This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

Comparison of Performance of Underground Vaults and Trenches for Disposal of Radioactive Waste

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Keywords: Contaminant transport, Radioactive waste, Radionuclides, Vadose zone, Aquifer

Abstract

At the U.S. Department of Energy Savannah River Site, disposal of radioactive wastes in shallow trenches and vaults was simulated with vadose zone models and decoupled aquifer models (McDowell-Boyer, et al., 2000). The vadose zone models provided contaminant fluxes to the aquifer models.

Two methods of shallow trench disposal were considered. The first method was direct placement in trenches (Simple Trench). The second method was to reduce the waste volume by surround it with 1 foot of grout (Grouted Trench). Vault disposal included grouting the waste in layers (Grouted Vault). Disposal in grouted trenches and vaults typically reduced aquifer concentrations because movement of infiltrating water through the grout and through the vault's concrete roof, walls and floor was much slower than movement through shallow trenches.

This report compares the predicted behavior of several radionuclides disposed in grouted trenches or vaults that exhibited higher aquifer concentrations than if they were disposed in shallow trenches. The general modeling approach is first presented for the vaults and the shallow trenches, then the details for the radionuclides are presented along with explanations or suggestions for the behavior.

SIMPLE TRENCH CONFIGURATION FOR VADOSE ZONE

The cross-section of one 20-ft wide by 20-ft deep trench was simulated (see Figure 1). Sixteen feet of waste was simulated in the base of the trench covered by 4 feet of clean backfill.

VADOSE ZONE FLOW FOR SIMPLE TRENCH

The flow analysis consisted of determining steady-state flow fields for three time periods. The first period was the initial 25 years when the trench was considered as operational, i.e., filled but without a cap. The steady-state flow field for this period and other periods are shown in Figure 2 with a shaded waste zone.

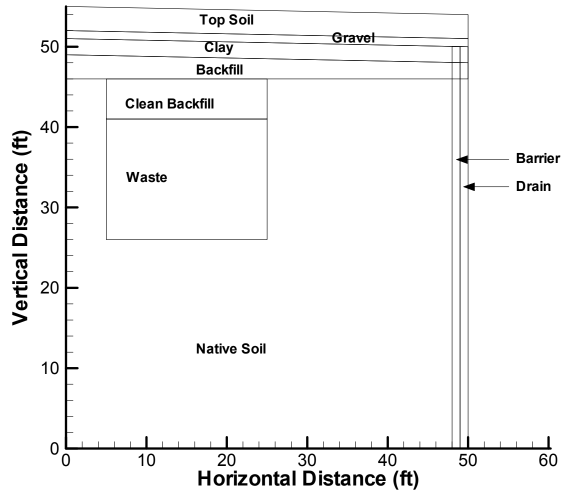
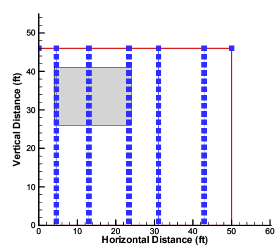
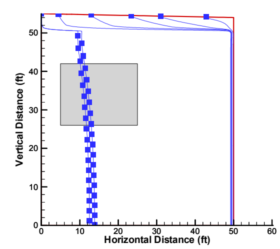


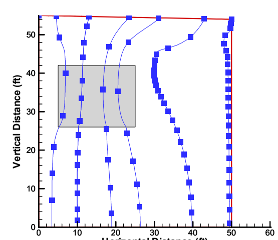
Figure 1. Simple trench geometry for vadose zone



A. Uncapped – 1 year timing



B. Intact cap – 100 year timing



C. Failed cap – 1 year timing

Figure 2. Pore velocity streamlines for simple trench with timing markers

The second period was the institutional control period that ranged from 25 years to 125 years, during which time a cap will be placed and maintained. A drainage system was represented artificially by a drain and a barrier in the model. The third period ranged from 125 years to 10,000 years. During this entire period waste settlement and cap failure were simulated by replacing several materials with overlying materials. A major change was placing topsoil in the waste zone with a saturated hydraulic conductivity that was 100 times higher than the initial waste and the surrounding soil.

