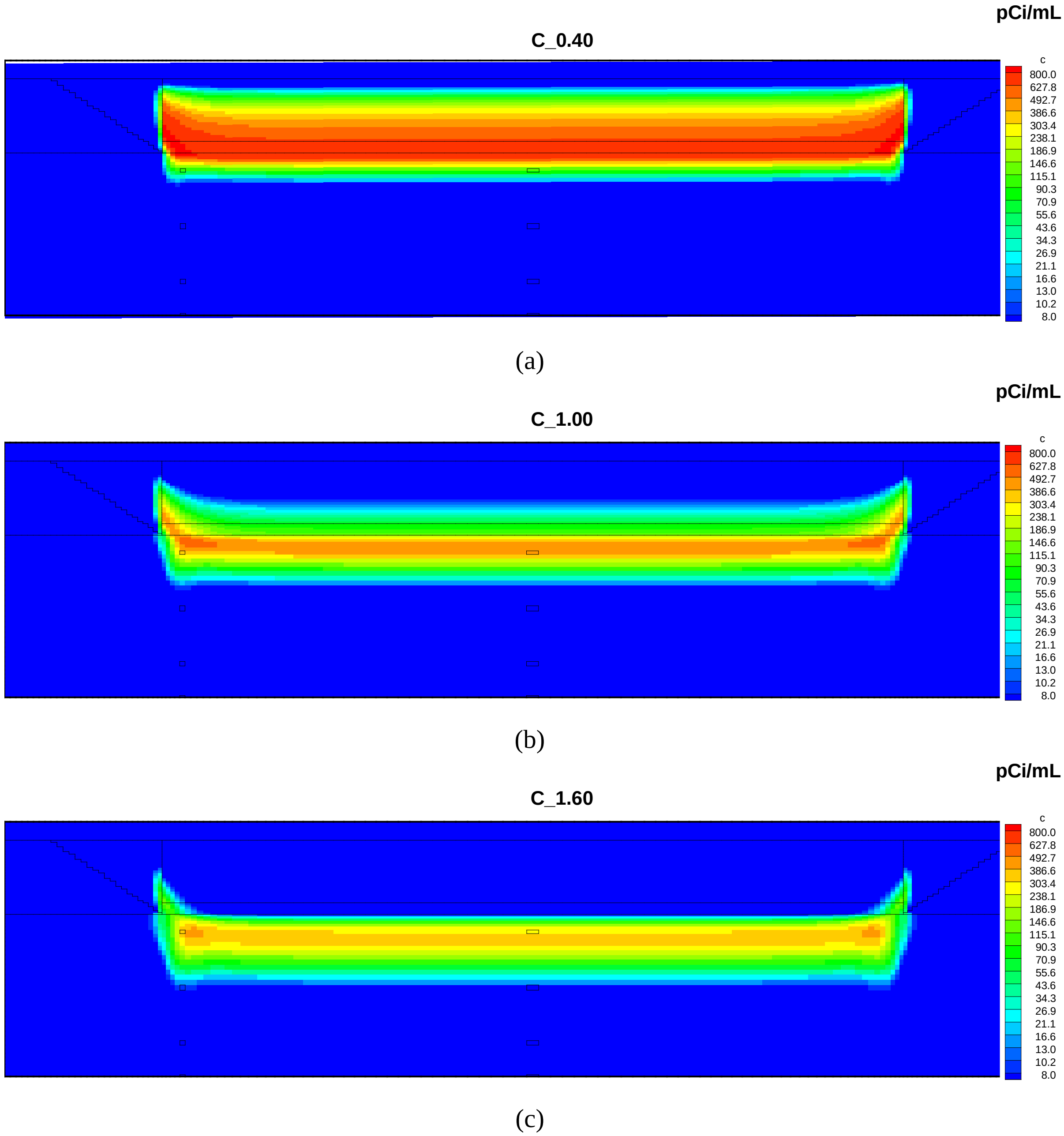
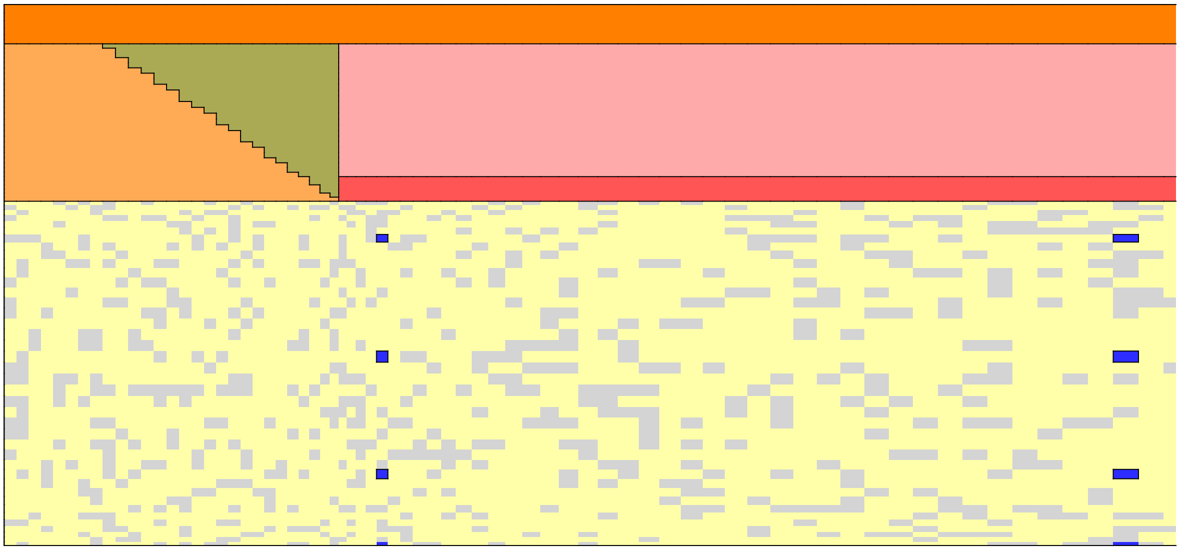
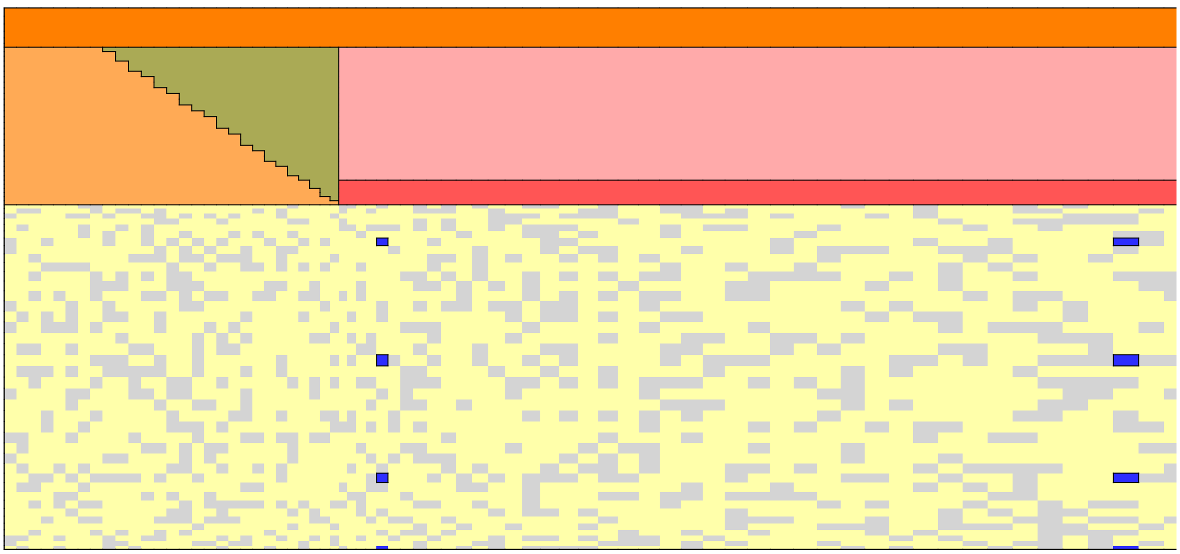


Figure 4-10. Simulated H-3 plume for Case02 at an elapsed times of (a) 0.4 yr, (b) 1.0 yr, and (c) 1.6 yr.

At the expense of reducing peak concentration, the plume duration can be expanded by introducing dispersion, which is expected due to heterogeneity. Case03 and Case04 introduce dispersion in the form of a non-zero dispersivity ranging from 5% to 10% of plume travel distance, taken as 35 ft. A dispersity of 10% is a common assumption (Zheng and Bennett 1995, Section 9.3.2). Case05 and Case06 create similar plume spreading by introducing explicit heterogeneity through a bi-modal permeability distribution, where the low-permeability fraction ranges from 25% to 35% (Figure 4-11). Heterogeneity creates a non-uniform velocity field (Figure 4-12) that results in portions of the plume moving at a different rate than the average.

