DISCLAIMER

This document is an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FINAL DRAFT

CONCEPTUAL MODEL
FOR REGIONAL RADIONUCLIDE TRANSPORT
FROM A BASALT REPOSITORY SITE

MASTER

A TECHNICAL MEMORANDUM

For

University of California
Lawrence Livermore Laboratory

By

William C. Walton
Michael L. Voorhees
and
Thomas A. Prickett, P. E.

Of

Camp Dresser & McKee, Inc.
Water Resources Division
Suite 1700
302 E. John Street
Champaign, Illinois 61820
Phone: 217/384-4374

May 23, 1980

DISSEMINATION OF THIS DOCUMENT IS UNLIMITED

169

TABLE OF CONTENTS

	<u>Page</u>
I. Summary	1
II. Introduction	5
III. Major Characteristics of Basalts	9
IV. Potential Basalt Repository Host Rocks	13
V. Typical Basalt Repository Host Rock	19
Conceptual Model	29
VI. Process and Parameters	33
Advective Transport	34
Hydrodynamic Dispersion	38
Sorption	42
Radioactive Decay	45
Thermal	45
Media Deformation	48
Difficulty of Predicting Parameter Values	49
VII. Modeling Computational and Output Requirements	53
VIII. References Cited	57

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Generalized Characteristics of Basalts	10
2	Map Showing Areas Where Tertiary and Quaternary Volcanic Rocks Are at or near the Surface	14
3	Map Showing Areas Where Quaternary Volcanic Rocks Are at or near the Surface in the Northwest United States	16
4	Map Showing Areas Where Columbia River Basalt Is at or near the Surface	18
5	Generalized Geologic and Hydrogeologic Characteristics of the Pasco Basin	21
6	Generalized Geologic and Hydrogeologic Cross Sections of the Pasco Basin	22
7	Conceptual Cross Sectional Model for Typical Basalt Repository Host Rock	30
8	Margins (Boundaries) of Columbia River Basalt Formations	31
9	Range of Values of Hydraulic Conductivity	39
10	Generalized Parameter Requirements and Flow Chart for Models	54

TABLES

<u>Table</u>		<u>Page</u>
1	Piezometric Heads In Selected Deep Basalt Wells Within The Hanford Site.	24
2	Summary Of Hydrogeologic Properties Of Sediments And Rocks Beneath The Pasco Basin.	26
3	Summary Of Distribution Coefficient Values For Unconfined Sediments And Umtanum Basalt.	27

SUMMARY

This technical memorandum was prepared to: 1) describe a typical basalt radionuclide repository site, 2) describe geologic and hydrologic processes associated with regional radionuclide transport in basalts, 3) define the parameters required to model regional radionuclide transport from a basalt repository site, and 4) develop a "conceptual model" of radionuclide transport from a basalt repository site.

In a general hydrological sense, basalts may be described as layered sequences of aquifers and aquitards. Tops and bottoms of lava beds and permeable interflow zones are normally aquifers. The massive relatively impermeable interior parts of lava beds and fine-grained materials often interbedded with more permeable sediments in interflow zones are aquitards.

Volcanic rocks such as basalts, rhyolites, andesites, and tuffs in the western continental United States are potential radioactive waste host rocks. Young basalts underlying the Snake River Plain in southern Idaho and parts of western Washington and Oregon, and northern California have high transmissivities and low potential as host rocks for radioactive waste repositories. The older, thicker, and less permeable Columbia River Basalt located in Washington, Oregon, and Idaho has potential to serve as a host rock. The relative impermeable and zeolite-rich tuff deposits in southern Nevada are also receiving attention as potential host rocks.

The Columbia River Basalt, centered near the semi-arid Pasco Basin, is considered by many to be typical basalt repository host rock. The repository might be located about a thousand meters below the surface.

A 1500-meter thick sequence of Columbia River Basalt apparently overlies a series of older basalts beneath the Pasco Basin. Individual basalt units range in thickness from more than 100 to a fraction of a meter. The Columbia River Basalt covers an area of more than 155,000 square kilometers in Washington, Oregon, and Idaho. The flow in deep basalts is generally toward the Columbia River. Horizontal hydraulic conductivities in the deeper basalts are low and range from 2.6×10^{-12} to 3.5×10^{-8} m/s; vertical hydraulic conductivities of dense basalt range from 3.5×10^{-12} to 1.4×10^{-8} m/s. The average porosity of basalt rocks is 2 percent.

Major layering exists in the basalt geologic column with numerous types of deposits of varying hydraulic conductivities and thicknesses and a wide variety of boundary conditions are possible. Interbedded high-low hydraulic conductivity sequences occur within the major layers as complex intraformational aquifer-aquitard features. Waste-transport routes will be determined by these sequences and gross transmissivities will have limited meaning.

Detailed description of the flow system including flow velocities with high-low hydraulic conductivity sequences are not possible with existing data. However, according to theory, waste-transport routes are ultimately towards the Columbia River and the lengths of flow paths from the repository to the biosphere may be relatively short.