The first flow field for the uncapped trench shows water that infiltrates at the surface migrating uniformly downward, because all materials are initially assigned the same properties. The second flow field for the intact cap shows water that infiltrates at the surface being shunted around the waste because of the cap and drainage system. The third flow field for the failed cap shows water being attracted to the waste zone because the hydraulic conductivity of topsoil in the waste zone is much greater than that for the surrounding native soil.

GROUTED TRENCH CONFIGURATION FOR VADOSE ZONE

The cross-section of one 20-ft wide by 20-ft deep grouted trench was simulated (see Figure 3). Fourteen feet of waste was simulated in the center of the trench, surrounded on all sides by 1 foot of grout, which was covered by 4 feet of clean backfill.

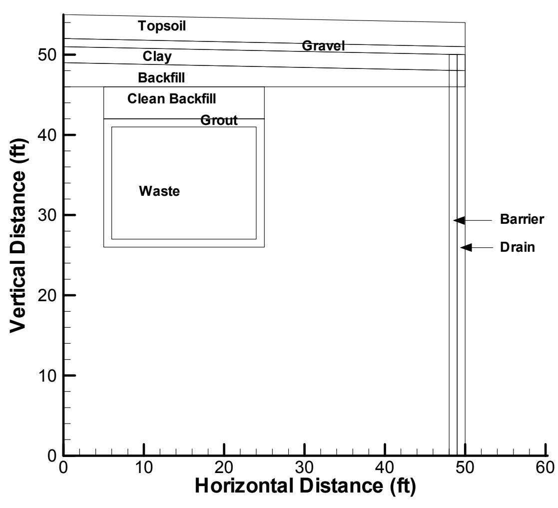
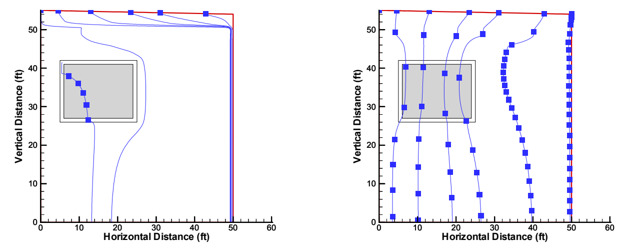


Figure 3. Grouted trench geometry for vadose zone

VADOSE ZONE FLOW FOR GROUTED TRENCH

Two stages were simulated for the grouted trench. The first stage was from 0-300 years for an intact cap, followed by a failed cap. The two steady-state flow fields for the grouted trench are shown in Figure 4. The first flow field for the intact cap shows water that infiltrates at the surface being shunted around the waste because of the cap and drainage system. The third flow field for the failed cap shows water being attracted to the waste zone because the hydraulic conductivity of topsoil in the waste zone is much greater than that for the surrounding native soil.



A. Intact cap – 100,000 year timing

B. Failed cap – 1 year timing

Figure 4. Pore velocity streamlines for grouted trench with timing markers

VAULT CONFIGURATION FOR VADOSE ZONE

The cross-section of half of one grouted vault was simulated (see Figure 5). Fourteen feet of waste was simulated in the center of the trench, surrounded on all sides by 1 foot of grout, which was covered by 4 feet of clean backfill.

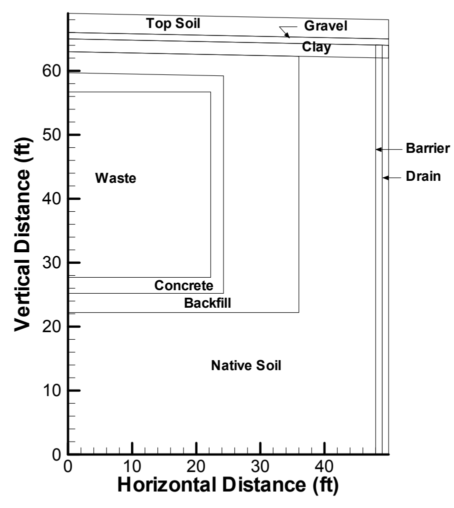
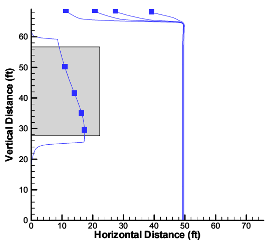


