PNL-SA-9894
Conf-820303--15

PNL-SA--9894

DE82 008605

Assessment of Effectiveness of Geologic Isolation Systems

AEGIS METHODOLOGY DEMONSTRATION: CASE EXAMPLE IN BASALT

F. Harvey Dove

January 1982

Prepared for Waste Management '82
Tucson, Arizona
March 8-11, 1982

Work supported by the
Office of Nuclear Waste Isolation
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy

Pacific Northwest Laboratory
Richland, Washington 99352

DISCLAIMER

AEGIS METHODOLOGY DEMONSTRATION: CASE EXAMPLE IN BASALT

F. Harvey Dove
Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

The Assessment of Effectiveness of Geologic Isolation (AEGIS) Project has been developing and applying methodology to evaluate the post-closure performance of a geologic repository for the deep disposal of nuclear waste. Methodology development began at the Pacific Northwest Laboratory (PNL) in 1972. Since the summer of 1978, methodology demonstrations have been completed for sites in bedded salt, granite, dome salt, and basalt. While the repository location was hypothetical, the geographical setting was actual, introducing new and increasing complexities into the analyses of each site. The basalt assessment was the most comprehensive application of AEGIS technology attempted to date. The demonstration in the Columbia Plateau was to accomplish a more careful and detailed release scenario analysis, including use of the Geologic Simulation Model for basalt, and a detailed consequence analysis commensurate with the available data, time, and funds.

AEGIS ANALYSES

Performance assessment of long-term waste isolation involves a number of distinct analytical steps. AEGIS currently has the technology for performing these analytical steps.[1,2] The AEGIS approach is applicable at various levels of sophistication, depending on the analytical need and the amount of information available. The analytical methods are continuously improved to overcome deficiencies identified during technology demonstrations and as the site selection and licensing processes develop. A simplified diagram of the AEGIS analyses is shown in Figure 1.

Available information contained in Federal publications, state publications, Rockwell International reports, selected university studies, local consultant reports, and other sources has been used to establish the data base and initial

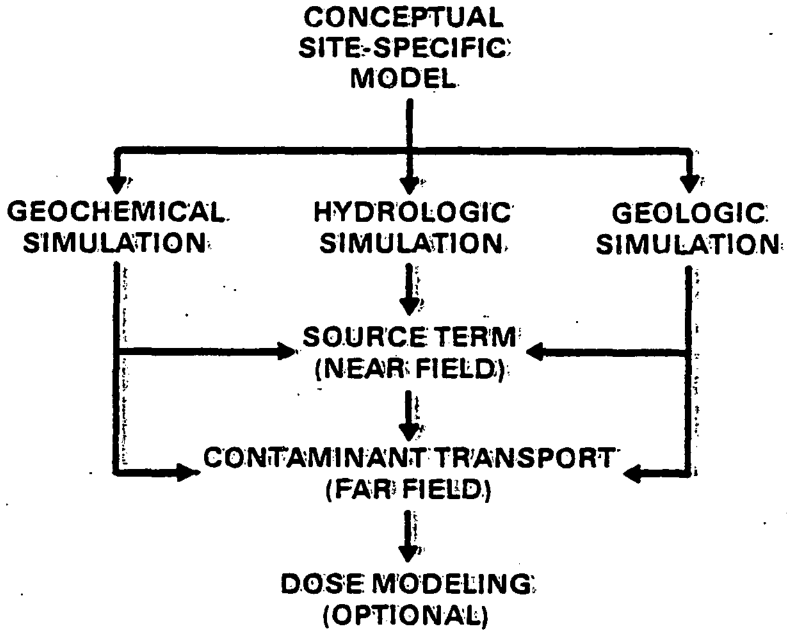

FIGURE 1. Simplified AEGIS Analyses

hydrologic and geologic interpretations for the site-specific application in basalt. Because an understanding of the dynamics of ground-water flow is essential to the development of both release scenarios and consequence analyses, a key step in the demonstration is the systems characterization contained in the conceptual model. Regional and local ground-water movement patterns have been defined with the aid of hydrologic computer models. Hypothetical release scenarios have been developed and evaluated by a process of expert opinion and by a process involving a Geologic Simulation Model for basalt. Although not a part of this analysis, the Geologic Simulation Model can be used to forecast future boundary conditions for the hydrologic simulation. Chemical reactivity of the basalt with ground water will influence the leaching and transport of radionuclides; solubility equilibria based on available data were estimated with geochemical models. After the radionuclide concentrations were mathematically introduced into the ground-water movement patterns, waste movement patterns have been outlined over elapsed time. Contaminant transport results were summarized for significant radionuclides that were hypothetically released to the biosphere. Dose modeling was not included in the basalt demonstration; however, computer models are available to predict the anticipated radiation dose levels for humans and their environment.