There are many physical, chemical, thermal, and nuclear processes with associated parameters that together determine the possible pattern of radionuclide migration in basalts and surrounding formations. Basically, these processes and parameters are interrelated and pertain to flow, mass transport, heat transport, and medium deformation. Physical processes are advective transport, dispersion, and medium deformation. Diffusion, adsorption, and precipitation are included in chemical processes. The thermal related processes include conduction and convection. Radioactive decay is the nuclear process.

Brief process descriptions and associated parameter lists are provided. Tables of parameter values found in the literature search are given to assist in the design of the conceptual model. The lists indicate ranges of values and their uncertainty.

The large areal and profile extent and complex hydrogeologic conditions dictate that numerical digital mathematical models be employed in assessing radionuclide migration risk. The models should be three-dimensional because horizontal and vertical flow and mass transport in several stacked and hydraulically connected layers must be analyzed.

Great difficulty is encountered in evaluating basalt vertical hydraulic conductivity and its variation in space. The list of vertical hydraulic conductivity values for basalts determined with available measurement techniques is short. Vertical hydraulic conductivity is one of the weakest links in the chain of predictable parameters. Vertical hydraulic gradients are most difficult to identify and quantify especially those in relatively impermeable basalt rocks. Sampling

techniques often significantly disturb artesian pressure heads and re-establishment of static conditions may require excessively long periods of recovery.

There is no standard technique for measuring longitudinal and transverse dispersivities or the other components of the basalt anisotropic dispersion tensor. Regional dispersivities are generally determined in connection with the calibration of transport digital computer models by adjusting dispersivities and sometimes porosity until the model simulates the observed concentrations. In light of complex heterogeneous and anisotropic conditions existing in most groundwater systems, on a macroscopic basis dispersivity can not be precisely defined.

Emphasis has been placed on the use of the distribution coefficient in simulating ion exchange. Distribution coefficients are commonly determined in the laboratory where it is difficult if not impossible to maintain or simulate the physical and chemical field integrity of a sample. The use of the distribution coefficient approach is limited because it takes into account only relatively fast mass transfer processes. In general, knowledge of hydrogeochemical processes is primitive.

INTRODUCTION

The feasibility of disposal of radioactive wastes in deep geologic basins has been investigated for about 25 years. A report by the National Academy of Sciences in 1957 highlighted the problems associated with the geological, biological, physical, and chemical aspects of waste containment. Host rocks receiving early attention are salt deposits, shales, and basalts.

Camp Dresser and McKee has written this technical memorandum for the Lawrence Livermore Laboratory of the University of California to identify and describe the parameters necessary to model radionuclide transport in basalts by groundwater. The research focuses on groundwater problems related to the storage of high-level radioactive wastes generated by nuclear power plants and specifically on those processes which might affect the regional groundwater resource. A primary concern of waste disposal in basalt is the possibility of groundwater intersecting the radioactive waste material and transporting radioisotopes to the biosphere. This technical memorandum describes the processes that are important in transporting radioactive wastes from a repository site in basalt by groundwater flow.

The objective of a deep repository site is to preclude radioactive wastes from reaching the biosphere by transport in groundwater or by chemical and thermal reactions, tectonism, erosion, volcanism, seismicity, glaciation, and climatic change until they have decayed below hazard limits. Desirable properties of host rocks for radioactive-waste repositories are low hydraulic conductivity; high plasticity,

sorption potential, and tectonic stability; great depth and thickness; and slow groundwater movement along flow paths to the surface (Bredehoeft et al., 1978). Groundwater transport to the biosphere is acknowledged to be the most probable hazard.

Transport of radioactive wastes is affected by advection with flow, dispersion including diffusion, and chemical interactions including adsorption and precipitation. Transport time tends to lengthen with low hydraulic conductivity, low hydraulic gradient, high sorption capacity, and long flow paths.

Hydraulic conductivity, hydraulic gradients, and flow-path lengths are all subject to change over long containment timespans (Burkholder et al., 1977). Predictive models must take into consideration existing and probable changes in rock geometry and properties with associated uncertainties. Because of the limited time available for this investigation, the effects of catastrophic geological events on the hydrogeology of basalts are not treated. No attempt has been made to evaluate the causes or likelihood of these catastrophic events.

A conceptual model for the Columbia River Basalt underlying the Pasco Basin is presented to assist in the future selection of mathematical models for assessing the risk associated with siting a repository in a typical basalt. The geometry and boundary conditions of the repository are considered as a source or sink within the basalt at a depth of 914 meters. Emission of heat, rates of radionuclide release to the groundwater, and production or adsorption rates related to moisture or gases generated within the repository and trans-

mitted to the neighboring groundwater are assumed to be given parameters. Such processes as volcanism, faulting, erosion, and such items as sabotage, nuclear warfare, drilling, and impact of meteorites are not addressed, but are considered as given mechanisms of nuclide contaminant failure. The conceptual model is based on readily available information concerning geometry, boundaries, and parameters which are assumed as given conditions. It is further assumed that source and sink functions such as groundwater pumpage, groundwater recharge rates, or thermal-heat production rates from depths below the repository are all known.