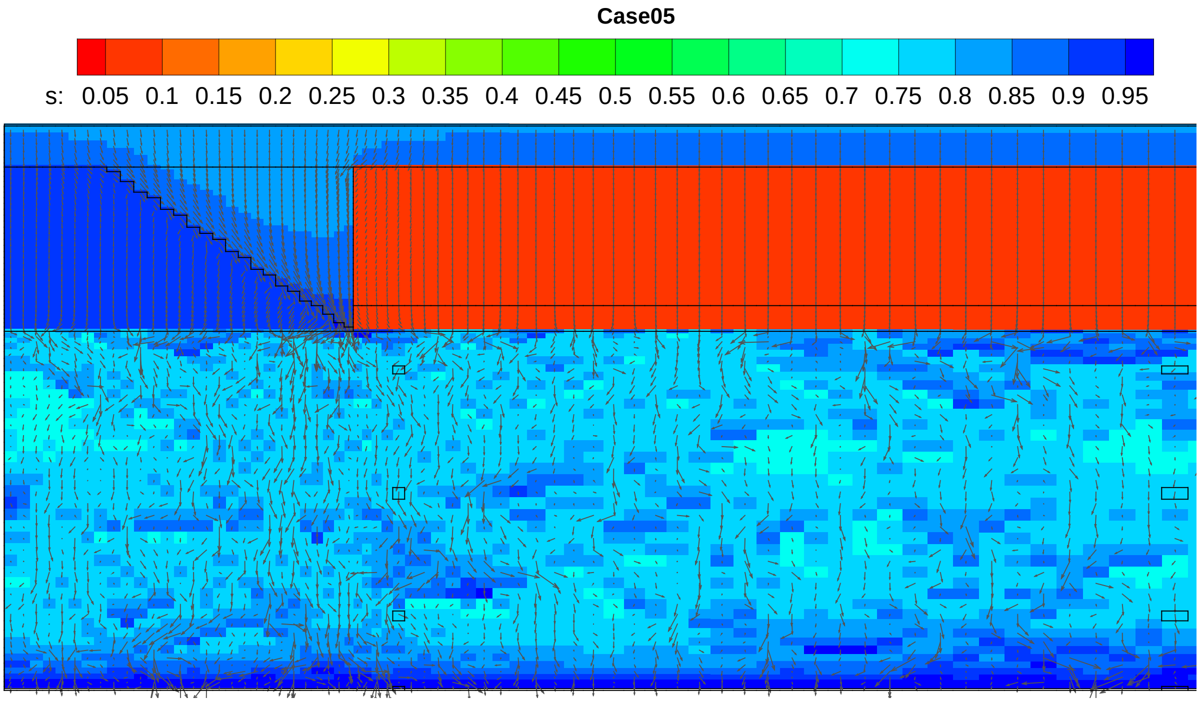


(a)

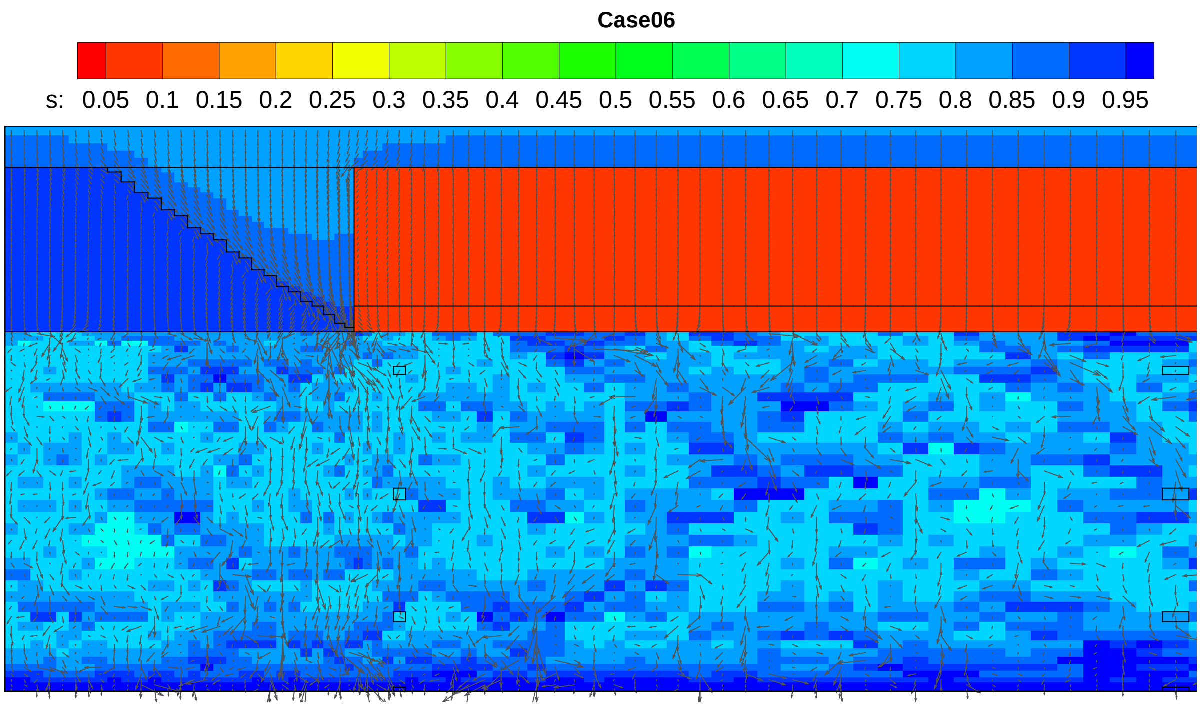


(b)

Figure 4-11. Random bi-modal hydraulic conductivity fields with low-permeability fractions of (a) 25% and (b) 35%.



(a)



(b)

Figure 4-12. Flow fields resulting from low-permeability fractions of (a) 25% and (b) 35%.

Cases03 through Case06 exhibit broader breakthrough curves with lower peaks generally in the range of 100 to 300 pCi/mL for the Upper lysimeters (Figure 4-5 through Figure 4-8). Table 4-2 tabulates peak concentrations for both the Upper and Lower lysimeter pairs, and defines a representative value for the Edge and Center pair at each elevation. For Cases01 through Case04, the maximum of the Center and Edge concentrations is taken as the Representative value. For Case05 and Case06 the average value is taken because simulated concentration exhibits significant variability due to the modeled heterogeneity. Case03 through Case06 are considered more realistic than the no-dispersion Case02. The averages for these cases are 257 and 76 pCi/mL for the Upper and Lower simulated lysimeter elevations, respectively.

Table 4-2. Simulated peak H-3 concentrations at UPPER and LOWER lysimeter locations.

Peak H-3 Concentration from Simulated Lysimeters	Case01	Case02	Case03	Case04	Case05	Case06	Case03 to Case06 average
UPPER_CENTER	107	411	267	213	275	91	
UPPER_EDGE	102	363	238	180	399	331	
Representative UPPER	107	411	267	213	337	211	257
LOWER_CENTER	66	114	74	59	81	90	
LOWER_EDGE	61	90	61	48	101	75	
Representative LOWER	66	114	74	59	91	83	76

While the Vadose Zone Monitoring System is focused on tritium, the overarching issue, which will be discussed in Section 6.0, is whether ET1 can be expected to meet performance objectives, considering contributions to the sum-of-fractions from all radionuclides disposed of in ET1. The other species indicated explicitly in Figure 2-1 are slow decaying relative to tritium and similarly mobile. The preceding vadose zone simulation cases were repeated for a non-decaying tracer species, which is used as surrogate for C-14, I-129, Nb-94 and Tc-99. However, vadose zone tracer simulation results are not explicitly presented, because they are similar to the H-3 results already presented.

4.2 Saturated zone model simulations

Four aquifer scenarios were considered, where “x” represents the last digit of a vadose zone case:

- Case0x: Uniform waste distribution + instantaneous disposal (PA case)
- Case1x: As-disposed-of ET1 waste distribution + instantaneous disposal
- Case2x: Uniform waste distribution + 10 year ET2 delay
- Case3x: As-disposed-of ET1 waste distribution + 10 year ET2 delay (best-estimate case)

All simulations were performed using the 2008 PA aquifer model (WSRC 2008), which analyzed ET1 and ET2 together as a disposal unit group. Subsequent Special Analysis modifications described by Swingle (2012) were not adopted in this study because the original PA model is suitable for assessing relative differences in modeling scenarios.

A 10 year difference in waste disposal times between ET1 and ET2 was assumed based on the volume consumption histories summarized in Figure 2-2 and Table 4-3. ET1 opened in 2001 and reached 25% volume consumption in 2002, 50% in early 2003, 75% in 2005, 88% in 2006, 99% in 2011 and 99.5% in 2015. ET2 opened in 2004 and reached 25% volume consumption in 2007, 50% in early 2011, 75% in 2014, and 76% in 2016. The 50% volume consumption (or median) dates for ET1 and ET2 differ by 8 years. ET2 disposals have slowed with the opening of ET3 and are expected to continue for several years past the 75% consumption date. The average disposal dates for ET1 and ET2 are thus expected to differ by more than 8 years, approximately 10 years as assumed in modeling herein.

Table 4-3. Disposal volume history for ET2 from WITS.

Date	Volume Consumption
June 2004 (trench opened)	0%
November 2007	25%
March 2011	50%
September 2014	75%
October 2016 (current)	76%

Simulated tritium and tracer concentrations are provided in Figure 4-13 through Figure 4-20. Scenario 2x produces a double peak reflecting the 10 year delta in disposal times between ET1 and ET2. The double peak largely disappears in Scenario 3x because ET1 waste is placed in the upgradient half of the disposal unit footprint, which compensates for the time delay in uniform ET2 burials. As such, the plumes emanating from ET1 and ET2 arrive at the 100 meter perimeter much closer in time compared to Scenario 2x.

Table 4-4 recomputes the WITS SOF for each aquifer and vadose modeling scenario, based on the relative differences in the peak concentrations from Figure 4-13 through Figure 4-20. The most realistic cases are considered to be those four in the Case33 through Case36 series. These cases consider B-25 box disposal and incorporate a realistic level of plume dispersion due to heterogeneity in soil properties (or waste release). The adjusted WITS SOF for these cases averages 0.89 compared to an actual WITS SOF of 0.87 (Figure 2-1). A second calculation considers the hypothetical possibility that the actual buried inventory of tritium (alone) is higher than that recorded in WITS. This calculation indicates that the tritium inventory could be up to 50% higher without exceeding an SOF of 1.0 for the average of Case33 through Case36.