Conceptual Site-Specific Model

The AEGIS conceptual model for the basalt demonstration has a regional aspect (21,000 square miles) characteristic of the Columbia Plateau Basalt (78,000 square miles) and a local aspect (2,000 square miles) similar to Pasco Basin. Definition of the hydrology and geology of both aspects depends on the information obtained from current and planned field programs of Rockwell Hanford Operations (RHO) and others. Regional flow of ground water tends to be southwestwardly across the model area. Exceptions to this general flow appear to be:

- at the northern perimeter of the Columbia Plateau Basalt where ground water may be flowing toward the edge of the plateau because of potentiometric highs within the model boundary
- north of the Blue Mountains where ground water tends to flow northward toward the Snake River
- in the western portion of Pasco Basin where ground water tends to flow generally eastward toward the Columbia River.

Hydrologic Simulation

The hydrologic simulation was divided into three major parts: 1) aquifer recharge calculations, 2) a regional hydrologic model, and 3) a local hydrologic model of the Pasco Basin. Published hydrologic data used in this analysis was gathered in 1979 or earlier. Interpretation of available data has generally emphasized a conservative evaluation. Ground-water investigations within the Hanford Site are still continuing, and the interpretation of more recent data may suggest changes to the potentiometric surfaces, transmissivity maps, and boundary conditions developed for the basalt demonstration.

An estimate of the amount of water transmitted through the ground-water system was required to bound the transmissivity values and to estimate the transmissivity distributions for the deeper basalts. A statistical interpretation method was used to correlate precipitation and potential evapotranspiration data with elevation. However, the Cascade rain shadow is projected across part of the region influencing the analytical results. Water balance and recharge estimates for the regional and Pasco Basin models are shown in Table 1.

TABLE 1. Water Balance and Recharge Estimates for the Regional and Pasco Basin Models

Estimates	Regional (million acre ft/yr)	Pasco Basin (acre ft/yr)
Precipitation	12.2	772,000
Actual Evapotranspiration (AET)	12.2	1,394,000
Pumping	0.20	27,000
Recharge	2.66	287,000
Irrigation	1.22	
Sage-Cheat	0.93	
Forest	0.15	
Dry Land Wheat	0.36	

Hydrologic models of different complexity are operational at Pacific Northwest Laboratory. The multiple layer two-dimensional Variable Thickness Transient (VTT) code[3] was selected as appropriate for the amount of data available and for the conditions existing in the regional systems. This model uses a finite difference formulation to represent the partial differential flow equation. The regional study area as defined for the VTT model was divided into a 55 by 55 square pattern with each grid 3 miles (15,840 ft) on a side. The regional system was modeled as a held potential surface layer and two underlying basalt layers. The regional model established the boundary conditions for the hydrologic model of Pasco Basin.

The local model simulates in greater detail a subregion of the regional hydrologic model. Simulation of this smaller region allowed for greater resolution to be obtained around the repository and along the potential ground-water pathways from the repository to the point of discharge into the biosphere. The Finite Element Three-Dimensional Ground-Water Model (FE3DGW)[4] was selected for modeling the local region. The FE3DGW model uses the Galerkin finite element method with deformable quadrilateral elements. The finite element grid was constructed using the structural and potentiometric surface contours from each of four layers. The resultant two-dimensional grid consists of 606 surface nodes and 555 surface elements. After calibration, water-table levels for the local model were in close agreement with the observed values within the Mabton Flow. The average difference at 10 wells is 46 ft. The Rattlesnake Ridge Flow shows a better comparison with the average difference for five wells being 30 ft.

