Effects of Point Sources in Trench Disposal of Radioactive Waste

by

L. B. COLLARD
Westinghouse Savannah River Company
Aiken, SC 29808

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L. B. Collard
Westinghouse Savannah River Company
Aiken, SC 29802

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Abstract

At the U.S. Department of Energy Savannah River Site, disposal of radioactive wastes in shallow trenches was simulated with vadose zone models and decoupled aquifer models. The vadose zone models provided contaminant fluxes to the aquifer models.

Previous vadose zone models employed an assumption that all wastes were uniformly distributed throughout the trench. In some cases waste streams from treating ground water and process water produced a limited volume of high-concentration I-129 wastes that would occupy far less than ten percent of the trench's volume. A parametric study was performed to determine the effects of limited volumes of high-concentration wastes placed at different locations throughout the trench.

Uniformly distributed waste filled about 2,000 boxes in the trench. For other simulations the waste inventory was concentrated in smaller volumes ranging from 4 boxes (500X concentration) to 1000 boxes (2X concentration). Waste locations varied both left to right and top to bottom.

Two K_d cases were simulated. Generic waste with a K_d of 0.6 ml/g represented clothes and tools. Resin with a K_d of 380 ml/g represented I-129 sorbed during water treatment.

Concentrations at a 100-m well under the worst conditions (highest concentration and closest to the well) could be about 4 times as high as the uniform case for a waste-specific K_d of 0.6 ml/g. The concentrations could be about 8 times as high as the uniform case for a K_d of 380 ml/g.

Results indicate that worst case conditions can produce undesirable results. Because field conditions are not expected to be a worst case, simulations of actual waste placement are planned.

VADOSE ZONE WASTE AND TRENCH CONFIGURATION

Ten trenches aligned along their long axis were excavated. Each trench was designed to be 640 ft long by 20 ft wide by 20 ft deep with a 10 ft separation between trenches. Sixteen feet of waste was placed in each trench and covered by 4 feet of clean backfill. For vadose zone analyses a two-dimensional cross-section was used (see Figure 1).

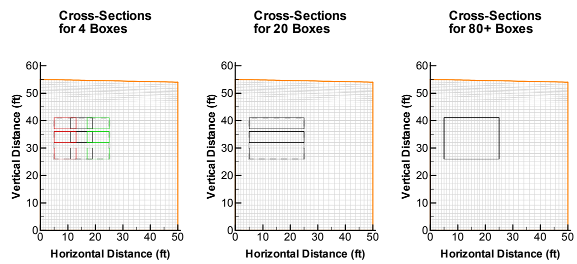

Figure 1. Vadose zone cross-section of one trench

For the purposes of this study, nine of the ten trenches were assumed uniformly filled with waste. The other trench was the point source trench. The point source trench had waste of various volumes placed at various locations to form the basis of the parametric study. In each case the waste inventory in each trench was 1 Ci..

To represent various point source sizes, the waste was spread over volumes approximately equal to 4, 20, 80, 160, 1000, or 2000 boxes, each box being 6 ft long by 4 ft wide by 4 ft tall. Placement of the boxes was varied vertically (Up, Center, and Down) and horizontally (Left, Center, and Right). Nine locations for the 4-box scenarios were used. Because the waste volume of 20 boxes encompassed the entire width of the trench, three locations were used with only a vertical variation. For waste volumes greater than 20 boxes, the entire waste zone was assumed filled with waste.

VADOSE ZONE FLOW ANALYSIS

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 cover. The steady-state flow field for this period and other periods is shown in Figure 2.

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.

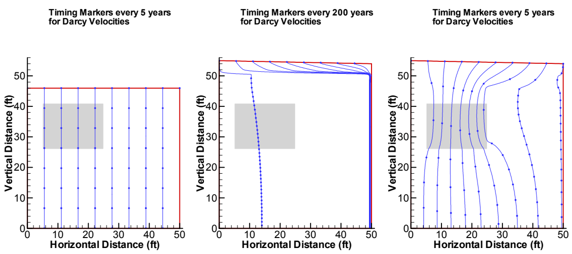

Figure 2. Streamlines for uncapped, capped, failed cap trench stages shown left to right

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 being much greater than that for the surrounding native soil.

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 spread over a specified volume at a specified location that depended on the scenario. The nine trenches uniformly filled with waste were represented by the 2000-box waste volume analysis for the point source trench.