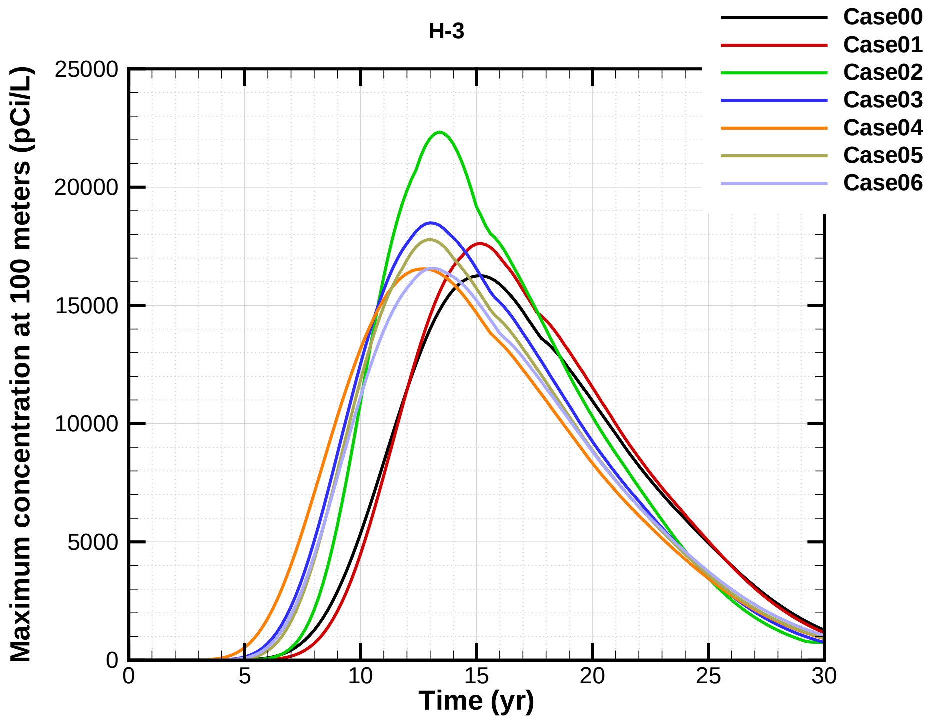


Figure 4-13. Simulated tritium concentration for aquifer scenario 0x.

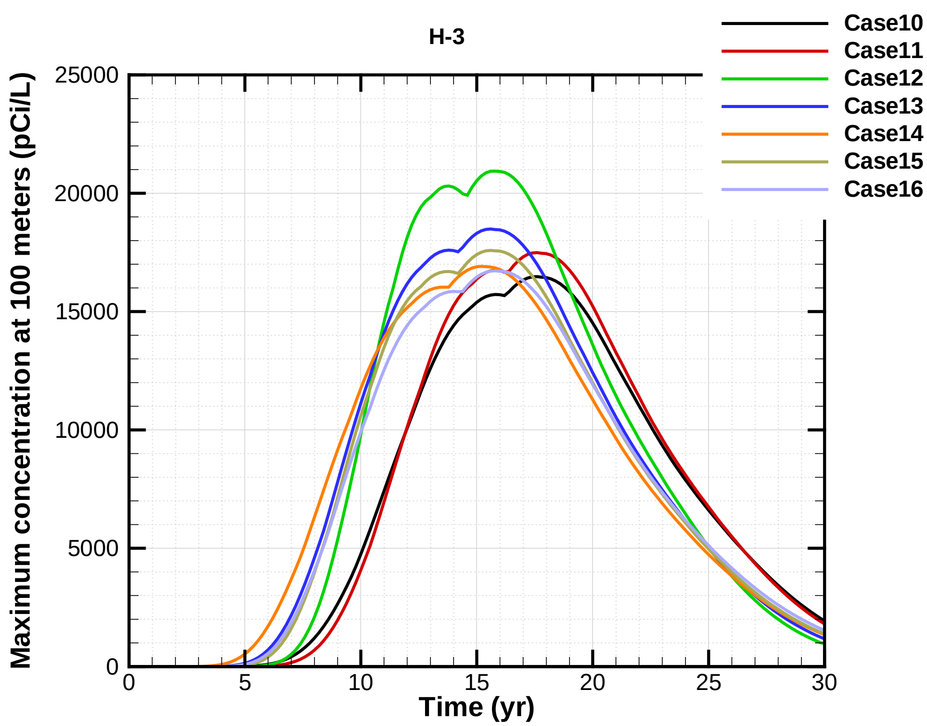


Figure 4-14. Simulated tritium concentration for aquifer scenario 1x.

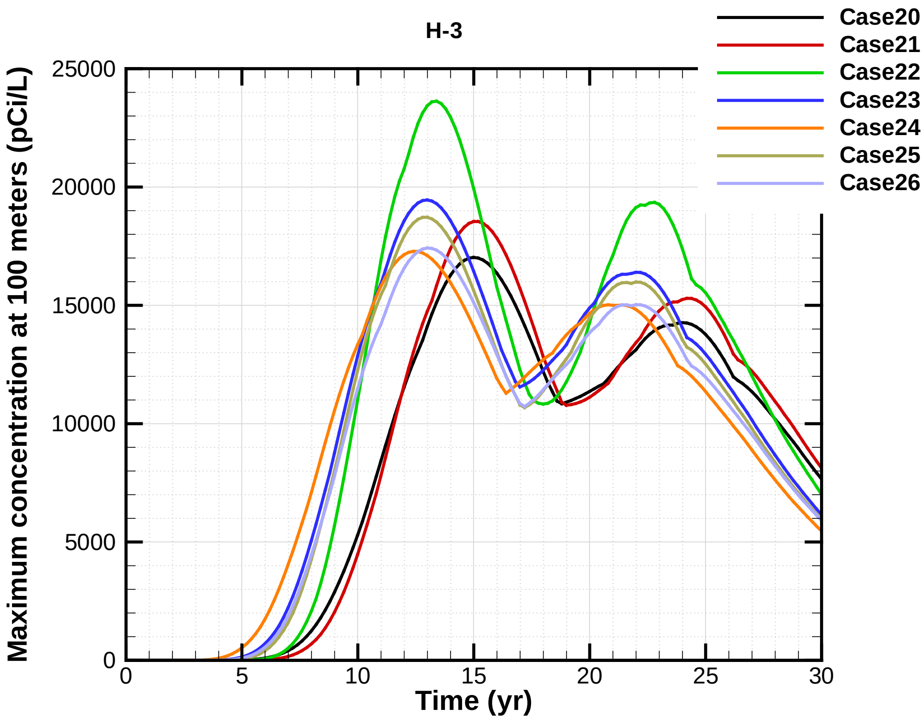


Figure 4-15. Simulated tritium concentration for aquifer scenario 2x.

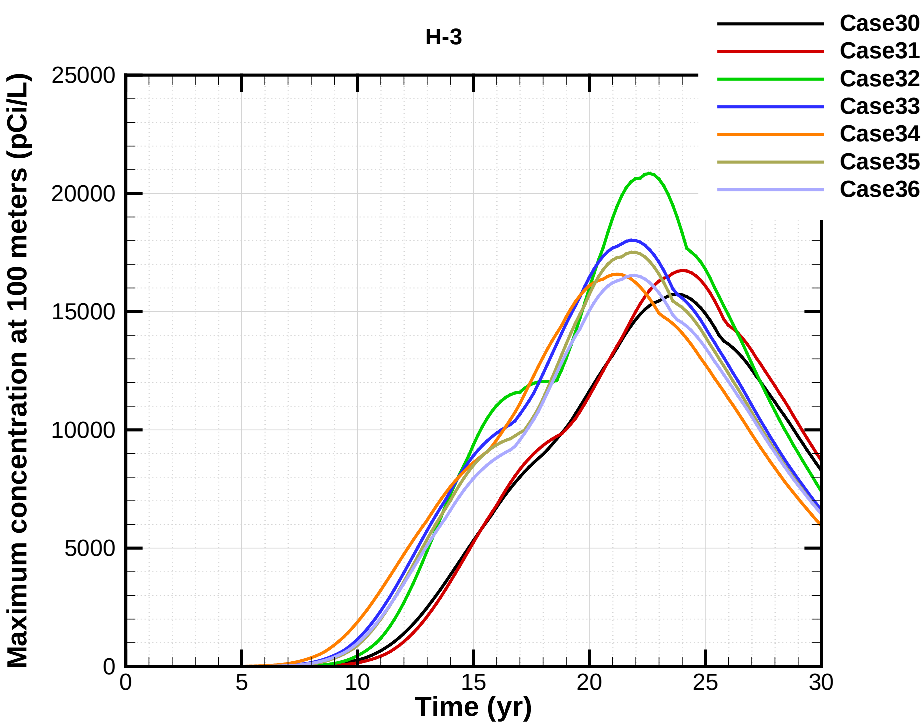


Figure 4-16. Simulated tritium concentration for aquifer scenario 3x.