The scope of work undertaken by Camp Dresser and McKee under purchase order number 6939009 involves those activities necessary to develop a "conceptual model" of regional radionuclide transport from a basalt repository site that 1) describes all the processes to be included in the model as well as their interrelationships; 2) briefly defines the parameters and variables associated with each process; 3) outlines the types of boundary conditions and initial values that must be accommodated; 4) provides estimates or ranges of estimates of all input parameters; and 5) specifies model computational and output requirements.

This memorandum is organized by first outlining the basic characteristics of basalts and how they hydraulically respond in a flow system; secondly, by describing likely geologic areas in the United States where basalt deposits might act as a host rock for a repository; thirdly, by delineating the characteristics of the conceptual model for radionuclide transport from a basalt

repository along with a description of a typical site; and fourthly, giving a detailed list of the processes and parameters necessary for modeling the regional flow system around a basalt repository.

A short discussion is given at the conclusion of the memorandum which briefly addresses model computational and output requirements. A conceptual model is herein defined as a representation of an actual system which leads to a preliminary understanding of the system and can be used in defining more sophisticated models of the system. Emphasis is placed on word and simple graphic descriptions of the system keeping in mind that the conceptual model must behave in a manner analogous to the actual system under a set of generalized conditions. The conceptual model broadly defines the geometry of the actual system, sets local, intermediate, and regional boundary and flow conditions, and assigns order-of-magnitude parameter values.

MAJOR CHARACTERISTICS OF BASALTS

Basalt is an igneous volcanic rock formed by the cooling and crystallization of liquid rock material (MacDonald, 1967). This report is chiefly concerned with extrusive basalts in the continental United States formed as the result of liquid rock material erupting from volcanic vents and fissures and flowing over the surface as lava. Intrusive basalts within sills, dikes, etc., are not considered herein.

Basalt rocks generally occur as numerous lava beds laid down one upon another with intervening sedimentary interflow zones deposited during periods between successive flows (see Mundorff et al., 1952; Newcomb et al., 1970). This sequence originally horizontal, or nearly so, may be altered by deformation of the earth's crust in the form of gentle warping of the lava beds, large-scale folds, or vertical displacements along faults. Individual lava beds may be extensive over many square kilometers and may range in thickness from a fraction of a meter to more than several 10s of meters, and interflow zones may range in thickness from a tenth of a meter to several meters. Stratigraphic discontinuities -- pinching out, overlapping, and fusion of lava beds and interflow zones -- occur at places (Newcomb, 1969).

The major characteristics of basalts are generalized and simplified in Figure 1. Groundwater occurs and moves most commonly in upper and lower parts of lava beds and in permeable unconsolidated sedimentary material between lava beds (interflow zones). The dense interior

Figure 1. Generalized Characteristics of Basalt.

parts of lava beds do not generally transmit or store large quantities of groundwater. However, these dense zones may be crossed vertically to some extent by joints and cracks formed as a result of rock shrinkage during the cooling process, or later tectonic stress. The degree of hydraulic connection between interflow zones can vary considerably. Usually, vertical joints and cracks in the center of lava beds become tighter with depth because of increased pressure from the weight of overlying rock.

The principal minerals found in the very fine grained, dense, and crystalline rock matrix of lava beds are feldspar (calcium-rich plagioclase) and ferromagnesian minerals (pyroxene, olvine, or amphibole). This matrix is generally less permeable than igneous rocks such as granites and gabbros (Davis, 1969).

Lava beds contain original interstices (water-bearing openings) in the form of vesicles produced near the top and bottom by the expansion of steam or other gas during cooling and crystallization. These vesicles are largely isolated or communicate with one another only imperfectly (Meinzer, 1923). Centers of lava beds may be massive and non-vesicular. Other possible original interstices include irregular cavities produced as liquid lava beneath a surficial crust moves away (lava tubes), and joints (columnar and other) as a result of shrinkage produced by cooling. The degree of interconnection of these interstices is variable. There may be rubbly basalt, pillow zones, ash, and cinders both above and below dense lava beds. Secondary interstices in the interior parts of lava beds may include joints and cracks produced by deformation which intersect imperfectly. The

original interstices of sedimentary interflow zones consist of the spaces between adjacent fragments of rock. Compaction and the formation of secondary minerals may reduce original interstitial space. At places, interflow zones may contain interbeds of fine-grained material of low permeability which retard the vertical movement of groundwater.

Porosity in basalt rocks tends to be concentrated in interflow zones and in the tops and bottoms of most lava beds. The porosity of interior parts of the lava beds is small. In general, groundwater in basalts occurs under artesian pressure conditions beneath discharge areas but not beneath recharge areas. Hydraulic conductivity is normally also concentrated in interflow zones and tops and bottoms of lava beds with interior parts of a lava bed having relatively low hydraulic conductivities or being nearly impermeable strata. The hydraulic conductivity of basalt rocks is commonly heterogeneous and anisotropic. The most permeable plane is parallel to lava beds and hydraulic conductivity is greatest in the direction of the steepest original dip of lava beds (Davis, 1969). Lava flow tops may be permeable because of their highly jointed nature, the presence of cinders and rubble, and the existence of vesicles interconnected by joints and cracks. The lower parts of lava beds are permeable where irregular openings are present, or where broken zones occur.

