7.0 Summary and Conclusions

Modeling of Amchitka's nuclear tests encompasses two major processes: 1) the flow modeling, which includes density-driven flow due to saltwater intrusion, and 2) the transport modeling that is a combination of advection, dispersion, retardation, source term and glass dissolution, matrix diffusion and radioactive decay. Modeling each of the two processes is based on a certain conceptualization of the flow or the transport. There are many assumptions that are aimed at reducing the complexity of the studied processes or are a result of the scarcity of data available at the island. Many of the processes encountered are associated with difficulties determining the values of the parameters governing them, and in some cases the processes themselves are not well understood. The selected modeling approach and the results presented in this study represent an attempt to overcome these difficulties and address these uncertainties.

The flow and transport modeling is based on a two-dimensional conceptualization of the island's cross section, which is represented for each test by a transect from the island's centerline (divide) through the test location and then to the sea. The two-dimensional modeling relies on a homogeneous, anisotropic conductivity field with no spatial variability except at the cavity and chimney. Flow and transport through fractures is the fundamental scenario considered.

A calibration is performed for each test location using head data and groundwater chemistry data from nearby boreholes as calibration targets. Simultaneous, exact matches of these two independent data sets are not achieved at any site, though the uncertainty expressed by the standard deviation in the base-case flow models encompasses the observed data. The head data are considered to be more reliable than the chemical data and are given more weight in the calibration. The chemical data are subject to questions of their degree of representing in-situ conditions due to borehole mixing and incomplete purging of drilling fluids. In addition, the chemical data are more likely than the head data to be in disequilibrium with current hydraulic conditions as a result of the last sea level change, as demonstrated in a sensitivity analysis. The final calibrations depict a deeper transition zone on the Bering Sea side of the island as compared to the Pacific.

A parametric uncertainty analysis evaluated the effect of uncertainty in seven key parameters on the resulting uncertainty in the transport results. The parameters evaluated are hydraulic conductivity, recharge, macrodispersivity, fracture porosity, small-scale dispersivity, glass dissolution, and matrix diffusion. The end result of this modeling stage is the reduction of the list of uncertain parameters from seven parameters to only four parameters. Three parameters are excluded from the list because the uncertainties associated with the values of these parameters show minor effects on the uncertainties of the transport results in comparison with the remaining parameters. Of the remaining list of the uncertain parameters, hydraulic conductivity, recharge and fracture porosity are treated as uncertain in the flow and transport modeling, while the uncertainty in matrix diffusion is handled as a sensitivity.

The flow and transport modeling for each site solves the flow and transport problems using random realizations for the values of the three parameters in the uncertain list while keeping all other parameters at fixed values (as if they are known with certainty). The ensemble of realizations of the transport solutions is then analyzed for individual nuclides with different release and retardation characteristics. Transport results indicate that the radionuclide movement at Long Shot is much faster than at Milrow and Cannikin. That is due to the location of the cavity being very shallow as compared to the other two tests. The working point of Long Shot is at a depth of 700 m, whereas the Milrow cavity is centered at about 1,218 m and that of Cannikin is at about 1,791 m below ground surface. Thus, Long Shot is above the transition zone in all realizations, whereas Milrow and Cannikin tend to be within or below the transition zone.

The location of the cavity relative to the varying location of the transition zone is an important factor influencing transport results. Below the transition zone, the generally toward-island-axis flow direction in the saltwater zone delays the particles' migration toward the breakthrough boundary by lengthening the flowpath. This is accentuated by much slower velocities in the saltwater section. If the location of the transition zone in a certain realization is causing the cavity to be located in the saltwater zone, transport is significantly delayed in that realization allowing for more radioactive decay. In comparing the transport results of the three tests, one can observe a certain pattern related to that factor. At Long Shot, for example, all of the realizations had mass flux breakthrough at the seafloor within the simulation time. At Milrow, 8 percent of the realizations did not break through at the seafloor within 2,200 years, while at Cannikin over 30 percent did not break through, even without considering the effects of retardation and decay. The same trend is evident in the percentage of mass breakthrough, when it does occur. Over 90 percent of the Long Shot realizations experienced 100 percent breakthrough, whereas percentage of breakthrough was typically much lower for the Milrow and Cannikin realizations that did reach the seafloor.