Geologic Simulation

The performance analysis of a repository system whose behavior must be studied over substantial periods of time needs a geologic simulation model to quantify potential system changes and their probabilities. Complex phenomenological codes are too expensive and unwieldy to be used to explore the consequences of every "scenario" of undesirable system changes devised in site characterization and qualification studies. The geologic simulation model must include simple versions of the more complex phenomenological codes so that it can act as a filter, allowing the complex codes to be applied to modeling those changed states of the system which have the greatest combination of probabilities and consequences. Such an analysis endeavors to describe the behavior of the repository system, the likely and possible changes of that behavior over the time period of interest, and the probabilities and uncertainties associated with both the inputs and outputs of the analysis. In developing the Geologic Simulation Model (GSM) for basalt,[5] numerous potentially disruptive natural phenomena were identified and analyzed. These phenomena form two groups, based on their potential for affecting the repository, as shown in Table 2.

TABLE 2. Potentially Disruptive Phenomena

Phenomena	Potential Effect
Group I	
Rock Deformation Magmatic Activity Meteorite Impact	Could Directly Disrupt Repository
Group II	
Climatic Change Glaciation Sea-Level Fluctuations Geomorphic Processes Hydrology	1. Probably Cause Significant Degradation or Disruption 2. Affect Hydrologic and Geologic Boundary Conditions

The completed AEGIS GSM was used to generate 500 Monte Carlo simulations of the behavior of the geologic/hydrologic system affecting a hypothetical repository in the Pasco Basin over the next million years. These simulations used data which were not subjected to a review adequate for the requirements of a real performance assessment. However, the general care used in generating the data, and the overall behavior of the GSM suggest that the results are plausible at this time.

Evolution of the simplified hydrologic system in the GSM resulted primarily from the effects of climatic changes and of movement on local faults. Thus, the time histories of Darcy velocity and travel time depend upon the accuracy of the Milankovitch climate driver and ancillary data and subroutines (for example, rainfall rates, glacial advances, Missoula floods, and river erosion), and upon the data and code of the Deformation Submodel which resulted in insignificant folding, fault offset, or relative elevation changes between the Pasco Basin and the ground-water recharge areas. None of the 500 simulations produced substantial changes to either Darcy velocity or travel time in the first 20,000 years of simulated time (beginning 100 years after closure).

A threshold value of Darcy velocity of an order of magnitude greater than the starting value was used in the GSM analyses to flag significantly increased flow rates.[6] Figure 2 shows that this threshold was not exceeded until about a quarter of a million years of simulated time had passed. However, a demonstration of the AEGIS technology would have been incomplete without consideration of some undesirable altered state of the geologic/hydrologic system. Faulting (probability of less than 10^{-7}) appears to be the most probable of the unlikely natural mechanisms by which the hypothetical repository could be disrupted in the first 20,000 years.

Geochemical Simulation

The chemical reactivity of the bedrock will influence the transport of solutes in ground water. The ion speciation-solubility WATEQ2 model was utilized to determine the solubility constraints for published water analyses.[7] The ground-water samples from transmissive zones of the Columbia Plateau basalts compute to be at equilibrium with calcite which provides both a solubility control for dissolved calcium and a pH buffer. Most of the ground-water samples