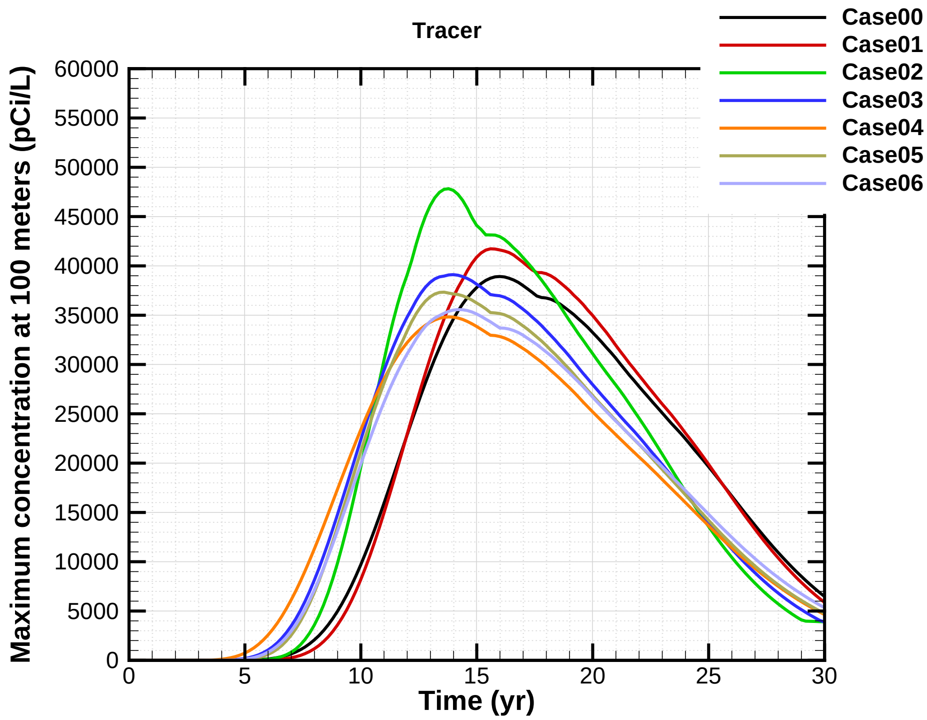


Figure 4-17. Simulated tracer concentration for aquifer scenario 0x.

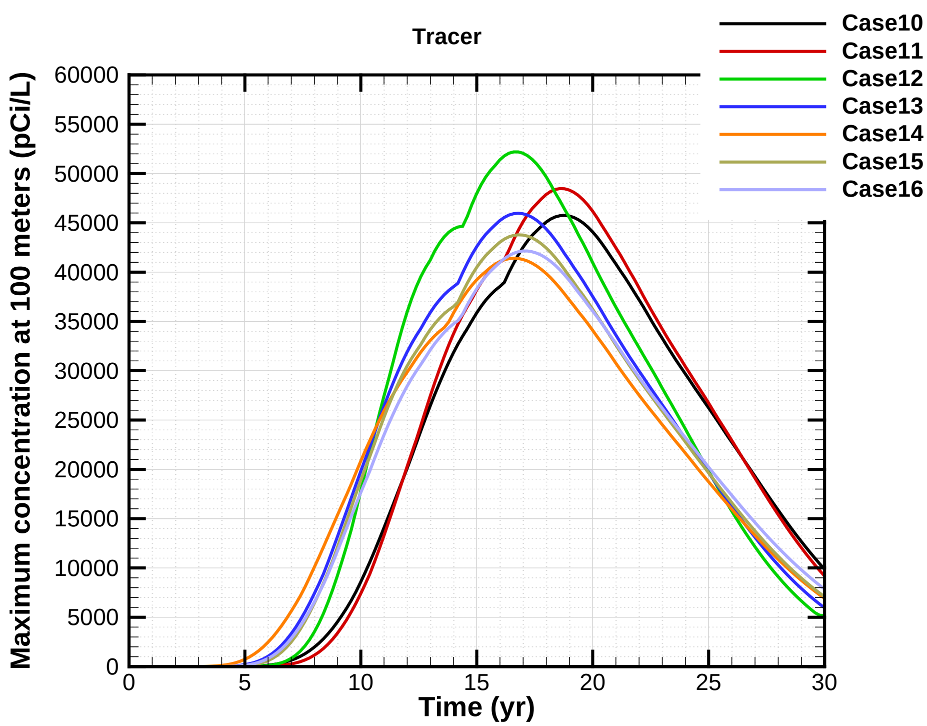


Figure 4-18. Simulated tracer concentration for aquifer scenario 1x.

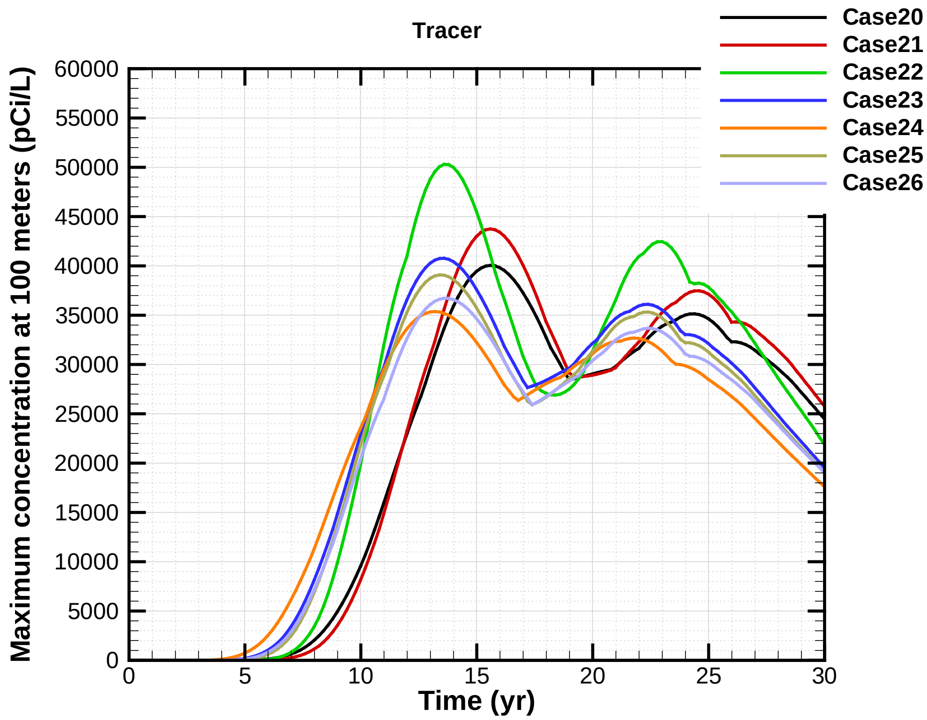


Figure 4-19. Simulated tracer concentration for aquifer scenario 2x.

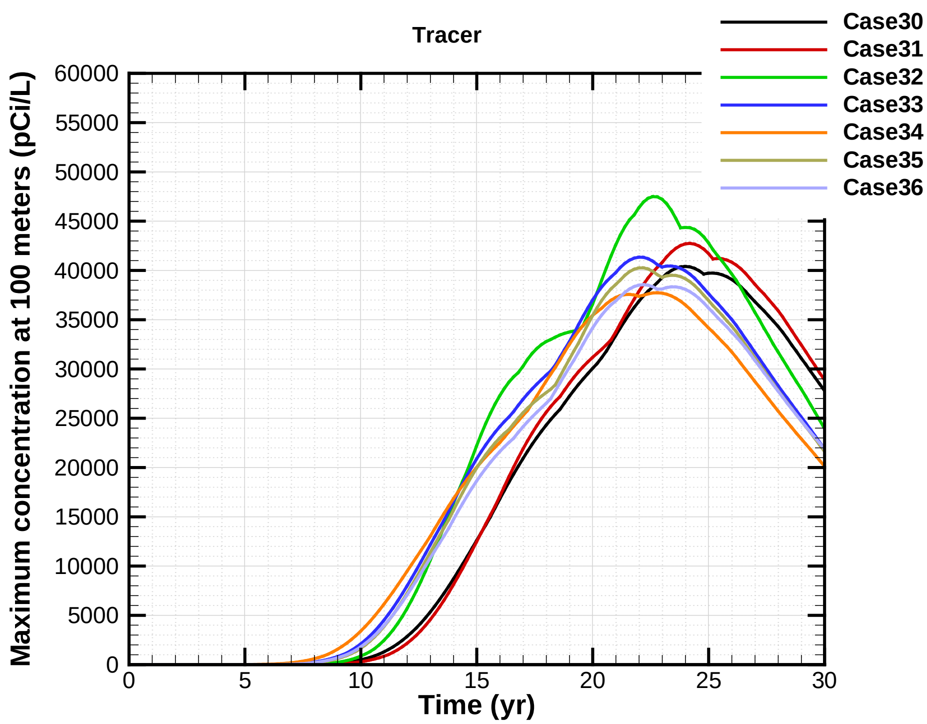


Figure 4-20. Simulated tracer concentration for aquifer scenario 3x.

Table 4-4. Projected WITS sum-of-fractions for aquifer scenarios 0x through 3x.