POTENTIAL BASALT REPOSITORY HOST ROCKS

Basalt formations for potential repository siting considered herein are located in areas underlain by extrusive Tertiary and Quaternary volcanic rocks (see McClain and Zerby, 1976; Piper, 1974). Figure 2 shows areas in the western continental United States where Tertiary or Quaternary volcanic rocks are at or near the surface. These rocks occur in vast areas, including large parts of Idaho, Washington, and Oregon. No Tertiary or Quaternary volcanic rocks are exposed in the eastern part of the United States.

Volcanic rocks such as rhyolite, andesite, and tuff generally contain fewer permeable zones than encountered in basalt (Davis, 1969) and are also potential radioactive waste host rocks. The geometry and properties of these kinds of rocks are probably best known at the Nevada Test Site (NTS) located about 121 kilometers northwest of Las Vegas, Nevada and at Los Alamos, New Mexico.

NTS is situated within a Tertiary volcanic province in which rhyolitic and quartz-latic ash-flow tuffs and ash-fall tuffs and rhyolites occur with thicknesses from a hundred to a thousand meters (Borg et al., 1976). The highest hydraulic conductivities are found in rhyolitic lavas and the lowest in zeolitized tuff. Interstitial porosities of tuffs range from less than 5 to more than 50 percent and hydraulic conductivities range from less than 1×10^{-12} to more than 1×10^{-6} m/s. Vertical movement downward in tuff aquitards is estimated at 4.6×10^{-12} to 1.8×10^{-14} m/s. Rhyolite transmissivities range from 1.1×10^{-5} to more than 1.1×10^{-2} m²/s and

Figure 2. Map Showing Areas Where Tertiary And Quaternary Volcanic Rocks Are At Or Near The Surface (from Meinzer, 1923).

average about 4.3×10^{-3} m²/s. Horizontal movement from NTS is estimated to range from 5.6×10^{-8} to 5.6×10^{-5} m/s through carbonate aquifers.

The early to mid-Tertiary age voluminous tuff deposits of the Timber Mountain - Oasis Valley Volcanic field in southern Nevada are being considered as potential repository host rocks (Heiken, 1979). These tuff deposits cover 10,900 square kilometers and in some basins may be over 1,100 meters thick. In zeolite-rich zones the rocks have the capacity to act as molecular sieves to retard radionuclides.

Vast young volcanic rocks of Quaternary age underlie the Snake River Plain in southern Idaho and parts of western Washington and Oregon, and northern California in the Pacific Northwest as shown in Figure 3. These basalts have relatively high transmissivities and groundwater movements and therefore low potential as host rocks for radioactive waste repositories. For example, basalts of Quaternary age underlying nearly all of the Snake River Plain are referred to as the Snake River Plain Aquifer (Mundorff et al., 1964). The aquifer is about 322 kilometers long by 48 to 97 kilometers wide, comprises an area of about 24,900 square kilometers, and is composed of a series of thin basalt flows each 3 to 23 meters thick. The basalt and interbedded sediment sequence may be 1,500 meters or more thick with the upper 150 meters being considerably more permeable than lower parts of the aquifer. Groundwater generally flows southwestward through the aquifer at flow rates of 3.5×10^{-5} to 7.1×10^{-5} m/s. Transmissivity of the aquifer ranges from 1.4×10^{-1}

Figure 3. Map Showing Areas Where Quaternary Volcanic Rocks Are At Or Near The Surface In The Northwest United States (from U. S. Geological Survey, 1967)

to $14 \text{ m}^2/\text{s}$ in upper parts to $1.4 \times 10^{-4} \text{ m}^2/\text{s}$ in lower parts; storage coefficients range from 1×10^{-3} to 2×10^{-1} (Norvitch, 1969).

To date, attention has focused on the potential of the Columbia River Basalt of Tertiary age located in Washington, Oregon, and Idaho as shown in Figure 4. This basalt is described in detail in the section of this memorandum entitled "Typical Basalt Repository Host Rock."

Figure 4. Map Showing Areas Where Columbia River Basalt Is At Or Near The Surface (from Deju and Fecht, 1979).

TYPICAL BASALT REPOSITORY HOST ROCK

The Columbia River Basalt, centered near the semi-arid (15.88 cm of precipitation annually) Pasco Basin and the Hanford Site, is considered by many to be a typical basalt repository host rock. Available information concerning the Columbia River Basalt (see Deju and Fecht, 1979; Newcomb et al., 1972) is summarized below to provide a framework for conceptual modeling of regional radionuclide transport from a repository site. The following discussion is not designed for the Hanford Site but rather is intended to serve as an example of the hydrology of plateau basalts.

The general concept of a repository includes one or more vertical shafts to a single level or to multiple levels located several hundred meters below the surface where a network of tunnels allows distribution of radioactive waste materials for terminal storage (Rockwell, 1977a). Fenix and Scisson (1969) identified at least three zones between the depths of 880 and 1,034 meters in the Grande Ronde Basalt of the Columbia River Basalt Group which deserve further consideration as a repository site.