After the first 25 years 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 25 years, 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 time period from 25 years to 125 years was completed, a similar auxiliary concentration adjustment was made.

Two different waste forms containing I-129 were analyzed. The first waste form was generic waste, such as clothing and tools, with an assigned Kd of 0.6 ml/g. The second waste form was CG-8 resin with a laboratory measured Kd of 380 ml/g. Other waste forms exist with Kds as high as about 132,000 ml/g, but these two waste forms represent a very mobile and a relatively immobile contaminant.

Contaminant fluxes at the water table for the generic waste with a Kd of 0.6 ml/g are shown in Figure 3. Because the original contaminant mass was 1 Ci, the contaminant fluxes are also fractional fluxes.

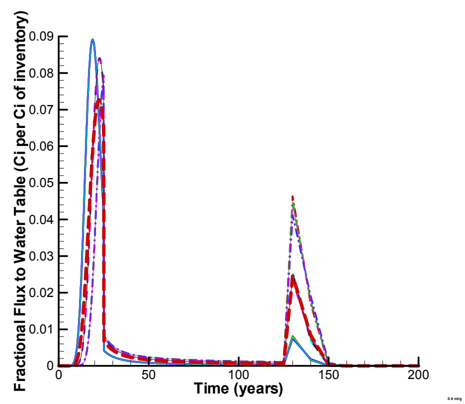

Figure 3. Fractional fluxes for generic I-129 waste

Figure 3 shows two time regions when spikes occur. The first region ends at 25 years, when the intact cap was assumed placed over the waste creating instantaneous reductions in the flow through the waste zone. The second time region showing a spike started at 125 years, when the cap was assumed to fail with instantaneous increases in the flow through the waste zone. The 80-box set shows the lowest primary peaks that cause the highest secondary peaks, because more of its source remained available.

Two important pieces of information from these curves are the peak fractional flux and the time of its occurrence presented in Table 1. Only the 4-box scenarios involve locations that vary across the width of the trench. The flux peaks occur during the first 25 years when the flow is uniform and vertically downward, thus flux location across the width of the trench had no impact on the peaks.

Table 1. Comparison of selected peak fractional fluxes at the water table for generic I-129 waste

Peak Frac. Flux	Time (yrs)	Flux vs. Uniform Case	Num. Boxes	Elev.	Left-Right
8.91E-02	18.8	1.23	4	Down	All*
8.41E-02	22.7	1.16	4	Middle	All*
7.93E-02	25.0	1.09	4	Up	All*
8.91E-02	18.8	1.23	20	Down	N/A
8.41E-02	22.7	1.16	20	Middle	N/A
7.93E-02	25.0	1.09	20	Up	N/A
7.27E-02	22.3	1.00	80+	Full	N/A

*Left, Center and Right all produced same results

For scenarios involving only 4 boxes, the peaks increase and the time of the peak decreases as the waste elevation is lowered. This result reflects the reduced distance that contaminants must travel as the waste elevation is lowered. Similar results occur for the 20-box scenarios. Actually, the peaks and times of their occurrences do not vary between the 4-box scenarios and the 20-box scenarios. This equivalence is a further manifestation of the independence on the waste location across the trench width.

Scenarios with 80 or more boxes filled the waste zone, thus contaminant fluxes at the water table were identical for a two-dimensional cross-section model. The peak flux for the 80-box scenario was about 10 percent less than the lowest peak flux for smaller volumes of waste located at the top of the waste zone. The smaller peak flux for the 80-box scenario was caused by the lower waste concentration. The shorter average travel distance for the 80-box scenario produced a peak at 22.3 years versus a peak at 25.0 years for the 4-box scenario at the top of the waste zone.

Resin I-129 waste with a Kd of 380 ml/g displayed much lower peak fractional fluxes (see Figure 4 and Table 2) than did generic I-129 waste with a Kd of 0.6 ml/g. The 4-box scenarios at the upper and middle elevations showed little differences in peak fluxes as the waste location varied across the width of the trench, but the right side location always had the greatest peak flux at the earliest time.