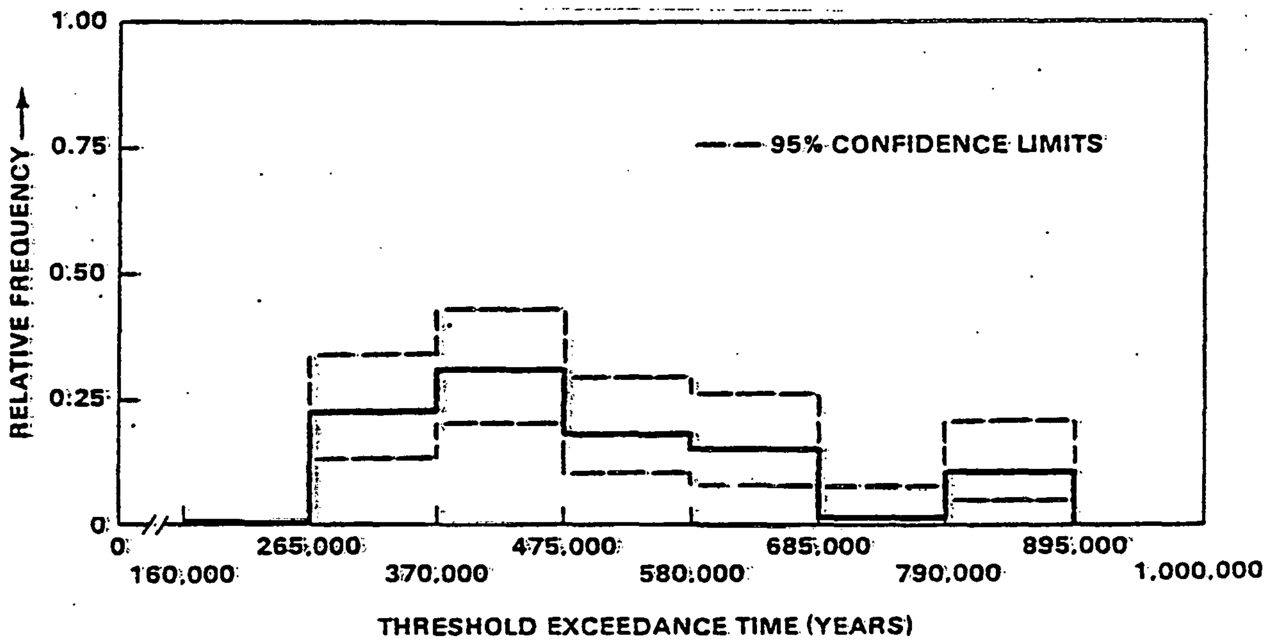

FIGURE 2. GSM Results Showing Relative Frequency of Threshold Exceedance Assuming Exceedance Occurs in One Million Years

compute to be at equilibrium with amorphic silica (glass), are saturated to oversaturated with respect to allophane, an amorphic alumino-silicate, and are variably oversaturated with regard to secondary clay minerals. These solubility equilibria are important factors with regard to chemical-retention processes associated with the possible migration of nuclear waste stored in the earth's crust. Specifically, the occurrence of secondary minerals, particularly amorphic phases, will enhance the sorption of dissolved radionuclides.

The analyses suggest that the processes of dissolution of basaltic glass and formation of metastable secondary minerals are continuing even though the basalts are of Miocene age and presumably have undergone a long history of contact with ground waters. The oversaturation with respect to the clay minerals indicates that their formation rate lags the dissolution rate of the basaltic glass. The modeling results indicate that metastable amorphic solids limit the concentrations of dissolved aluminum, iron and silicon.

Source Term

A simple source term for spent fuel based on uranium solubility constraints and congruent leaching was used in this technology demonstration. The assumed breach scenario is that of a new thrust fault intercepting the repository. Characteristics interpreted from fault data indicate that: 1) the major folds and faults in the Pasco Basin are oriented northwest-southeast to east-west, 2) Umtanum Ridge, Gable Mountain, Yakima Ridge, the Rattlesnake Hills, and the Saddle Mountains are associated with reverse/thrust faults or possible reverse/thrust faults, 3) the reverse/thrust faults associated with Umtanum Ridge, Gable Mountain and the Rattlesnake Hills dip to the south, 4) reverse/thrust fault dips generally range from near horizontal to near vertical, 5) at and near Gable Mountain-Gable Butte the faults dip between 10° and 45°, and 6) tectonic breccia zones range up to about 100 m wide, but as we assume that a "new" fault will disrupt the repository, a narrow (e.g., 2 m wide) fault zone was selected.

In the repository, spent fuel waste packages are assumed to sit in a 12-ft by 120-ft grid of holes in the floor, with each hole 4 ft in diameter by 19.5 ft deep. The 12-ft centers lie north-south. In this analysis, no credit has been taken for engineered barriers included in backfill, overpack, or waste package design other than geometry. The fault strike is assumed to lie north 60° west, and the dip is assumed to be 30°. It is also assumed that the interception of a hole anywhere along its 19.5-ft depth will breach a waste package. (Actually, the waste packages are shorter than the hole depth.) Water flows along the fault plane from transmissive zones below the repository, through the repository, and to upper transmissive zones. Shear at the fault plane is assumed to cut spent fuel waste packages in two, leaving two remnants, each open on one end, into which water can flow. Therefore, the fault can breach waste packages over this 19.5-ft range of elevations, which corresponds to a width in the horizontal direction of 33.8 ft. The repository is assumed to extend 10,400 ft east-west and 7,650 ft north-south, such that the maximum length of the fault intercepting the repository is 12,000 ft. The fractional repository area over which waste packages can be breached is 0.005.