As shown in Figure 4, the Columbia River Basalt covers an area of more than 155,000 square kilometers in the Columbia Plateau of Washington, Oregon, and Idaho. In cross section, the basalt and associated rocks have a bowl-like geometry locally modified by anticlinal ridge fold systems with associated faults. The basalt may be between 3,048 and 5,791 meters thick (Rockwell, 1978; Raymond and Tillson, 1968) in the Pasco Basin. Basement rocks underlying the basalt are probably sandstones and shales and granitic rocks.

A 1,524-meter thick sequence of basalt apparently overlies a series of older basalts beneath the Pasco Basin (Swanson et al., 1978) with about 100 basalt flows being identified in a 3,231-meter deep borehole. Individual basalt units range in thickness from more than 7.6 meters to a fraction of a meter.

The geologic and hydrogeologic characteristics of the Pasco Basin are generalized in Figure 5; regional cross sections are presented in Figure 6. Since the repository would be placed in the Grande Ronde Basalt because of its depth and low hydraulic conductivity characteristics, this discussion will focus on that formation. The older Columbia River Basalt Group Rocks and Pre-Columbia River Basalt Group Rocks underlying the Grande Ronde Basalt presumably have hydrogeological characteristics similar to those above the Grande Ronde Basalt but with lower vertical and horizontal hydraulic conductivities. The Grande Ronde Basalt is at least 152 meters thick in the Pasco Basin, widespread over the Columbia Plateau in Washington, and is present along the lower Columbia River Valley. In general, the Grande Ronde Basalt and overlying Vantage Sandstone and Saddle Mountains and Wanapum Basalts are in turn overlain by unconsolidated sediments with variable but relatively higher vertical and horizontal hydraulic conductivities. The Umtanum member near the center of the Grande Ronde Basalt acts as an aquitard as do most fine-grained interbeds in interflow zones (Newcomb et al., 1972).

The water table in near surface sediments and rocks at the Hanford Site slopes in general towards the Columbia River from

Figure 5. Generalized Geologic And Hydrogeologic Characteristics Of The Pasco Basin (after Deju and Focht, 1979).

Geologic Time Scale			Geologic Characteristics					Hydrogeologic Characteristics
Era	Period	Epoch	Radiogenic Dates years B.P.	Stratigraphic	Bed or flow unit	Lithologic Character	Thickness (meters)	
Cenozoic	Quaternary	Holocene	6,600	Alluvium Colluvium and Eolian Sediments	Mazama Ash	Ash fall, Crater Lake, Oregon	.2-.3	Occur everywhere above the water table
			10,000		Glacier Peak Ash	Ash fall, Glacier Peak, Washington	.05	
			12,500		St. Helens Ash	Ash fall, Mt. St. Helens, Washington	.05	
		Pleistocene	>12,000 <18,000	Glaciofluvial Sands and Gravels (Montford formation)	Touchet Silt	Fine-grained facies of the Glaciofluvial deposits. Bedded in quiet water		Occur above the water table except between the high terraced plateaus and the Columbia River. Has very high hydraulic conductivity and storage
			40,000		Pasco Gravels	Predominantly coarse grained gravels. Cobbles and sands with cut and fill structure	0-120	
			Palouse Soil		Calcareous sand and silt Eolian deposits, mainly derived from Ringold Formation	0-25	Occur everywhere above the water table	
	Tertiary	Pliocene	1,000,000 15,000,000	Ringold Formation	Upper Ringold	Locally capped by caliche. Mostly well-bedded fluvial silts and sands with some gravels	0-125	Sands and gravel beds have very high hydraulic conductivities and storage. Some beds of silty clay or clay are relatively impermeable
					Middle Ringold	Sands and gravels well sorted compact but variably cemented	0-120	
					Lower Ringold	Silts and clays with interbedded gravels and sands. Clay is characteristically blue but may be green, brown or tan	0-125	
		Miocene	11,000,000 15,000,000	Columbia River Basalt Group	Saddle Mts. and Wanapum Basalt	Basalt flows and interbeds tuff and tuffaceous sandstone	0-700	Flows are dense. Vertical hydraulic conductivity is low. Hydraulic conductivities of interflow zones is low.
					Vantage Sandstone	Weakly cemented sandstone	0-10	
					Grande Ronde Basalt	Basalt flows and interbeds	0-500	

Older Columbia River Basalt Group Rocks

Pre-Columbia River Basalt Group Rocks

Basement Rocks

Figure 6. Generalized Geologic And Hydrogeologic Cross Sections Of The Pasco Basin (after Deju and Fecht, 1979).

elevations exceeding 152 meters to elevations of 107 meters (Liverman, 1975). Recharge from precipitation occurs locally as does bank storage from the Columbia River. Recharge from waste management activities at the Hanford Site and land irrigation outside the Hanford Site (Summers and Deju, 1974; Tanaka et al., 1974) also occurs.

The piezometric surface in the uppermost (to depths of about 518 meters) basalt rocks is trough-shaped in the vicinity of the Hanford Site about an axis coinciding roughly with the course of the Columbia River (Liverman, 1975). Recharge to upper basalts occurs where the water table is higher than the piezometric surface and from outside the Hanford Site including regional recharge from irrigation. Discharge is ultimately to the Columbia River with a mean stage elevation of 107 meters. Elevations of piezometric head range from 152 to 107 meters above mean sea level within the Hanford Site.