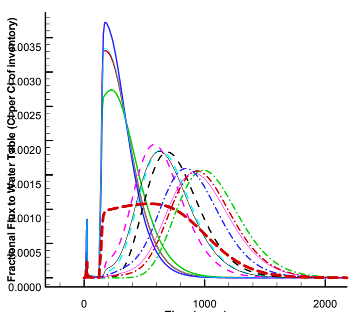

Figure 4. Fractional fluxes for resin I-129 waste

The 4-box scenarios at the bottom showed differences in peak fluxes at the water table as the waste location varied across the width of the trench. The peak fractional fluxes from waste were 3.31E-3, 2.74E-3, and 3.73E-3 for waste at the bottom left, middle and right, respectively.

Peak fractional fluxes that after 125 years were affected by the failed cap flow field. The apparent travel time for water (Darcy velocities) moving from the surface to the water table is 29.1 years, 28.4 years and 29.7 years for water moving through the left side, middle and right side of the waste zone, respectively. The paths for water at the edges are longer than the path for water in the middle, thus the slightly longer travel times for water at the edges combined with the path differences shows that the water speed is about equal across the trench width.

Most differences in the peak fractional fluxes can be attributed to only recording data at 10-year intervals for 130 years and beyond. Had more frequent recording been employed, the peaks across the width for waste at the bottom likely would have been more similar as were the peaks for waste at other elevations.

The peak fractional fluxes increased as the waste was placed at lower elevations. For the 4-box scenarios the peak fractional fluxes changing from an average of 1.57E-3 at the top to 1.88E-3 in the center to 3.26E-3 at the bottom. The changes for the 20-box scenarios were nearly identical.

Each 4-box and 20-box scenario had a greater peak fractional flux than the 80-box scenario flux of 1.08E-3. The waste concentration for the 20-box scenarios increased the peak fractional flux by about 40%, 70% and 200% for waste placed at the top, middle and bottom, respectively.

Table 2. Selected peak fractional fluxes at the water table for resin I-129 waste

Peak Frac. Flux	Time (yrs)	Flux vs. Uniform Case	Num. Boxes	Elevation	Left-Right
3.31E-03	170.1	3.06	4	Down	Left
2.74E-03	230.1	2.54	4	Down	Center
3.73E-03	180.1	3.45	4	Down	Right
1.86E-03	640.1	1.72	4	Middle	Left
1.83E-03	690.1	1.69	4	Middle	Center
1.94E-03	580.1	1.80	4	Middle	Right
1.56E-03	940.0	1.44	4	Up	Left
1.57E-03	990.1	1.45	4	Up	Center
1.59E-03	850.1	1.47	4	Up	Right
3.35E-03	180.1	3.10	20	Down	N/A
1.84E-03	620.1	1.70	20	Middle	N/A
1.53E-03	910.1	1.42	20	Up	N/A
1.08E-03	540.1	1.00	80+	Full	N/A

AQUIFER CONFIGURATION

Figure 5 shows the outlines of the various waste locations for the one trench containing point sources. For clarity, the 2000-box and 1000-box outlines are not shown, which occupy the entire trench and half the trench, respectively. The contaminant flux at the water table was assumed uniformly spread over its footprint when it was input as a source term to the aquifer model.

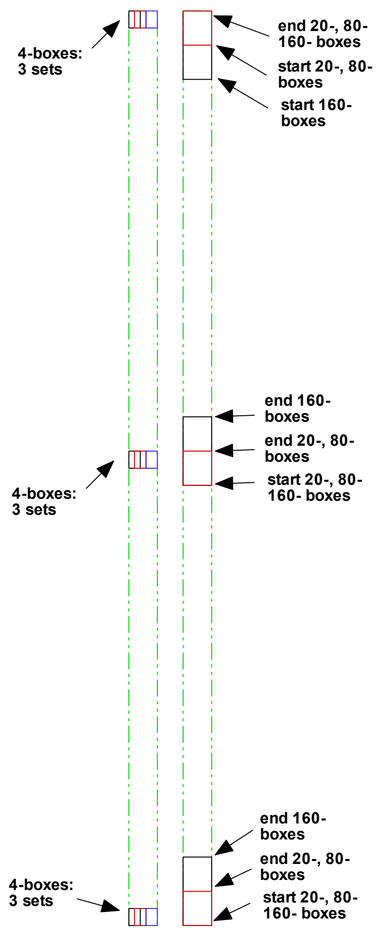

Figure 5. Plan View of Aquifer Model Showing Modeling Cases by Number of Boxes

The plan view for the aquifer model is shown in Figure 6. Each of the two large rectangular areas shows the perimeter for a set of five trenches. The point source trench is shown as a thin, dashed rectangle within the left set of five trenches. Performance requirements for waste disposal allow a 100-m buffer area. Circles with a radius of 100-m are shown in the figure with centers at the upper-left corner of each perimeter, because the general direction of travel for water is to the upper-left. The 100-m buffer used was defined as the left-to-right line located 100-m above (in the y-direction) the upper edge of the perimeters.