An explanation for these aspects is shown in Figure 7.1. The figure shows the three transition zones at the three sites and the corresponding cavity location. For each test, the vertical distribution of concentration (averaged over the MC realizations considered) at the right edge of the cavity is plotted (solid lines). The dotted lines in the figure indicate the elevation of the top and bottom of the cavity at the three sites. As can be seen in the figure, the Long Shot cavity is always located at the freshwater side and very far from the center of the transition zone. This leads to the direct movement of radionuclides from the cavity toward the seafloor. The Milrow cavity and that of Cannikin, on the other hand, are located at the saltwater side of the transition zone (on average). This means that in many realizations, the cavity comes in contact with the circulatory and very slow flow pattern occurring at the lower edge of the transition zone. This explains why 25 realizations at Milrow do not produce any mass breakthrough within 2,200 years. For Cannikin, the cavity is also located in the saltwater side of the transition zone (on average), and in addition is deeper. This results in a larger number of realizations coming in contact with the circulatory flow pattern, and longer flowpaths to the seafloor when they do.

The differences in cavities relative to the transition zone between the three sites are reflected in the breakthrough curves. Considering tritium, the earliest peak mean breakthrough occurs at Long Shot, in 25 to 30 years after the test at a normalized peak mean concentration of about 1.8×10^{-4}. Both Milrow and Cannikin have peak mean tritium breakthrough at about 100 years after each test, with peak normalized concentrations of 1.6×10^{-8} for Milrow and 1.9×10^{-9} for Cannikin. In all

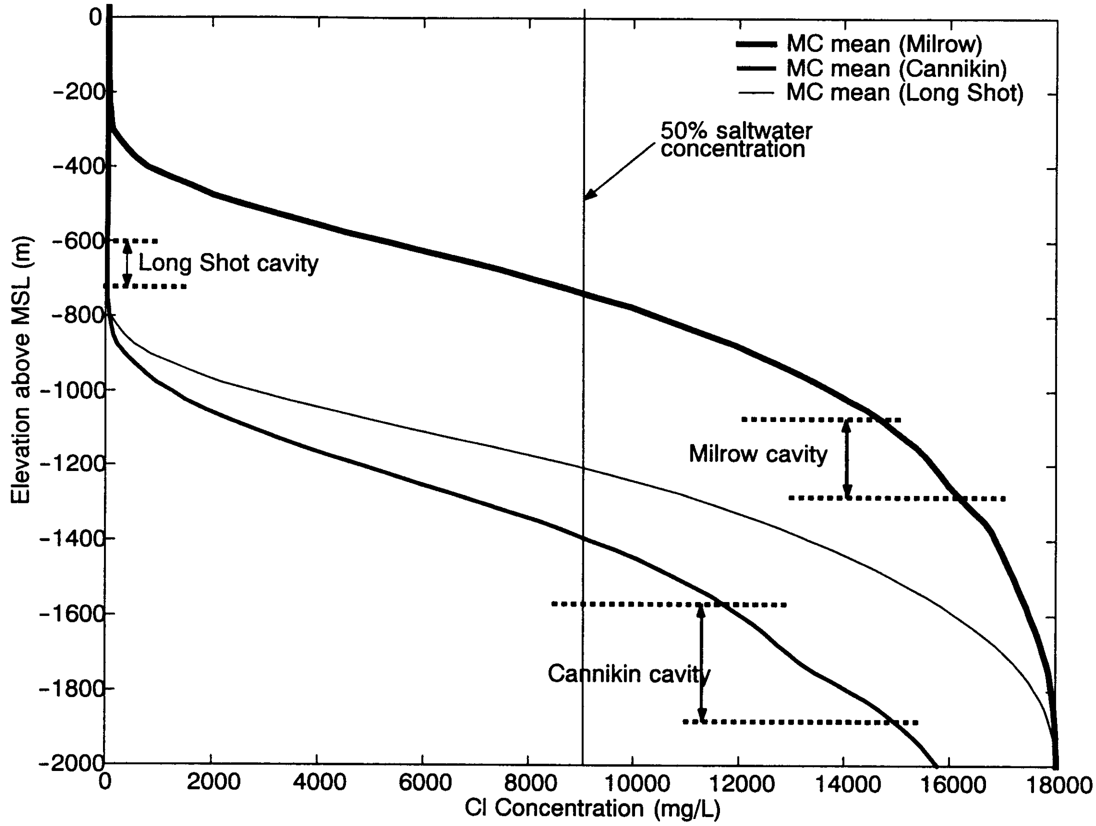

Figure 7.1. Cavity location relative to the expected transition zone profile for the three tests.