Available water level data for deep wells DC-1 and DC-6 within the Hanford Site are summarized in Table 1. Well DC-6 is near the Columbia River and DC-1 is about 8 kilometers east of the river. No continuous trend in piezometric head with depth is apparent. In general, piezometric heads at greater depths than 518 meters are above the water table and the mean stage of the Columbia River. Theoretically, the Columbia River is a discharge area and piezometric heads should increase with depth. The piezometric surface in the lowermost basalt rocks should be trough-shaped in the vicinity of the Hanford Site about an axis coinciding roughly with the course of

Table 1. Piezometric Heads in Selected Deep Basalt Wells
within the Hanford Site
(after Deju and Fecht, 1979; Piper, 1975)

Well Number	Depth Interval (meters)	Piezometric Head Elevation* (meters above MSL)	Water Table Elevation (meters above MSL)	River Mean Stage Elevation (meters above MSL)
DC-1	110-127	123	123	107
	334-363	122		
	600-658	124		
	832-887	125 (Grande Ronde above Umtanum)		
	1,024-1,096	119 (Grande Ronde below Umtanum)		
	1,150-1,200	116		
	1,244-1,305	112		
DC-6	683-692	137 (Grande Ronde)	110	107
	732-741	136		
	748-757	139		
	825-835	129		
	883-895	138		
	922-931	140 (top of Umtanum)		
	1,019-1,028	135 (below Umtanum)		
	1,103-1,113	128		
	1,113-1,122	132		
	1,123-1,132	131		
	1,125-1,134	132		

*Heads determined by packer tests within the depth intervals noted.

the Columbia River. There exists an imperfectly understood regional system of horizontal and vertical movement in the basal* rocks.

Available information concerning the hydrogeologic properties of sediments and rocks beneath the Pasco Basin are listed in Table 2 (Deju and Summers, 1975; Deju and Ledgerwood, 1976; La Sala and Doty, 1970; Price, 1960; Agapito et al., 1977; Summers, 1978; Raymond and Tillson, 1968; Gephart et al., 1979; Rockwell, 1978; Tanaka, 1977; and MacNish and Barker, 1973). The vertical hydraulic conductivities of the dense interiors of basalts range from 1.4×10^{-8} to 3.5×10^{-12} m/s.

Regional longitudinal and transverse dispersivities in unconfined sediments have been estimated as 30 to 18 meters, respectively (PNL, 1977b). Dense basalts with a porosity of 1 percent may have a longitudinal dispersivity of 3.4×10^{-1} meters and the dispersivity of a more vesicular basalt with a porosity of 10 percent may have a dispersivity of 3.4 meters (Hill and Grimwood, 1978). Distribution coefficients for selected radionuclides in sediments and in the Umtanum member of the Grande Ronde Basalt are presented in Table 3 (Rhodes, 1957; Tamura, 1971; Schneider and Platt, 1974; Routson et al., 1975; Ames, 1978).

Young water (less than 500 years old) in confined sediments and rocks may be classified as calcium-magnesium-sulfate-bicarbonate water with low (200-300 mg/l) dissolved solids. Older water (more than 500 years old) in upper confined rocks is of the sodium-bicarbonate type with total larger total dissolved solids (300-500 mg/l). Water in the Grande Ronde Basalt may be described as a sodium-calcium water and is much older than 2,000 years old (Silar, 1969;

Table 2. Summary of Hydrogeologic Properties
of Sediments and Rocks Beneath the Pasco Basin
(after Deju and Fecht, 1979)

	Material	Horizontal Hydraulic Conductivity (m/s)	Storage Coefficient	Porosity (%)	Remarks
26	Unconfined Aquifer Glaciofluvial sediments	4.2×10^{-3} - 4.2×10^{-2} 2.1×10^{-2}	5×10^{-2} - 4×10^{-1} (3×10^{-2})	Estimated 5-20	Mostly dry (above water table)
	Unconfined Aquifer Upper and middle Ringold sediments	3.5×10^{-6} - 7.1×10^{-4} 2.1×10^{-4}	8×10^{-4} - 2×10^{-1} (1×10^{-3})	Estimated <12	--
	Confined Aquifer Lower Ringold	3.5×10^{-7} - 2.5×10^{-5} 7.1×10^{-6}	Estimated $\approx 10^{-3}$	Estimated 5-20	Mostly clayey material
	Saddle Mountains Basalt Dense basalts	1.1×10^{-7} - 3.5×10^{-5} 1.1×10^{-7}	2.7×10^{-5} - 1.2×10^{-3} (1×10^{-4})	1.00-3.95 (2.00)	Most of hydraulic conductivity is in interflow zones
	Brecciated basalts Interflow zones	1.1×10^{-7} 7.1×10^{-6}			
	Wanapum Basalt Dense basalt	7.1×10^{-8} - 3.5×10^{-5} 7.1×10^{-8}	2.7×10^{-5} - 1.2×10^{-3} (1×10^{-4})	1.00-4.00 (2.00)	Most of hydraulic conductivity is in interflow zones
	Brecciated basalts Interflow zones	2.8×10^{-7} 3.5×10^{-6}			
	Grande Ronde Basalt Umtanum	2.6×10^{-12} - 3.5×10^{-8} 3.5×10^{-12}	1×10^{-5} - 1×10^{-3} ($< 1 \times 10^{-4}$)		Lowest hydraulic conductivity found
	Dense basalt	1.1×10^{-8}			
	Brecciated basalts	3.5×10^{-8}			
	Interflow zones	1.1×10^{-6}		(3.00)	