Reported uranium release rates from spent fuel range down to 10^{-5} kg/m^2 day at 25°C, and a typical spent fuel surface area is 0.2 m^2/kg. Based on this alone, the release duration would not exceed 1400 years. At 1400 years, the waste package temperature would be over 110°C, and the actual release duration would be much shorter at the higher temperature. Assuming a volumetric ground water flow rate per meter width of fault of 0.1 to 1.0 m^3/yr, and a waste package hole diameter of 1.22 m, the volumetric flow rate available to waste package remnants would be 0.24 to 2.4 m^3/yr. Using the predicted equilibrium uranium concentration in a waste package at the predicted waste package temperatures, and a 1300 kg uranium inventory per waste package, the release duration ranges from 1300 years (faulting at 100 years, 2.4 m^3/yr) to 16,000 years (faulting at 10,000 years, 0.24 m^3/yr). The effective duration is half as long for a package sheared into remnants of equal size. Considering half of 1300 years and that 1/200 of the waste packages leach, then based on repository inventories, the release rate is less than 10^{-5}/year.

Transport Modeling

The one-dimensional Multicomponent Mass Transport (MMT1D) model,[8] based on the method of discrete parcel random walk, was used to simulate the movement and to predict the concentrations of radioisotopes released by the waste repository. The hypothetical repository was assumed to be located beneath the Hanford Meteorological Station (latitude 46° 33' 47", longitude 119° 35' 54") in the center of the Umtanum flow at about 3,700 ft below ground surface. This places the repository at approximately 3100 ft below mean sea level. A summary of the streamline characteristics for a release from the repository and transport north to the Columbia River is included in Table 3.

TABLE 3. Summary of the Minimum, Maximum, and Average Values for the Streamline Length, Travel Time, and Velocity for Eleven Streamlines

Description	Minimum	Maximum	Average
Length (ft)	40,000	51,000	45,000
Time (yr)	13,000	17,000	15,000
Velocity (ft/yr)	2.82	3.29	3.03

The transport analysis was divided into two cases, long- and short-term predictions. The long-term analysis was used to predict which nuclides, if any, would escape to the biosphere in the two million years after the fault intersection event. This analysis was used to determine the maximum rate of arrival (Ci/yr), time of maximum arrival rate, and the total amount of activity released to the environment during this two-million-year period. The short-term analysis predicted the distances traveled and the radionuclide concentrations after 1000 years and 10,000 years, because these appear to be emerging as the times of particular interest to the proposed regulatory criteria for geologic disposal.

The transport analysis for the first 1000 years following initiation indicated zero release to the accessible environment. For purposes of this study, the "accessible environment" includes the basalt and alluvial ground-water system at a one-mile distance from the repository boundary in the X-Y or plan dimension. In this first 1000 years, the maximum distance any contaminated waters migrated from the repository was 1300 ft. This maximum migration was for the leading dispersive edge of the contaminant plumes for the nonretarded isotopes ^{14}C and ^{129}I. The peak concentrations for the nonretarded isotopes were located approximately 200 ft from the repository. The maximum migration distance for the rest of the isotopes, all of which are retarded, was on the order of 100 ft. In all, 16 isotopes had concentration peaks in excess of the maximum permissible concentration (MPC), but this contaminant plume represents only 0.021 gpm and is located approximately 3000 ft below ground surface and within the 1-mile buffer zone around the repository. Assuming a 100-gpm well as a practical minimum for a well drilled to this depth, the dilution factor of 4700 would reduce the radionuclide concentrations in all withdrawn waters below MPC values.

For the 10,000-yr analysis it is not clear whether any of the nuclides would actually leave the 1-mile buffer zone around the repository and enter the accessible environment. Peak ground-water concentrations for ^{14}C and ^{129}I (the nonretarded radioisotopes) were located 5000 ft from the repository. The peak ground-water concentrations for all the other isotopes were less than

100 ft from the repository. In all, 16 isotopes had peak ground-water concentrations in excess of MPC. As indicated for the 1000-yr analysis, the dilution factor of 4700 provided by a 100-gpm well would reduce all withdrawn ground-water concentrations well below MPC. For the sake of conservatism we assumed that the accessible environment was reached. The cumulative arrival for ^{14}C and ^{129}I are well within EPA draft standards as shown in Table 4.