cases, adding one standard deviation increases the concentrations approximately one order of magnitude. The time and normalized mass for each radionuclide considered is a function of its radioactive half-life, as well as the flow and transport results. For example, the peak mean concentration of ^{14}C occurs at about 100 years at Long Shot, as the peak for tritium at 20 to 30 years is driven in large part by the short tritium half-life.

The incorporation of uncertainty in the transition zone location (through uncertainty in recharge and hydraulic conductivity), while consistent with the uncertainties from island data, leads to a large variation in transport results from one realization to the next. As described above, the transport calculated for a realization with the Milrow cavity intersecting the transition zone is dramatically different than for a realization with the transition zone below the cavity. For both Milrow and Cannikin, the early-time portion of the breakthrough curves is dominated by the realizations representing the transition zone at or below the cavities.

A variety of sensitivity studies are presented. With the exception of evaluating matrix diffusion, the alternate scenarios are performed on several realizations selected to be representative of the gamut of flow behavior. As a result, the sensitivity results are not directly comparable to the Monte Carlo results, but do allow identification of the general magnitude of impact that process uncertainty contributes. A variety of numerical solution issues, matrix diffusion, colloid transport, uncertainty in island half-width, sea level changes, and geothermal processes are evaluated using the 2-D models. The impact of the 2-D simplification, flow in the rubble chimney, Cannikin Lake, nuclear heat and flow in fault zones are all evaluated with 3-D models.

The presence of the nuclear chimney, with its high vertical conductivity, is found to dominate many of the other conceptualizations (the chimneys are included in the base-case Monte-Carlo calculations). Numerical solution issues, sea level changes, geothermal processes, the 2-D simplification, Cannikin Lake, and fault zones all have relatively limited impact on transport results for the realizations analyzed, or result in significantly less transport than the base-case. Matrix diffusion, colloid transport, island half-width, and nuclear heat are potentially more significant.

The impact of flow field conceptual processes (e.g., thermal processes, faults, the half-width, and Cannikin Lake) on transport varies strongly with cavity location in the domain relative to the transition zone. Variations in transport caused by these features are on the order of several times (larger and smaller), not orders of magnitude. Conversely, some of the base-case model parameters have uncertainties spanning many orders of magnitude that translate directly into velocities, and therefore they have greater impact on the results than the uncertainties in heat and 3-D flow evaluated here. In addition, the uncertainties in retardation properties, evaluated as the matrix diffusion parameter and colloids, can also affect results by orders of magnitude. Matrix diffusion uncertainty is conservatively evaluated here (only lower diffusion is evaluated, not higher), with data suggesting the process is larger and allowing much less transport than simulated.

Considering the supporting data as well as the modeling results, the most significant uncertain parameter is the porosity assigned to the fracture system. Not only does the porosity directly control travel times, it is uncertain through many orders of magnitude and there are no island-specific data to support a mean value nor distribution. It should be noted that this is a common problem for fracture-flow environments, and one that is not easily remedied. It should additionally be emphasized that the fracture flow approach taken here for a conceptual model is also an assumption. At the overburden pressures encountered at depths of thousand of meters, and given the abundant data supporting relatively high matrix porosity values, a porous medium assumption may be equally valid and would result in extremely long travel times (recall that only 29 of 100 realizations had breakthrough in 5.5 million years in a porous medium analysis for Milrow). Additional uncertain parameters are the matrix diffusion coefficient and glass dissolution rate, though the significance of their impact depends on the half-life of the radionuclide and the predicted flow velocities.

The quantification of uncertainty due to key model parameters, expressed as the standard deviation of the breakthrough curves, allows many of the uncertainties discussed above to be included in the risk assessment. The modeling results presented here are but one part of the risk assessment process that evaluates the potential hazard posed by the three underground nuclear tests on Amchitka. The results of the risk assessment will determine whether the uncertainties identified here are of potential significance or can be tolerated within an acceptable margin of safety.