Table 3. Summary of Distribution Coefficient Values
for Unconfined Sediments and Umtanum Basalt
(after Deju and Fecht, 1979)

<u>Radionuclide</u>	<u>Distribution Coefficient (ml/g)</u>	
	<u>Unconfined Sediments</u>	<u>Umtanum Basalt</u>
⁹⁰ Sr	5-38	151 ± 18
¹³⁷ Cs	12-200	296 ± 31
Pu	200	19.8 ± 4.0
V	<1	
²⁴¹ Am	~1,200	231 ± 18
⁹⁹ Tc	<<1	
⁸⁹ Ru	26-750	
¹⁰⁶ Ru		38.0 ± 8.1

Crosby and Chatters, 1965; La Sala and Doty, 1971). The ground-water thermal gradient with depth beneath the Pasco Basin is about 3.7×10^{-2} °C per meter (Benson, 1978).

CONCEPTUAL MODEL

A generalized and simplified conceptual model cross section in the Pasco Basin is presented in Figure 7 to illustrate essential features of the possible waste-transport routes to the biosphere. The illustration shows that major layering exists in the geologic column with numerous types of deposits of varying hydraulic conductivities and thicknesses and that a wide variety of boundary conditions are possible. There are six major layers in the system consisting in ascending order as follows: (1) basement rocks, (2) Older and Pre-Columbia River Basalt Group rocks, (3) Grande Ronde Basalt, (4) Wanapum Formation (Younger Columbia River Basalt Group rocks), (5) Saddle Mountains Formation (Younger Columbia River Basalt Group rocks), and (6) Ringold and glaciofluvial sediments. The repository would be placed in layer 3. The margins (boundaries) of layers 3, 4, and 5 are shown in Figure 8. The margins of layers 1, 2, and 6 have not been mapped in detail.

The gross transmissivities of layers 1 and 2 are unknown but probably are in the order of magnitude of 1.1×10^{-5} or less m^2/s . The gross transmissivities of the other layers are: layer 3 - $5.1 \times 10^{-5} \text{ m}^2/\text{s}$, layer 4 - $9.7 \times 10^{-6} \text{ m}^2/\text{s}$, layer 5 - $1.6 \times 10^{-3} \text{ m}^2/\text{s}$, and layer 6 - $4.3 \times 10^{-2} \text{ m}^2/\text{s}$ (Deju and Fecht, 1979). Effective porosities of the basalt layers average about 2 percent; the estimated average effective porosity of the sediments is 5 percent.

Interbedded high-low hydraulic conductivity sequences occur within the major layers as complex intraformational aquifer-aquitard features. Waste-transport routes will be determined by these sequences

Figure 7, Conceptual-Cross Sectional Model For Typical Basalt Repository Host Rocks.

(Normal To Main Axis of Pasco Basin)

- 1 Very low hydraulic conductivity Basement Rocks
 - 2 Very low hydraulic conductivity Pre and Older Columbia River Basalt Group Rocks
 - 3 Very low to low hydraulic conductivity Grande Ronde Basalt
 - 4 Low hydraulic conductivity Wanapum Basalt
 - 5 Low to medium hydraulic conductivity Saddle Mountains Basalt
 - 6 Medium to high hydraulic conductivity sediments
- Generalized flow path

Saddle Mountains Basalt
(layer 5)

Wanapum Basalt
(layer 4)

Kilometers

Grande Ronde Basalt
(layer 3)

Figure 8. Margins (boundaries) of
Columbia River Basalt Formations
(from Deju and Fecht, 1979).

and gross transmissivities will have limited meaning. The sequences may be represented by an analogous anisotropic aquifer (see Freeze and Cherry, 1979).

The general groundwater flow system (see Toth, 1963, and Freeze and Witherspoon, 1968) of the Columbia River Basalt and associated sediments in the Pasco Basin is depicted in Figure 7. Detailed description of the flow system (including flow velocities) with high-low hydraulic conductivity sequences are not possible with existing data. Figure 7 is provided only to emphasize that waste-transport routes are ultimately towards the Columbia River and the lengths of flow paths from a repository to the biosphere may be relatively short.

It is popular to focus attention on the gravity potential wherein the configuration of the water table is the driving force related to groundwater flow. Other potentials (chemical, and particularly the thermal related forces) may be just as important to the flow of groundwater at the depths dictated by radioactive waste isolation needs.

Caution must be exercised in choosing groundwater divides as lateral boundaries of the system since these divides are moveable either by manmade groundwater pumping processes or by natural long-term climatic and erosional phenomena.