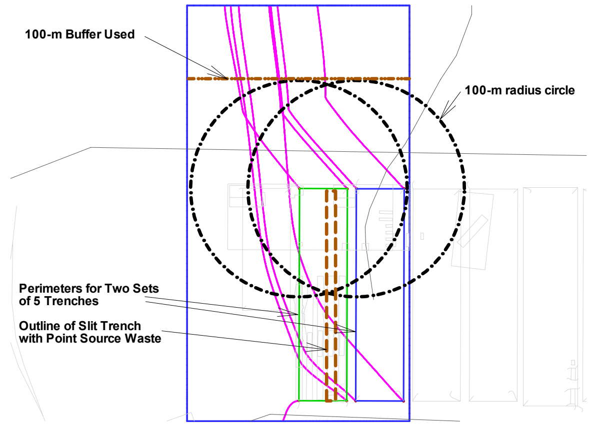

Figure 6. Plan view of aquifer model showing particle tracks and 100-m buffer

AQUIFER FLOW ANALYSIS

The aquifer flow analysis consisted of calculating one steady-state flow field subset that was cut from the regional model. Figure 6 shows one anomalous water path in the lower-left corner of the left set of five trenches. This likely had no impact on waste placed in the point source trench because of the distance between them. Only a small area of the uniformly distributed waste would be affected.

AQUIFER CONTAMINANT TRANSPORT ANALYSIS FOR GENERIC I-129 WASTE

The aquifer contaminant transport model included the steady-state flow field from the aquifer flow model and the contaminant flux at the water table from the vadose zone contaminant transport model. Results of interest were the peak concentrations beyond the 100-m buffer. Because the aquifer cell sizes varied and the location of the peak was unknown a priori (and could vary based on waste location), an auxiliary program was developed to report concentrations for a moving 20 ft by 20 ft horizontally-oriented window. At each cell level, the lower-left hand corner of the 20 ft by 20 ft window was stepped from one cell to another and the average concentration within the window was calculated. The highest concentration for all the windows was reported at each recorded time step for each waste scenario.

Concentration histories for all the waste scenarios with generic I-129 waste are shown in Figure 7. Peak concentrations for each waste scenario are shown in Table 3, along with the times of their occurrence, descriptions of the waste scenarios, and values that were normalized by dividing by results for the scenario with only uniformly distributed waste. For brevity, waste plan view locations are identified as west to east (left to right) and south to north (bottom to top).

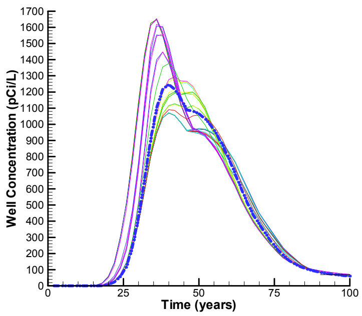

Figure 7. Concentrations for generic I-129 waste scenarios

Table 3. Selected peak concentrations for 10- and quasi-single trench waste scenarios for generic I-129 waste