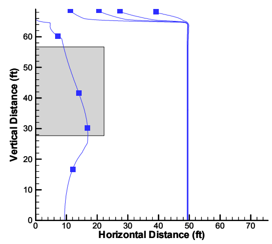
Figure 5. Grouted vault geometry for vadose zone

VADOSE ZONE FLOW FOR GROUTED VAULT

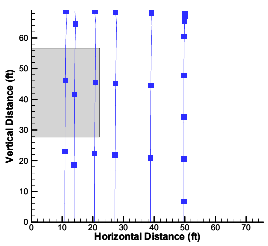
The flow analysis consisted of determining steady-state flow fields for three time periods. The first period covered the first 575 years with an intact vault. The second stage lasted until 1050 during which time the vault was in a degraded state with higher saturated hydraulic conductivities. The third stage covered the time when the cap and the vault were assumed to be in a failed state with much greater saturated hydraulic conductivities.



A. Intact vault – 100,000 year timing



B. Degraded vault – 500 year timing



C. Failed vault – 5 year timing

Figure 6. Vault Geometry for vadose zone cross-section

VADOSE-ZONE CONTAMINANT TRANSPORT ANALYSIS

The vadose-zone contaminant transport analysis combined the initial waste loading with the three steady-state flow fields to produce a contaminant flux at the water table, which was subsequently input to an aquifer contaminant transport model. The contaminant transport model originated with 1 Ci of waste for each radionuclide in the waste zone.

After the first stage (e.g., 25 years for the Simple Trench) the steady-state flow field switched from the uncapped trench to the intact cap, with associated water content changes. Preserving contaminant mass balance with water content changes required stopping the primary analysis computer program, Porflow©, after analyzing the first stage, then running an auxiliary computer program to convert the contaminant concentration in each cell. The conversion formula was $C_{t2} = C_{t1} * W_{t1} / W_{t2}$; where C_i is the contaminant concentration, w_i is the volumetric water content, t refers to the time period. After the analysis for the second stage was completed, a similar auxiliary concentration adjustment was made.

Generic I-129 Waste

Generic I-129 (e.g., I-129 on contaminated clothing) showed higher aquifer concentrations for both the grouted trench and the grouted vault than for the simple trench. Contaminant fluxes at the water table and peak aquifer concentrations at a hypothetical 100-m well are shown in **Figure 7**. Because the original contaminant activity was 1 Ci, the contaminant fluxes are also fractional fluxes.

For the Simple Trench shown at the left in **Figure 7** a sharp reduction in flux (black, dashed line) occurred when the intact cap was placed at 25 years. The peak flux is not quite as high as for the Grouted Trench, but it is significantly higher than the peak flux for the Grouted Vault. The well concentration for the Simple Trench (black solid line) is plotted against the right-hand Y-axis and show a lower peak relative to its peak flux than do the other plots for the Grouted Trench and the Grouted Vault.

The Grouted Trench shows a wider high-flux band than does the Simple Trench, and its peak aquifer concentration is higher. The Grouted Vault shows a much lower peak flux, while the high-flux band is the widest of the three plots. The peak aquifer concentration for the Grouted Vault is much greater than that for the Simple Trench, but is slightly lower than that for the Grouted Trench.