Configuration	Case00	Case01	Case02	Case03	Case04	Case05	Case06	Case10	Case11	Case12	Case13	Case14	Case15	Case16	Case20	Case21	Case22	Case23	Case24	Case25	Case26	Case30	Case31	Case32	Case33	Case34	Case35	Case36
Instantaneous disposals in ET1 and ET2	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
As-disposed-of timing in ET1 and ET2															x	x	x	x	x	x	x	x	x	x	x	x	x	x
Uniform ET1 waste distribution	x	x	x	x	x	x	x								x	x	x	x	x	x	x							
As-disposed-of ET1 waste distribution								x	x	x	x	x	x	x								x	x	x	x	x	x	x
Uncontained waste (soil)	x	x						x	x						x	x						x	x					
B-25 waste containers			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x
Homogeneous soil: 0% low permeability	x	x	x	x	x			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x		
Heterogeneous soil: 25% low permeability						x							x							x							x	
Heterogeneous soil: 35% low permeability							x							x							x							x
Dispersivity = 0 ft	x	x	x					x	x	x					x	x	x					x	x	x				
Dispersivity = 1.75 ft (5% of 35 ft)				x							x							x							x			
Dispersivity = 3.5 ft (10% of 35 ft)					x							x							x							x		
Vadose zone model description:	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.
Performance Objective	**Case00**	**Case01**	**Case02**	**Case03**	**Case04**	**Case05**	**Case06**	**Case10**	**Case11**	**Case12**	**Case13**	**Case14**	**Case15**	**Case16**	**Case20**	**Case21**	**Case22**	**Case23**	**Case24**	**Case25**	**Case26**	**Case30**	**Case31**	**Case32**	**Case33**	**Case34**	**Case35**	**Case36**
100m H-3 peak	16257	17616	22327	18491	16543	17787	16572	16477	17492	20934	18490	16912	17585	16723	17024	18542	23625	19453	17281	18720	17422	15731	16739	20845	18019	16581	17509	16528
Ratio to PA Case00	1	1.08	1.37	1.14	1.02	1.09	1.02	1.01	1.08	1.29	1.14	1.04	1.08	1.03	1.05	1.14	1.45	1.20	1.06	1.15	1.07	0.97	1.03	1.28	1.11	1.02	1.08	1.02
100m Tracer peak	38928	41734	47829	39114	34826	37336	35572	45757	48475	52196	45971	41410	43786	42142	40052	43743	50291	40772	35370	39081	36717	40408	42744	47497	41344	37737	40264	38554
Ratio to PA Case00	1	1.07	1.23	1.00	0.89	0.96	0.91	1.18	1.25	1.34	1.18	1.06	1.12	1.08	1.02889	1.12	1.29	1.05	0.91	1.00	0.94	1.04	1.10	1.22	1.06	0.97	1.03	0.99
WITS inventory																												
As-disposed Sum Of Fractions	**WITS**	**Projected . . .**																										
C-14	0.262	0.281	0.322	0.263	0.234	0.251	0.239	0.308	0.326	0.351	0.309	0.279	0.295	0.284	0.270	0.294	0.338	0.274	0.238	0.263	0.247	0.272	0.288	0.320	0.278	0.254	0.271	0.259
H-3	0.185	0.200	0.254	0.210	0.188	0.202	0.189	0.188	0.199	0.238	0.210	0.192	0.200	0.190	0.194	0.211	0.269	0.221	0.197	0.213	0.198	0.179	0.190	0.237	0.205	0.189	0.199	0.188
I-129	0.245	0.263	0.301	0.246	0.219	0.235	0.224	0.288	0.305	0.329	0.289	0.261	0.276	0.265	0.252	0.275	0.317	0.257	0.223	0.246	0.231	0.254	0.269	0.299	0.260	0.238	0.253	0.243
Nb-94	0.017	0.018	0.021	0.017	0.015	0.016	0.016	0.020	0.021	0.023	0.020	0.018	0.019	0.018	0.017	0.019	0.022	0.018	0.015	0.017	0.016	0.018	0.019	0.021	0.018	0.016	0.018	0.017
Tc-99	0.145	0.155	0.178	0.146	0.130	0.139	0.132	0.170	0.181	0.194	0.171	0.154	0.163	0.157	0.149	0.163	0.187	0.152	0.132	0.146	0.137	0.151	0.159	0.177	0.154	0.141	0.150	0.144
sof	0.854																											
Other	0.014	0.015	0.017	0.014	0.013	0.013	0.013	0.016	0.017	0.019	0.017	0.015	0.016	0.015	0.014	0.016	0.018	0.015	0.013	0.014	0.013	0.015	0.015	0.017	0.015	0.014	0.014	0.014
SOF	0.87	0.93	1.09	0.90	0.80	0.86	0.81	0.99	1.05	1.15	1.02	0.92	0.97	0.93	0.90	0.98	1.15	0.94	0.82	0.90	0.84	0.89	0.94	1.07	0.93	0.85	0.91	0.86
Ratio to WITS SOF	1	1.07	1.26	1.03	0.92	0.99	0.94	1.14	1.21	1.33	1.17	1.06	1.12	1.07	1.03	1.13	1.33	1.08	0.94	1.04	0.97	1.02	1.08	1.23	1.07	0.98	1.04	1.00
Volume fraction	99.5%					**Case03-06 average:**	**0.84**						**Case13-16 average:**	**0.96**						**Case23-26 average:**	**0.87**						**Case33-36 average:**	**0.89**
						Ratio to WITS SOF:	0.97						Ratio to WITS SOF:	1.10						Ratio to WITS SOF:	1.01						Ratio to WITS SOF:	1.02
Tritium multiplier		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
As-disposed Sum Of Fractions	**WITS**	**Projected . . .**																										
C-14	0.262	0.281	0.322	0.263	0.234	0.251	0.239	0.308	0.326	0.351	0.309	0.279	0.295	0.284	0.270	0.294	0.338	0.274	0.238	0.263	0.247	0.272	0.288	0.320	0.278	0.254	0.271	0.259
H-3	0.185	0.301	0.381	0.316	0.282	0.304	0.283	0.281	0.299	0.357	0.316	0.289	0.300	0.285	0.291	0.317	0.403	0.332	0.295	0.320	0.297	0.269	0.286	0.356	0.308	0.283	0.299	0.282
I-129	0.245	0.263	0.301	0.246	0.219	0.235	0.224	0.288	0.305	0.329	0.289	0.261	0.276	0.265	0.252	0.275	0.317	0.257	0.223	0.246	0.231	0.254	0.269	0.299	0.260	0.238	0.253	0.243
Nb-94	0.017	0.018	0.021	0.017	0.015	0.016	0.016	0.020	0.021	0.023	0.020	0.018	0.019	0.018	0.017	0.019	0.022	0.018	0.015	0.017	0.016	0.018	0.019	0.021	0.018	0.016	0.018	0.017
Tc-99	0.145	0.155	0.178	0.146	0.130	0.139	0.132	0.170	0.181	0.194	0.171	0.154	0.163	0.157	0.149	0.163	0.187	0.152	0.132	0.146	0.137	0.151	0.159	0.177	0.154	0.141	0.150	0.144
sof	0.854																											
Other	0.014	0.015	0.017	0.014	0.013	0.013	0.013	0.016	0.017	0.019	0.017	0.015	0.016	0.015	0.014	0.016	0.018	0.015	0.013	0.014	0.013	0.015	0.015	0.017	0.015	0.014	0.014	0.014
SOF	0.87	1.03	1.22	1.00	0.89	0.96	0.91	1.08	1.15	1.27	1.12	1.02	1.07	1.02	0.99	1.08	1.29	1.05	0.92	1.01	0.94	0.98	1.04	1.19	1.03	0.95	1.01	0.96
Ratio to WITS SOF	1	1.19	1.41	1.15	1.03	1.10	1.04	1.25	1.32	1.47	1.29	1.17	1.23	1.18	1.14	1.25	1.48	1.21	1.05	1.16	1.08	1.13	1.19	1.37	1.19	1.09	1.16	1.10
Volume fraction	99.5%					**Case03-06 average:**	**0.94**						**Case13-16 average:**	**1.06**						**Case23-26 average:**	**0.98**						**Case33-36 average:**	**0.99**
						Ratio to WITS SOF:	1.08						Ratio to WITS SOF:	1.22						Ratio to WITS SOF:	1.13						Ratio to WITS SOF:	1.14

5.0 Model uncertainty analysis

Revising the ET1 conceptual model to incorporate boxes in the waste zone significantly improved agreement with the VZMS data. However, all of the modeling cases yield a peak H-3 concentration somewhat below the sample mean and bootstrapping median values, which may point to other model biases. One candidate is the hydraulic properties for native sediments, which may overpredict saturation and thus underpredict concentration. Simulated saturation in the Lower Vadose Zone sediment is 73%. Supporting the hypothesis of a model bias is Section 5.8 of Phifer et al. (2006), which notes that VZMS field measurements of waste content range from roughly 0.15 to 0.30 suggesting saturation levels of 35% to 75%. Also, the speed of soil moisture movement in the vadose zone has been measured in the field to be approximately $v = 7$ ft/yr under natural recharge conditions (Horton 1975, Haskell and Hawkins 1964, Horton and Hawkins 1964). Pore velocity is computed as $v = U/nS$. Natural recharge has been estimated at about $U = 15$ in/yr (Hubbard and Emslie 1984) and porosity for Lower Vadose Zone sediments is $n = 0.39$ (Phifer et al. 2006, Table 5-18). Saturation can then be estimated as

$$S = \frac{U}{nv} = \frac{15\text{ in/yr}}{(0.39)(7\text{ ft/yr})} \cdot \frac{\text{ft}}{12\text{ in}} = 46\%$$

which is significantly lower than 73%. To assess the impact of a potential water content model bias, the Lower Vadose Zone porosity is modified from 0.39 (Phifer et al. 2006) to 0.25 in the vadose zone flow model. The modified porosity is computed as $(0.39)(46\%/73\%)$ as a means to achieve a simulated water content similar to field measurements.

Figure 5-1 through Figure 5-6 illustrate the breakthrough curves resulting from adjusted water content. The peak concentrations are observed to be larger than those in Figure 4-3 through Figure 4-8 as expected. Using Case02 as an example, the peak concentration in the Upper_Center lysimeter increased from 411 to 516 pCi/mL. Further peak concentration values are given in Table 5-1, and Table 5-2 presents the projected SOF impact resulting from adjusted water content applied to all modeling cases. The Case33 through Case36 average (see Section 4.2 for further discussion) becomes SOF = 1.05, slightly above the performance objective.