9 Uniform Trenches + 1 Point Source Trench						Minus 9 Uniform Trenches	
Time (yr)	Conc. (pCi/L)	Num. Box	Elev.	Dir.	Norm Conc.	Conc. (pCi/L)	Norm. Conc.
40	1070.641	4	Down	SW	0.86	-51.27	-0.41
40	1070.617	4	Down	SE	0.86	-51.30	-0.41
42	1289.524	4	Down	CW	1.03	167.61	1.34
36	1649.100	4	Down	NW	1.32	527.19	4.23
40	1070.384	4	Mid	SW	0.86	-51.53	-0.41
42	1201.719	4	Mid	CW	0.96	79.81	0.64
36	1619.346	4	Mid	NW	1.30	497.43	3.99
40	1070.349	4	Up	SW	0.86	-51.56	-0.41
42	1127.787	4	Up	CW	0.90	5.87	0.05
38	1447.969	4	Up	NW	1.16	326.06	2.62
40	1071.332	20	Down	SW	0.86	-50.58	-0.41
36	1655.149	20	Down	NW	1.33	533.24	4.28
40	1070.961	20	Up	SW	0.86	-50.95	-0.41
38	1448.005	20	Up	NW	1.16	326.09	2.62
40	1070.482	80	N/A	SW	0.86	-51.43	-0.41
42	1201.370	80	N/A	CW	0.96	79.46	0.64
36	1553.898	80	N/A	NW	1.25	431.98	3.47
40	1070.571	160	N/A	SW	0.86	-51.34	-0.41
42	1216.277	160	N/A	CW	0.98	94.36	0.76
38	1558.866	160	N/A	NW	1.25	436.95	3.51
40	1090.599	1000	N/A	S	0.87	-31.31	-0.25
40	1377.033	1000	N/A	N	1.10	255.12	2.05
40	1246.571	2000	N/A	N/A	1.00	124.66	1.00

Table 3 also contains information for a quasi-single trench in the rightmost columns. The need for a quasi-single trench analysis arose after completing the modeling runs, when it was recognized that concentrating waste in only one trench did not adequately represent field operations, where concentrated wastes likely would occur in multiple trenches. In an attempt to provide results more representative of field operations, the effects of the nine trenches with uniform waste distributions were subtracted from the original model results to isolate the single point source trench, thus producing the quasi-single trench analysis.

Effects of the nine trenches with uniformly distributed waste were calculated as 90 percent of the peak concentration for waste uniformly distributed in all ten trenches. Peak concentrations for the quasi-single trench were calculated by subtracting the 90 percent value from peak concentrations for each 10-trench analysis, thus the ordering and differences did not vary, but the ratios compared to base value did. The base value for the 10-trench analysis (1247 pCi/L) was the peak concentration for waste uniformly spread over 10 trenches. The base value for the quasi-single trench analysis (124.7 pCi/L) was the peak concentration estimated for waste uniformly spread over 1 trench, assuming that each trench contributed equally to the 10-trench peak. Particle tracks from Figure 6 indicate that each trench will not contribute the same mass of contaminant at the same time, thus the assumption contains some error. That error was manifested as negative values in Table 3 indicating that the waste results are non-linear and significant plume interaction exists. Only positive values for the quasi-single trench are considered further.

For the 10-trench analyses peak concentrations are smaller for the 4-box waste scenario with waste at the bottom of the southern end than they are for uniformly distributed waste. Even though the waste is more concentrated it has a longer average distance to travel. The peak contaminant flux that was about 23% greater for the 4-box waste scenario was more than offset by the longer aquifer travel distance. Peak concentrations for 4-box waste at the bottom of the trench essentially did not vary when the waste was placed at different locations across the width of the trench (ranging from 1070.617 to 1070.641 pCi/L for waste at the south end). Peak concentrations for the 4-box scenarios at the bottom of the trench increased from about 1071 pCi/L/Ci at the south end to about 1292 in the center and about 1649 at the north end of the trench.

The time of occurrence of the peak concentrations was expected to monotonically decrease as the waste was placed closer to the north end. However, the location of the window used to calculate the peak concentration was not fixed and the flow paths varied depending on the waste location, thus the times of the peaks varied.

For 10-trench analyses, peak concentrations and the ratio of peak concentrations to uniformly distributed waste ranged from 772 to 1013 pCi/L and from 0.87 to 1.14, respectively. For quasi-single trench analyses, peak concentrations and the ratio of the positive peak concentrations relative to uniformly distributed waste ranged from 34 to 211 pCi/L and from 0.38 to 2.37, respectively.

AQUIFER CONTAMINANT TRANSPORT ANALYSIS FOR RESIN I-129 WASTE

Peak concentrations for resin I-129 waste (see Figure 8 and Table 4) ranged from about 49 to 94 pCi/L. Because its Kd was higher its peak concentrations were lower than the peak concentrations for the generic I-129 waste (1071 to 1655 pCi/L). Several waste scenarios produced peak concentrations less than that for uniformly distributed waste, where the center of the waste was located the furthest distances from the peak window.