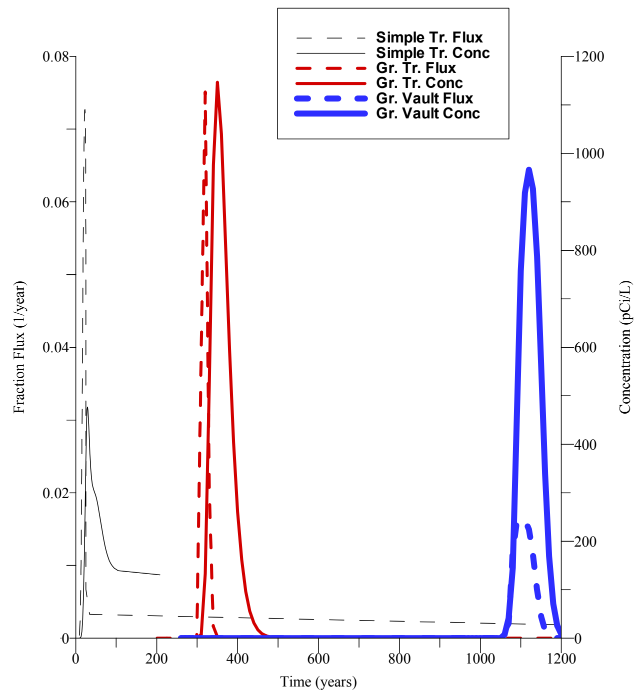


Figure 7. Generic I-129 fluxes at the water table and aquifer concentrations for a Simple Trench, a Grouted Trench and a Grouted Vault

Peak fluxes, peak well concentrations and the times for each are summarized in Table 1 for generic I-129. The time of the peak increased with the grouted trench from 29 years to 350 years. The grouted vault further delayed the peak to 1120 years.

Table 1. Comparison of fluxes and well concentrations for generic I-129 waste

Disposal Unit	Peak Fractional Flux	Time (years)	Peak Well Concentration (pCi/L)	Time (years)
Simple Trench	7.27E-2	22.4	477	29
Grouted Trench	7.51E-2	320	1150	350
Grouted Vault	1.63E-2	1100	966	1120

Explanation of Results for Generic I-129

An investigation into the unexpected results starts with examining the distribution coefficients (Kds) showing how contaminants would partition between the solids and liquid. The only differences were in the waste zone and they are shown in Table 2.

Table 2. Waste zone Kds for generic I-129

Disposal Unit	Kd in Waste Zone (ml/g)
Simple Trench	0.6
Grouted Trench	0.6
Grouted Vault	2

The only difference is that the Kd is higher for the grouted vault, which would tend to reduce the well concentrations, thus the waste zone Kd does not explain the increase in the well concentration for the grouted trench and grouted vault.

Decay differences for the different peak times did not explain the results. Because I-129 has a very long half-life of about 1.7E7 years and the peak for the Simple Trench occurred first, decay did not significantly affect the results.

The next part of the investigation was to examine the changes in the vadose zone model as the jump was made from one steady-state flow stage to another. Two major differences could appear. First, the moisture contents could change dramatically. However, the concentrations were changed inversely in order to preserve mass balance in the liquid. Because Porflow applies the K_d to the wetted fraction of the matrix, the concentration adjustment works appropriately on the solids as well, with the equation being

$$C_s = S * K_d * C_L$$

Where C_s is the concentration on the entire solids (Ci/g)
S is the saturation (unitless)
K_d is the distribution coefficient (ml/g)
C_L is the concentration in the liquid (Ci/ml)

For example if the K_d is 80 ml/g, the concentration in the liquid is 0.2 Ci/ml and the matrix is 25% saturated, then the concentration in the liquid is 0.25 * 80 * 0.2 or 4 Ci/g. If the saturation doubles to 0.50, then C_L must be halved to 0.1 Ci/ml to preserve mass balance in the liquid. For this case C_s becomes 0.50 * 80 * 0.1 or 4 Ci/g.

Because the amount of contaminant in the liquid remained constant and the amount of contaminant crossing the water table was the end result of the vadose zone model, merely increasing or decreasing the amount of liquid in the vadose zone model could not significantly affect the well concentrations.

The second major difference is that the change in liquid velocity from one stage to another could hasten the contaminant movement to the water table differentially. The stage with the highest average liquid velocity apparently would result in the highest well concentration, because the quantity of liquid from the vadose zone is not included in the aquifer model. The average liquid velocity was estimated by releasing a particle from the center of the waste zone and determining its approximate arrival time at the water table as shown in Table 3.

Table 3. Average liquid travel times and pore velocities

Disposal Unit	Average liquid travel time (years) / Average liquid velocity (ft/yr) Stage 1	Stage 2	Stage 3
Simple Trench	15.6	1270	4.2
	2.1	2.6E-2	8.0
Grouted Trench	2.2E5	2.2E5	4.4
	1.5E-4	1.5E-4	7.6
Grouted Vault	2.8E5	1350	8.9
	1.5E-4	3.1E-2	4.7

The simple trench has the greatest velocity, followed by the grouted trench, then the grouted vault, so the simple trench would tend to have the greatest well concentration based on velocities. An additional factor when extending the liquid velocity to the contaminant velocity is that the Kd for grouted vault waste zone is more than 3 times higher than the Kd for the other disposal units (see Table 2). To compensate for the higher Kd (3X) in terms of retardation and the well concentration (2X) relative to the simple trench, the grouted vault must have an average liquid velocity that is 6X that of the simple trench.