Table 5-1. Simulated peak H-3 concentrations at UPPER and LOWER lysimeter locations w/adjusted water content.

Peak H-3 Concentration from Simulated Lysimeters	Case01	Case02	Case03	Case04	Case05	Case06	Case03 to Case06 average
UPPER_CENTER	111	516	348	278	376	136	
UPPER_EDGE	107	419	294	228	498	425	
Representative UPPER	111	516	348	278	437	281	336
LOWER_CENTER	83	181	121	94	133	145	
LOWER_EDGE	76	135	96	75	158	120	
Representative LOWER	83	181	121	94	145	132	123

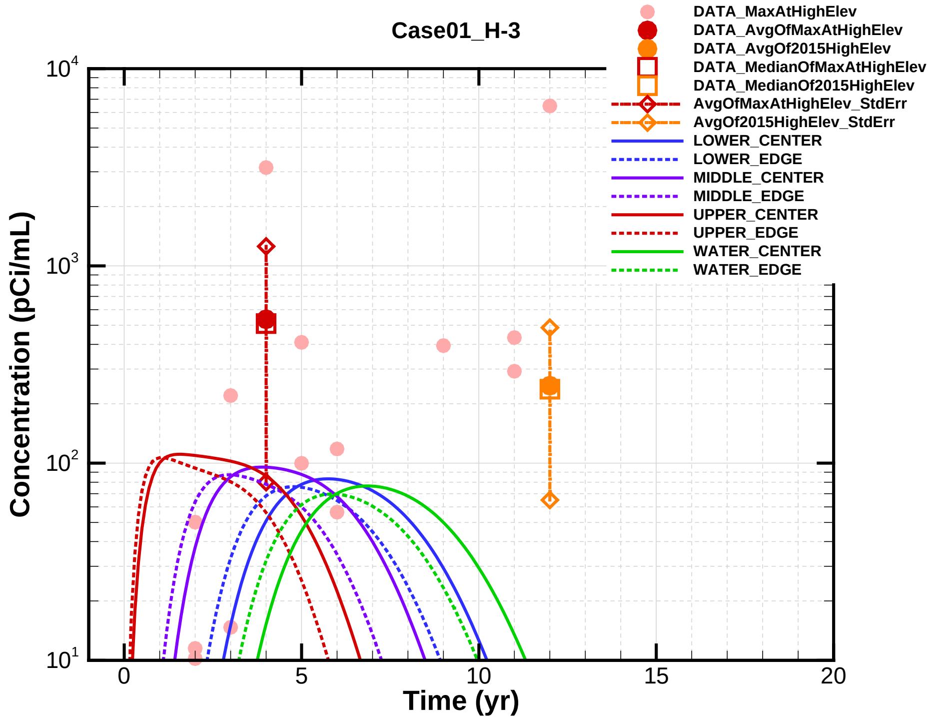


Figure 5-1. Simulated vadose zone concentrations for modeling Case01 w/adjusted water content -- PA + grid refinement + no side slope usage.

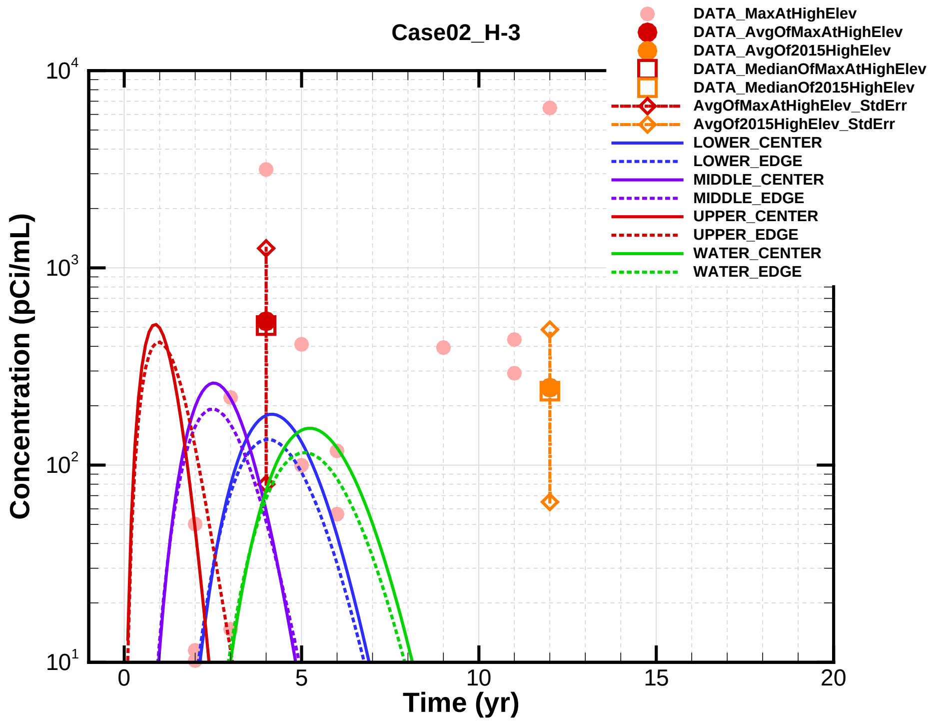


Figure 5-2. Simulated vadose zone concentrations for modeling Case02 w/adjusted water content -- B-25 boxes + no dispersion.

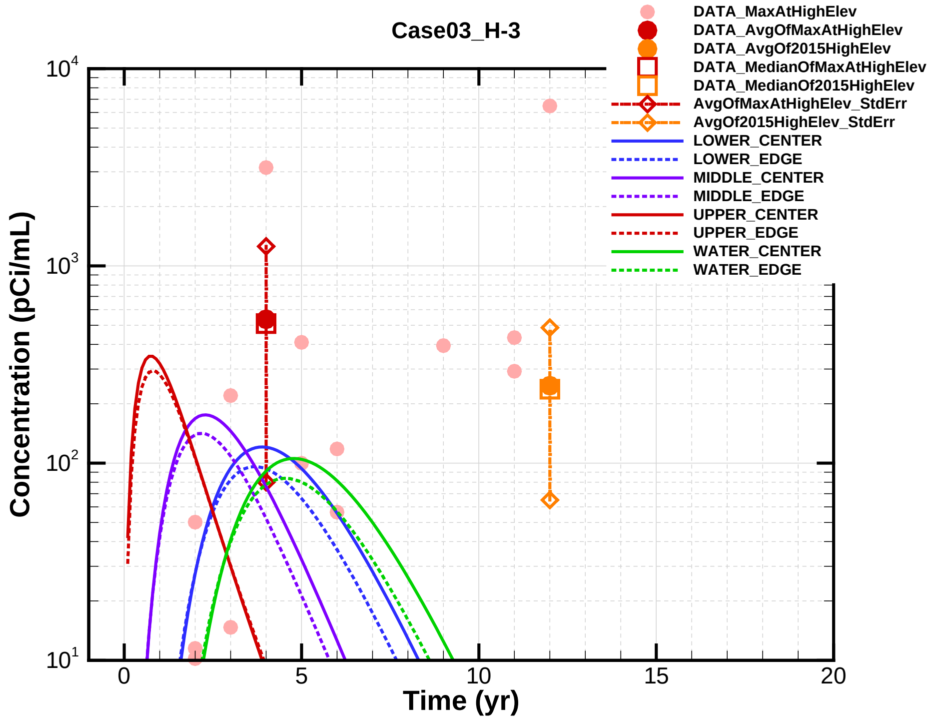


Figure 5-3. Simulated vadose zone concentrations for modeling Case03 w/adjusted water content -- B-25 boxes + 5% dispersivity.

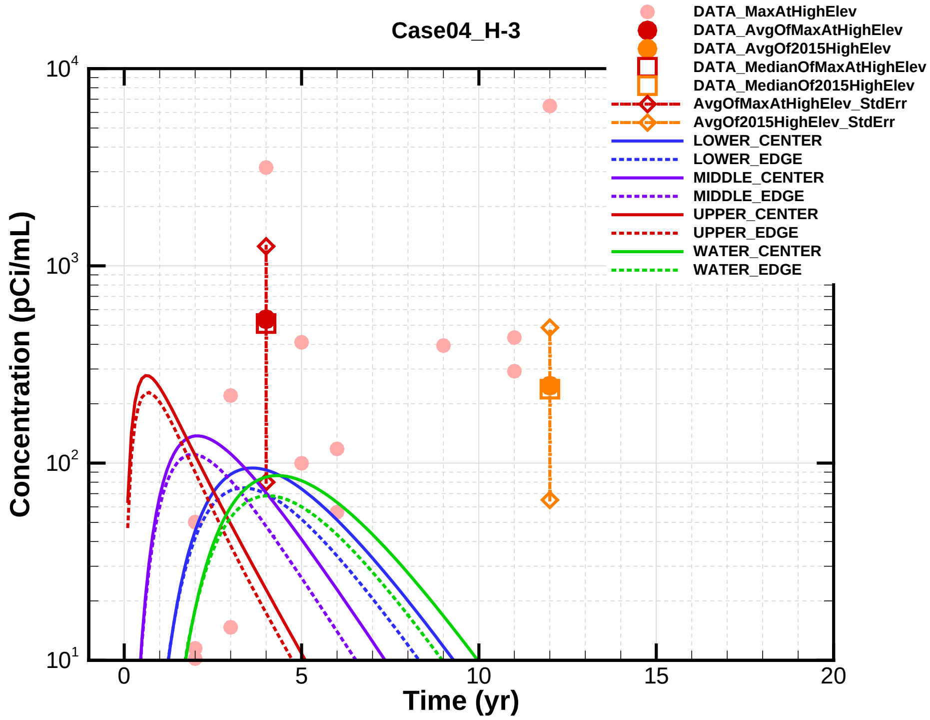


Figure 5-4. Simulated vadose zone concentrations for modeling Case04 w/adjusted water content -- B-25 boxes + 10% dispersivity.