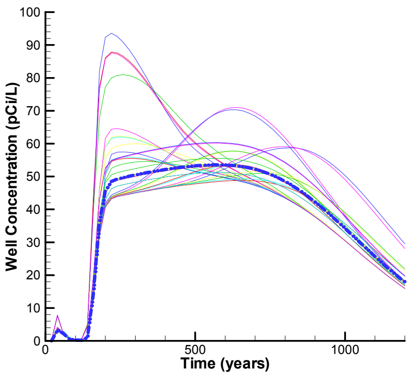

Figure 8. Concentrations for resin I-129 waste scenarios

Peak concentrations for 4-box waste at the bottom of the trench varied little when the waste was placed at different locations across the width of the trench (ranging from 54.578 to 57.483 pCi/L for waste at the south end). Peak concentrations for the 4-box scenarios at the bottom of the trench increased from about 56 pCi/L at the south end to about 62 pCi/L in the center and about 88 pCi/L at the north end of the trench.

The time of occurrence monotonically decreased as the 4-box scenario waste at the bottom of the trench was placed closer to the north end. This expected behavior likely was exhibited by the resin waste (as opposed to the generic I-129 waste behavior), because of its higher Kd that delayed and broadened the peaks, thus reducing sensitivity to the window location.

For the 10-trench analyses, peak concentrations and the ratio of the peak concentrations relative to uniformly distributed waste ranged from 49 to 93 pCi/L and from 0.91 to 1.72, respectively. For the quasi-single trench analyses, peak concentrations and the ratio of the peak concentrations relative to uniformly distributed waste ranged from 0.65 to 45 pCi/L and from 0.12 to 8.33, respectively.

Table 4. Selected peak concentrations for 10- and quasi-single trench waste scenarios for resin I-129 waste

9 Uniform Trenches + 1 Point Source Trench						Minus 9 Uniform Trenches	
Time (yr)	Conc. (pCi/L)	Num. Box	Elev.	Dir.	Norm. Conc.	Conc. (pCi/L)	Norm. Conc.
280	55.510	4	Down	SW	0.48	7.31	1.37
260	57.483	4	Down	SE	0.45	9.28	1.73
240	62.026	4	Down	CW	0.41	13.83	2.58
220	87.869	4	Down	NW	0.38	39.67	7.41
640	53.411	4	Mid	SW	1.10	5.21	0.97
620	57.682	4	Mid	CW	1.07	9.48	1.77
640	71.019	4	Mid	NW	1.10	22.82	4.26
660	48.852	4	Up	SW	1.14	0.65	0.12
720	50.922	4	Up	CW	1.24	2.72	0.51
820	58.736	4	Up	NW	1.41	10.54	1.97
280	55.902	20	Down	SW	0.48	7.70	1.44
220	87.559	20	Down	NW	0.38	39.36	7.35
660	49.289	20	Up	SW	1.14	1.09	0.20
800	59.091	20	Up	NW	1.38	10.89	2.03
580	51.231	80	N/A	SW	1.00	3.03	0.57
580	53.696	80	N/A	CW	1.00	5.50	1.03
560	60.336	80	N/A	NW	0.97	12.14	2.27
580	51.251	160	N/A	SW	1.00	3.05	0.57
580	53.803	160	N/A	CW	1.00	5.60	1.05
560	60.127	160	N/A	NW	0.97	11.93	2.23
580	53.133	1000	N/A	S	1.00	4.93	0.92
560	55.529	1000	N/A	N	0.97	7.33	1.37
580	53.555	2000	N/A	N/A	1.00	5.36	1.00

SUMMARY

Several conclusions arise from this work. First, the location of point sources across the trench width has minimal effect. Second, peak concentration decreased as the center of the waste was moved away (either vertically or horizontally) from the concentration window. For some locations the point source waste produced smaller concentrations than did uniformly distributed waste. Third, point sources for the resin waste with a greater Kd has a greater relative impact than did point sources for generic I-129 waste with a lower Kd. The worst conditions (highest concentration and shortest distance) in the 10-trench case could produce peak concentrations about 1.1 times as high as the uniform case for waste with a K_d of 0.6 ml/g and about 1.7 times as high for waste with a Kd of 380 ml/g. For the quasi-single trench case the low Kd waste produced peak concentrations about 2.4 times as high than the uniform case while the high Kd waste produced peak concentrations 8.3 times as high.