Another consideration is that the aquifer flow fields could be significantly different. An independent study (Flach and Millings, 2003) showed that the aquifer flow fields in the general vicinity are sufficiently similar that separate analyses are not required, thus differences in the aquifer flow fields was not responsible for the differences.

Having eliminated the most apparent candidates for differences, a deeper look into the effects of stage timing emerged as a candidate. For the simple trench, the peak flux appears at 22.4 years and the peak well concentration appears at 29 years, but the cap was placed at 25 years. The effect of the cap was to shut off the flow of contaminants to the water table, much like closing a valve. For the other disposal units, the peak well concentration required about 30 years to develop after the peak flux was observed, but the simple trench was not afforded this luxury.

For a peak contaminant flux to have the maximum impact, it must be supported by a sufficient mass of other contaminant flux arriving at nearly the same time. Thus a narrow spike of contaminant flux typically will produce a lower peak well concentration than a wider surge of contaminant flux, if the peaks are the same. Even if the narrow spike has a slightly higher peak than a wider surge of contaminant flux, the wider surge of contaminant flux typically will produce a higher peak well concentration. That situation is evident for the simple trench, when the assumed placement of a cap greatly reduced the continual flux of contaminants that would otherwise have sustained the peak well concentration. The high release of contaminants during the first stage also reduced the remaining inventory, which in turn reduced the peak well concentration that could develop after the cap failed.

Se-79 Waste

Contaminant fluxes at the water table and peak aquifer concentrations at a hypothetical 100-m well for Se-79 are shown in **Figure 8**. Peak fluxes and well concentration information is summarized in Table 4.

Table 4. Comparison of fluxes and well concentrations for Se-79 waste

Disposal Unit	Peak Fractional Flux	Time (years)	Peak Well Concentration (pCi/L)	Time (years)
Simple Trench	5.23E-4	2800	2.97	4700
Grouted Trench	5.67E-4	2880	4.27	9670
Grouted Vault	5.28E-4	3930	12.0	6580

Explanation of Results for Se-79

Se-79 has its greatest peak well concentration for the grouted vault. The apparent cause is that 0.1 Kd in the waste zone for the vault (see **Table 5**) is significantly lower that the 150 and 170 Kds in the waste zone for the other disposal units. The grouted vault has little contaminant movement for the initial two stages (through 1050 years), but afterwards the average liquid velocity is about 4.7 ft/yr (see **Table 3**), which is more than half that of the simple trench (8 ft/yr). The grouted trench likely has a greater peak well concentration than does the simple trench because the Kd in the grout underlying the waste zone is 0.1 and because the waste zone is two feet thinner to accommodate the grout. The thinner waste zone increases the leach rate which is inversely proportional to the waste thickness.

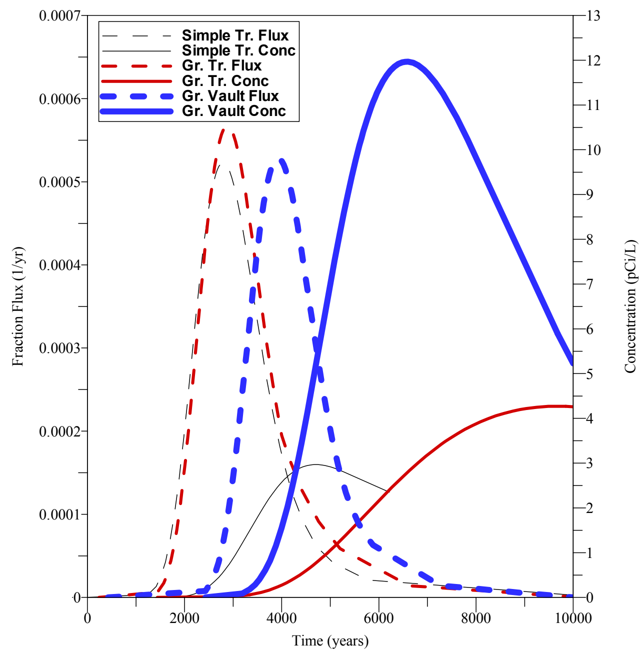


Figure 8. Se-79 fluxes at the water table and aquifer concentrations for a Simple Trench, Grouted Trench and a Grouted Vault