TABLE 4. Summary of Cumulative Arrival Quantities and Maximum Arrival Rates for All Isotopes Reaching the Accessible Environment in the First 10,000 Yr for the Base Case

Isotope	Maximum Arrival Rate (fract/yr)[a]	Maximum Arrival Rate (curies/yr)	Cumulative Arrival Over First 10,000 Yr (curies)	EPA Proposed Standards (curies)[b,c]
^{14}C	1.7×10^{-7}	5.9×10^{-3}	1.6×10^{1}	2.0×10^{2}
^{129}I	5.5×10^{-7}	8.2×10^{-4}	2.0×10^{0}	9.0×10^{2}

(a) Fraction of the total repository inventory (for that isotope) per year. The rate in curies per year divided by the initial repository inventory (for that isotope) at t = 10 yr.
(b) Per 1000 metric ton of heavy metal (MTHM).
(c) Proposed standard for iodine removed from earlier drafts.

The long-term simulations predict the rates that radionuclides would enter the biosphere following the fault intersection event. Most of the fission and activation products are too short-lived or are so greatly retarded that they will never enter the biosphere. However, some nuclides (^{226}Ra, ^{229}Th, ^{230}Th, ^{232}Th, ^{233}U) have more total curies exiting than were present in the original inventory. This is due to the effect of chain decay.

CONCLUSIONS

The AEGIS technology has been successfully demonstrated. For the same data, similar unpublished results have been obtained by RHO and INTERA Environmental Consultants, Inc. for contaminant transport. In addition to establishing the utility of computer codes and assessment methodology, the AEGIS technology demonstration in basalt has also produced some practical guidance for future field data gathering programs.

The results of this basalt demonstration indicate that the geohydrologic systems separating the nuclear waste from the natural biosphere discharge site mitigate the consequences of the postulated fault intersection event. This analysis suggests that the basalt system satisfies the 1000- and 10,000-yr proposed standards for release to the accessible environment (limited release of ^{129}I and ^{14}C). The reader should be cautioned, however, that the results are valid only for one particular set of parameters and one postulated release scenario. A complete sensitivity analysis must be performed to evaluate the range of effects that might be observed under different release conditions and for the different ranges in parameters.

REFERENCES

1. Dove, F. H. 1981. "A Short Description of the AEGIS Approach," In: J. F. Relyea (Editor), Waste/Rock Interaction Technology Program FY-80 Information Meeting, October, PNL-3887.

2. Dove, F. H. 1981. "AEGIS Methodology and a Perspective from AEGIS Methodology Demonstrations," Proceedings of the Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High-Level Radioactive Waste, Gatlinburg, Tennessee, March 9-13, PNL-SA-9110.

3. Reisenauer, A. E. 1980. Variable Thickness Transient Groundwater Hydrologic Model. (3 volumes) PNL-3160, Pacific Northwest Laboratory, Richland, WA.

4. Gupta, S. K. et al. 1980. Finite-Element Three-Dimensional Groundwater (FE3DGW Flow Model--Formulation, Program Listings and Users' Manual. PNL-2939, Pacific Northwest Laboratory.

5. Petrie, G. M. et al. 1981. Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau. PNL-3542, Pacific Northwest Laboratory, Richland, WA.

6. Zellmer, J. T. and J. W. Lindberg. 1981. "A Study of Present and Perturbed Ground-Water Flow Rates Through a Hypothetical Basalt Nuclear-Waste Repository to Establish a Significance Criterion," Proceedings, Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High-Level Radioactive Waste, Gatlinburg, Tennessee, March 9-13, PNL-SA-9112.

7. Ball, J. W. et al. 1979. "WATEQ2 - A Computerized Chemical Model for Trace and Major Element Speciation and Mineral Equilibria of Natural Waters," In: E. A. Jenne (Editor), Chemical Modeling in Aqueous Systems. Am. Chem. Soc. Symposium Series, No. 93, pp. 815-835.

8. Washburn, J. T. et al. 1980. Multicomponent Mass Transport Model: A Model for Simulating Migration of Radionuclides in Ground Water. PNL-3179, Pacific Northwest Laboratory, Richland, WA.