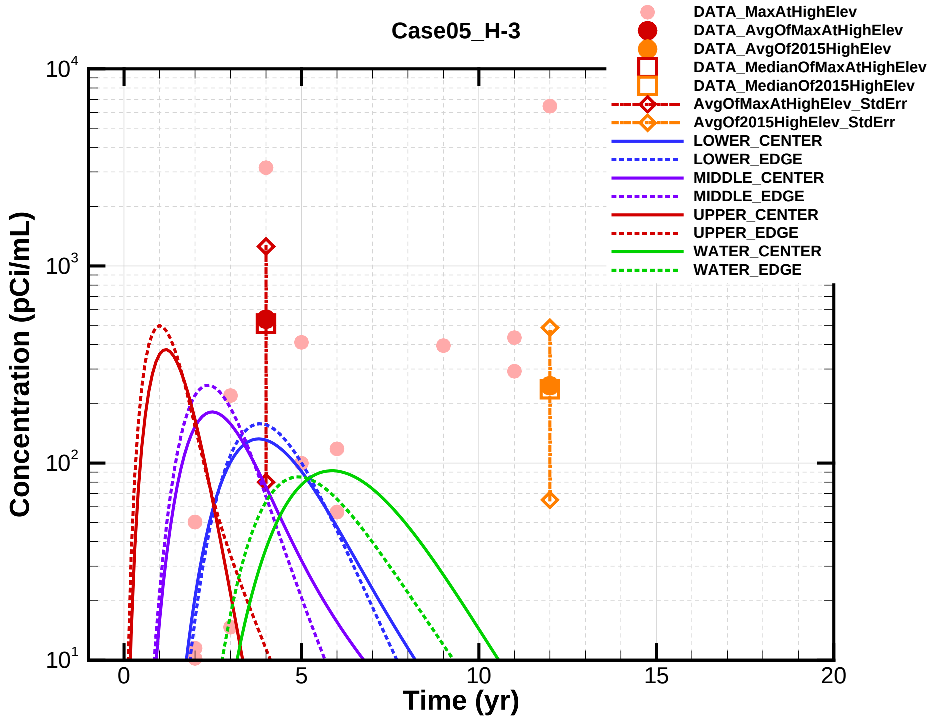


Figure 5-5. Simulated vadose zone concentrations for modeling Case05 w/adjusted water content -- B25 boxes + 25% low permeability in undisturbed soil.

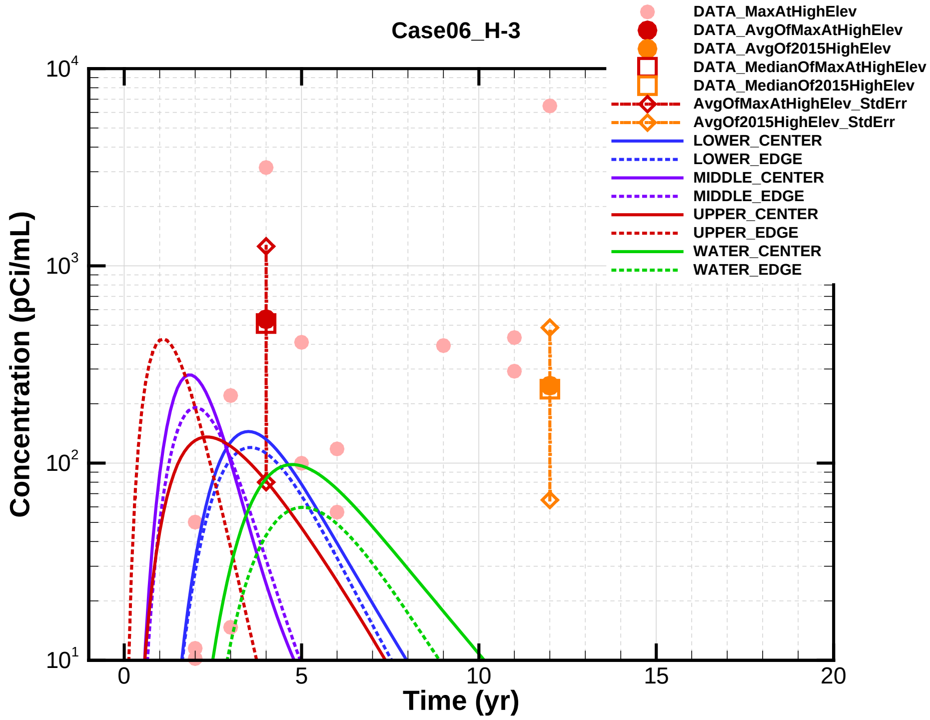


Figure 5-6. Simulated vadose zone concentrations for modeling Case06 w/adjusted water content -- B25 boxes + 35% low permeability in undisturbed soil.

Table 5-2. Projected WITS sum-of-fractions for aquifer scenarios 0x through 3x w/adjusted vadose zone water content.

Configuration	Case00	Case01	Case02	Case03	Case04	Case05	Case06	Case10	Case11	Case12	Case13	Case14	Case15	Case16	Case20	Case21	Case22	Case23	Case24	Case25	Case26	Case30	Case31	Case32	Case33	Case34	Case35	Case36
Instantaneous disposals in ET1 and ET2	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
As-disposed-of timing in ET1 and ET2															x	x	x	x	x	x	x	x	x	x	x	x	x	x
Uniform ET1 waste distribution	x	x	x	x	x	x	x								x	x	x	x	x	x	x							
As-disposed-of ET1 waste distribution								x	x	x	x	x	x	x								x	x	x	x	x	x	x
Uncontained waste (soil)	x	x						x	x						x	x						x	x					
B-25 waste containers			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x
Homogeneous soil: 0% low permeability	x	x	x	x	x			x	x	x	x	x			x	x	x	x	x			x	x	x	x	x		
Heterogeneous soil: 25% low permeability						x							x							x							x	
Heterogeneous soil: 35% low permeability							x							x							x							x
Dispersivity = 0 ft	x	x	x					x	x	x					x	x	x					x	x	x				
Dispersivity = 1.75 ft (5% of 35 ft)				x							x							x							x			
Dispersivity = 3.5 ft (10% of 35 ft)					x							x							x							x		
Vadose zone model description:	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.	PA flux	PA w/no waste in side	B25 box	B25 + dispersi on = 5%L	B25 + dispersi on = 10%L	B25 + 25% low perm.	B25 + 35% low perm.
Performance Objective	**Case00**	**Case01**	**Case02**	**Case03**	**Case04**	**Case05**	**Case06**	**Case10**	**Case11**	**Case12**	**Case13**	**Case14**	**Case15**	**Case16**	**Case20**	**Case21**	**Case22**	**Case23**	**Case24**	**Case25**	**Case26**	**Case30**	**Case31**	**Case32**	**Case33**	**Case34**	**Case35**	**Case36**
100m H-3 peak	16257	21845	28640	25197	22777	24204	23155	16477	21206	25701	23843	22194	22848	22182	17024	23049	30342	26632	23998	25597	24443	15731	20544	26606	23834	22040	23235	22330
Ratio to PA Case00	1	1.34	1.76	1.55	1.40	1.49	1.42	1.01	1.30	1.58	1.47	1.37	1.41	1.36	1.05	1.42	1.87	1.64	1.48	1.57	1.50	0.97	1.26	1.64	1.47	1.36	1.43	1.37
100m Tracer peak	38928	44435	52158	45987	41227	44121	42537	45757	50343	54417	50939	47453	48984	48065	40052	46606	55053	48253	43194	46304	44592	40408	44756	51343	46548	43276	45608	44391
Ratio to PA Case00	1	1.14	1.34	1.18	1.06	1.13	1.09	1.18	1.29	1.40	1.31	1.22	1.26	1.23	1.02887	1.20	1.41	1.24	1.11	1.19	1.15	1.04	1.15	1.32	1.20	1.11	1.17	1.14
WITS inventory																												
As-disposed Sum Of Fractions	**WITS**	Projected . . .																										
C-14	0.262	0.299	0.351	0.310	0.277	0.297	0.286	0.308	0.339	0.366	0.343	0.319	0.330	0.323	0.270	0.314	0.371	0.325	0.291	0.312	0.300	0.272	0.301	0.346	0.313	0.291	0.307	0.299
H-3	0.185	0.249	0.326	0.287	0.259	0.275	0.264	0.188	0.241	0.292	0.271	0.253	0.260	0.252	0.194	0.262	0.345	0.303	0.273	0.291	0.278	0.179	0.234	0.303	0.271	0.251	0.264	0.254
I-129	0.245	0.280	0.328	0.289	0.259	0.278	0.268	0.288	0.317	0.342	0.321	0.299	0.308	0.303	0.252	0.293	0.346	0.304	0.272	0.291	0.281	0.254	0.282	0.323	0.293	0.272	0.287	0.279
Nb-94	0.017	0.019	0.023	0.020	0.018	0.019	0.019	0.020	0.022	0.024	0.022	0.021	0.021	0.021	0.017	0.020	0.024	0.021	0.019	0.020	0.019	0.018	0.020	0.022	0.020	0.019	0.020	0.019
Tc-99	0.145	0.166	0.194	0.171	0.154	0.164	0.158	0.170	0.188	0.203	0.190	0.177	0.182	0.179	0.149	0.174	0.205	0.180	0.161	0.172	0.166	0.151	0.167	0.191	0.173	0.161	0.170	0.165
sof	0.854																											
Other	0.014	0.016	0.019	0.017	0.015	0.016	0.015	0.016	0.018	0.020	0.018	0.017	0.018	0.017	0.014	0.017	0.020	0.017	0.016	0.017	0.016	0.015	0.016	0.018	0.017	0.016	0.016	0.016
SOF	0.87	1.03	1.24	1.09	0.98	1.05	1.01	0.99	1.12	1.25	1.17	1.09	1.12	1.10	0.90	1.08	1.31	1.15	1.03	1.10	1.06	0.89	1.02	1.20	1.09	1.01	1.06	1.03
Ratio to WITS SOF	1	1.18	1.43	1.26	1.13	1.21	1.16	1.14	1.30	1.44	1.34	1.25	1.29	1.26	1.03	1.24	1.51	1.32	1.19	1.27	1.22	1.02	1.17	1.39	1.25	1.16	1.23	1.19
Volume fraction	99.5%					**Case03-06 average:**	**1.03**						**Case13-16 average:**	**1.12**						**Case23-26 average:**	**1.09**						**Case33-36 average:**	**1.05**
						Ratio to WITS SOF:	1.19						Ratio to WITS SOF:	1.29						Ratio to WITS SOF:	1.25						Ratio to WITS SOF:	1.21