Table 5. Waste zone Kds for Se-79

Disposal Unit	Kd in Waste Zone (ml/g)
Simple Trench	150
Grouted Trench	170
Grouted Vault	0.1

Sn-126 Waste

Contaminant fluxes at the water table and peak aquifer concentrations at a hypothetical 100-m well for Sn-126 are shown in Figure 9. Peak fluxes and well concentration information is summarized in Table 6.

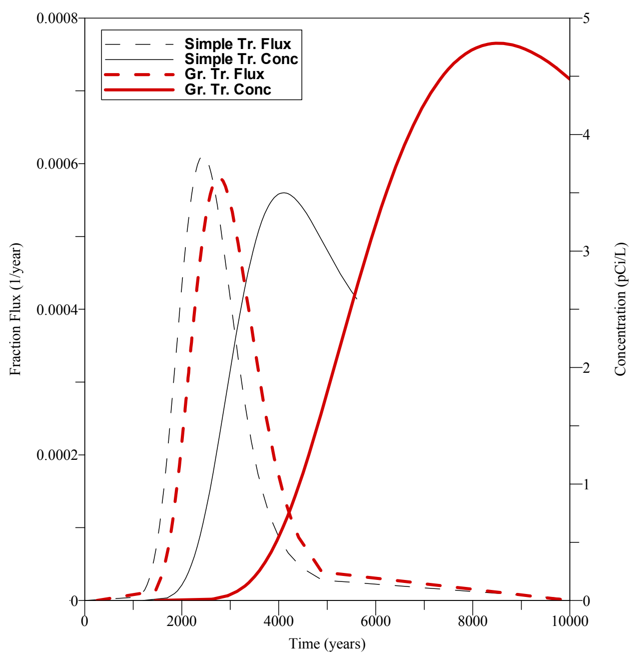


Figure 9. Sn-126 fluxes at the water table and aquifer concentrations for a Simple Trench and Grouted Trench

Table 6. Comparison of fluxes and well concentrations for Sn-126 waste

Unit	Peak Fractional Flux	Time (years)	Peak Well Concentration (pCi/L)	Time (years)
Simple Trench	6.11E-4	2450	3.50	4100
Grouted Trench	5.81E-4	2760	4.78	8520

Explanation of Results for Sn-126

The simple trench has a higher waste zone Kd (see **Table 7**), that is offset by its higher average liquid velocity. The peak flux for the simple trench is slightly higher than the peak flux for the grouted trench. If based only on the contaminant fluxes at the water table generated by the vadose zone model, the simple trench model would produce a higher well concentration. Thus, minor differences in the aquifer model due to slightly different locations likely caused the grouted trench model to produce a higher well concentration.

Table 7. Waste zone Kds for Sn-126

Disposal Unit	Kd in Waste Zone (ml/g)
Simple Trench	130
Grouted Trench	55

SUMMARY

Three radionuclides were examined that exhibited higher well concentrations for either a grouted trench disposal or a grouted vault disposal relative to disposal in a simple trench. In the first case for generic I-129 with the simple trench showing a high relative flux, but the lowest relative well concentration, it was suggested that the timing of the cap placement reduced the sustainability of the peak well concentration.

For the second case with Se-79, two comparisons were made. In the first comparison, the grouted vault had the lowest waste zone Kd, thus likely causing it to have the highest well concentration. For the second comparison, the grout in the grouted trench combined with the reduced thickness of the waste zone likely cause the grouted trench to have a higher well concentration than the simple trench.

For the third case with Sn-126, the differences were much smaller. Those differences were attributed to variations in the aquifer model, because the disposal units occupy different locations.

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