6.0 Discussion

6.1 Observed versus expected tritium concentrations in the vadose zone

The exact nature of ET1 tritium release and migration through the vadose zone through FY2015 is inherently uncertain due to limited sampling locations and events. Similarly, model simulation outputs are inherently uncertain due to uncertain modeling assumptions and inputs. While uncertainties in data and modeling preclude making inferences with 100% confidence, certain conclusions can be drawn with reasonable confidence.

From Table 3-3, the sample average (mean) of peak tritium concentration at shallow depths is 536 pCi/mL and the median ranges from 315 to 510 pCi/mL when the data are assumed to be drawn from a log-normal distribution, depending on the analysis method. In 2015, the mean tritium concentration at shallow depths was 247 pCi/mL and the median value using a bootstrapping method is 237 pCi/mL. In comparison, representative simulated peak concentrations at shallow depths are 257 (Phifer et al. 2006 material properties) and 336 pCi/mL (adjusted water content) based on two revised models that account for predominantly B-25 box disposals (Table 4-2 and Table 5-1). These shallow lysimeter model results are similar to the data medians, and well within the 95% confidence intervals for the estimated data distributions (Table 3-3). Furthermore, the model results generally lie within the 50% confidence intervals (25% to 75% cumulative probability) for shallow lysimeters. Thus little evidence exists to support a hypothesis that the simulated and actual plume concentrations are significantly different.

For the deeper vadose zone, the median of FY2015 Action Level lysimeter data is 112 pCi/mL (Table 3-3) compared to model predictions of 76 (Phifer et al. 2006 material properties) and 123 pCi/mL (adjusted water content) where waste zone properties represent B-25 box disposal. Again, the model predictions are well within the sample 95% confidence interval, and also within the 50% confidence interval, indicating consistency between the revised models and field data.

6.2 Expectation of meeting DOE 435.1 performance objectives

When using soil properties from Phifer et al. (2006) and assuming B-25 box disposal, Table 4-4 indicates that ET1 can be expected to meet performance objectives under as-disposed-of conditions for ET1 and ET2. In fact, a 50% higher actual tritium inventory could be accommodated without exceeding an SOF of 1.0. When using a modified Lower Vadose Zone porosity to remove a potential bias in simulated water content, Table 5-2 indicates an SOF of 1.05, 5% over the performance objective. However, the PA disposal limit calculation assumes plume interaction with disposal unit groups adjoining ET1 and ET2 (i.e. east and center Slit Trench groups), an effect that lowers ET disposal limits by 19% (Table 6-2 of WSRC 2008). The phased operation of E-Area disposal units will minimize the potential for any inter-disposal unit group plume interaction. The assumed 19% penalty is thus largely absent in fact, and more than compensates for the 5% overage. Therefore ET1 is not likely to exceed performance objectives.

It should be noted that the modeling results and findings presented herein are specific to the ET1 and 2 disposal unit pair and current disposal practices, and not necessarily applicable to different disposal practices and other engineered trench units, for example, ET3.

6.3 Recommended actions

Considering the model improvements developed herein and continued acquisition of tritium data from the VZMS, the following actions are recommended:

1) In the upcoming PA revision, the E-Area PA vadose model should be revised to account for B-25 box and similar containerized waste disposals. Furthermore, the hydraulic properties assigned to

the vadose zone should be reassessed and revised if found to produce a significant bias in simulated moisture content.

2) Upon approval of the next PA, tritium administrative limits for action level lysimeters should be revised to reflect concentrations predicted by the revised PA vadose zone model.

3) Solid Waste should consider incorporating existing groundwater monitoring information as part of the PA monitoring program (specific actions to be developed). It is important to keep in mind that compliance with the DOE Order 435.1 performance objectives is assessed in groundwater rather than the vadose zone.

4) Vadose zone monitoring should continue to be maintained and expanded for trench units because it provides an early indication of trench disposal unit performance relative to PA assumptions and modeling forecasts, and addresses GW monitoring limitations due to the existing Mixed Waste Management Facility tritium plume beneath E-Area.

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Appendix A. Effective Properties of a Blended Material

Selected symbols

- V = volume
- m = mass
- F = flow / flux

Subscripts

- none = total or effective
- i = component
- v = void volume
- w = water volume
- s = solid phase

Volume fraction

$$V = V_1 + V_2$$

$$1 = \frac{V_1}{V} + \frac{V_2}{V} = f_1 + f_2$$

Porosity

$$V_v = V_{v1} + V_{v2}$$

$$n = \frac{V_v}{V} = \frac{V_{v1}}{V_1}\frac{V_1}{V} + \cdots = f_1 n_1 + f_2 n_2$$

Bulk density

$$m_s = m_{s1} + m_{s2}$$

$$\rho = \frac{m_s}{V} = \frac{m_{s1}}{V_1}\frac{V_1}{V} + \cdots = f_1 \rho_1 + f_2 \rho_2$$

Solid density

$$\rho_s = \frac{m_s}{V_s} = \frac{m_{s1}}{V_{s1}}\frac{V_{s1}}{V}\frac{V}{V_s} + \cdots = \rho_{s1}\left(\frac{V_1 - V_{v1}}{V} \cdot \frac{V}{V - V_v}\right) + \cdots$$

$$= \rho_{s1}\left[(1 - V_{v1}/V_1)\frac{V_1}{V} \cdot \frac{V}{V - V_v}\right] + \cdots = \rho_{s1}\left[(1 - V_{v1}/V_1)\frac{V_1}{V} \cdot \frac{1}{1 - V_v/V}\right] + \cdots$$

$$= \rho_{s1}\left[(1-n_1)f_1 \cdot \frac{1}{1-n}\right] + \cdots = \frac{f_1(1-n_1)\rho_{s1} + f_2(1-n_2)\rho_{s2}}{1-n}$$

Water content

$$V_w = V_{w1} + V_{w2}$$

$$\theta = \frac{V_w}{V} = \frac{V_{w1}}{V_1}\frac{V_1}{V} + \cdots = f_1\theta_1 + f_2\theta_2$$

Saturation

$$\theta = Sn = f_1\theta_1 + \cdots = f_1 S_1 n_1 + \cdots$$

$$S = \frac{f_1 S_1 n_1 + f_2 S_2 n_2}{n}$$

Saturated hydraulic conductivity (and unsaturated conductivity)

$$F = F_1 + F_2$$

$$-AK\frac{dh}{dz} = -A_1 K_1 \frac{dh}{dz} + \cdots$$

$$K = \frac{A_1}{A}K_1 + \cdots = \frac{V_1}{V}K_1 + \cdots = f_1 K_1 + f_2 K_2$$

$$K = f_1 K_1 + f_2 K_2$$

Relative permeability

$$k_r K = f_1 k_{r1} K_1 + \cdots$$

$$k_r = \frac{f_1 k_{r1} K_1 + f_2 k_{r2} K_2}{K}$$

Summary

$$1 = f_1 + f_2$$

$$n = f_1 n_1 + f_2 n_2$$

$$\rho = f_1 \rho_1 + f_2 \rho_2$$

$$\rho_s = \frac{f_1(1 - n_1)\rho_{s1} + f_2(1 - n_2)\rho_{s2}}{1 - n}$$

$$\theta = f_1 \theta_1 + f_2 \theta_2$$

$$S = \frac{f_1 S_1 n_1 + f_2 S_2 n_2}{n}$$

$$K = f_1 K_1 + f_2 K_2$$

$$k_r = \frac{f_1 k_{r1} K_1 + f_2 k_{r2} K_2}{K}$$

Special case

$$n_2 = 1$$

$$S_2 = 0$$

$$K_2 = 0$$

$$n = f_1 n_1 + f_2$$

$$\rho = f_1 \rho_1$$

$$\rho_s = \rho_{s1}$$

$$\theta = f_1 \theta_1$$

$$S = \frac{f_1 S_1 n_1}{n}$$

$$K = f_1 K_1$$

$$k_r = k_{r1}$$

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Distribution:

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D. A. Crowley, 773-42A
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P. N. Fairchild, 704-55E
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D. T. Hobbs, 773-A
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