PROCESS AND PARAMETERS

There are many physical, chemical, thermal, and nuclear processes with associated parameters that together determine the possible pattern of radionuclide migration in basalts and surrounding formations. Basically, these processes and parameters are inter-related and pertain to flow, mass transport, heat transport, and medium deformation. Physical processes are advective transport, dispersion, and medium deformation. Diffusion, adsorption, dissolution, and precipitation are included in chemical processes. The thermal related processes include conduction and convection. Radioactive decay is the nuclear process.

Process and parameter descriptions and equations were covered in detail in CDM's report "Processes and Parameters Involved in Modeling Radionuclide Transport from Bedded Salt Repositories" (April 1979) and will not be repeated herein. Processes are briefly described and associated parameter values for basalt found in a literature search are given to assist in the design of the conceptual model. The lists are not exhaustive and only indicate ranges of values and their uncertainty.

It is recognized that basalts are fractured rocks with complex patterns of porosity and hydraulic conductivity in contrast to uniformly porous sand and gravel deposits. Flow behavior and parameters of fractured rocks differ from those of uniformly porous deposits. An extensive review of analytical fractured rock flow models is given by Wilson (1970) and Streltsova (1976). At least on a regional scale,

with large spatial extent, fractured media may be treated as an equivalent porous media (see Kibbe and Boch, 1978).

Major processes that control the migration of radionuclides are advection, hydrodynamic dispersion, geochemical reactions, and radioactive decay.

Advective Transport

Advection involves transport by flowing groundwater with dissolved substances normally spreading into and occupying an increasing volume of the groundwater system down gradient from the substance source. In the case of a conservative substance, no reactions such as adsorption occur between the substance and the porous media skeleton that alter dissolved substance concentration. The total mass of the dissolved substance in the flow regime does not change, but the mass occupies an increasing volume of the porous media. The parameters and variables involved in this process are shown below:

<u>Parameters</u>	<u>Variables</u>
hydraulic conductivity	velocity
viscosity	pressure
density	concentration
porosity	temperature

The following table presents a summary of reported parameter values for the Columbia River Basalt in the Pasco Basin and degree of certainty in estimating values.

<u>Parameter</u>	<u>Reported Values</u>	<u>Degree of Certainty</u>
Hydraulic conductivity		
Horizontal	3.9×10^{-11} - 2.4×10^{-5} m/s	needs improvement
Vertical	3.5×10^{-12} - 1.3×10^{-10} m/s	highly uncertain
Viscosity	1.8 - 0.2 cp	well known
Density	1.00 - 0.90 gm/cm ³	well known
Porosity	1 - 20%	needs improvement

Reported values of hydraulic conductivity (K) for the Columbia River Basalt in the Pasco Basin are summarized on the next page.

<u>Formation</u>	<u>Reported Horizontal Hydraulic Conductivity m/s</u>	<u>Reference</u>
Saddle Mountains Formation		
Dense Basalt	1.1×10^{-7}	La Sala and Doty (1970)
Fractured, Weathered, or Brecciated	1.1×10^{-7}	"
Interflow Zone: sand, gravel, and clay	7.1×10^{-6}	"
Wanapum Formation		
Dense Basalt	7.1×10^{-9}	"
Vesicular Basalt	2.5×10^{-8}	"
Fractured, Weathered, or Brecciated	3.2×10^{-7}	"
Tuff	3.5×10^{-7}	"
Interflow Zone: sand, gravel, and clay	3.5×10^{-6}	"
Grange Ronde Basalt		
Dense Basalt	1.1×10^{-8}	"
Vesicular Basalt	2.8×10^{-8}	"
Fractured, Weathered, or Brecciated	2.8×10^{-7}	"
Tuff	1.1×10^{-8}	"
Interflow Zone: sand, gravel, and clay	1.1×10^{-8}	"
Umtanum Member	3.9×10^{-11} - 1.7×10^{-9}	Gephart et al. (1979)
Dense Basalt.		
<1,000 ft	1.1×10^{-7}	La Sala and Doty (1971)
Dense Basalt,		
>1,000 ft	5.6×10^{-9} - 1.1×10^{-8}	and Fenix and Scisson (1969)
Vesicular Basalt	5.6×10^{-9} - 4.2×10^{-8}	
Fractured, Weathered, or Brecciated Basalt	5.6×10^{-9} - 2.4×10^{-5}	"
Basalt Interflow Zones:		
Sand, clay, and tuff	1.1×10^{-8} - 1.2×10^{-5}	"

<u>Formation</u>	<u>Reported Vertical Hydraulic Conductivity m/s</u>	<u>Reference</u>
Basalt, Depth <1,000 ft	3.5×10^{-12} - 1.3×10^{-10}	Tanaka (1977)

Reported hydraulic conductivities for other selected volcanic rocks are as follows:

<u>Volcanic Rocks</u>	<u>Reported Hydraulic Conductivity (m/s)</u>	<u>Reference</u>
Snake River Plain Aquifer (Idaho)		Robertson et al. (1974); Robertson (1977); Schmalz (1972)
Upper Basalts	3.5×10^{-3} - 3.5×10^{-1a}	
Lower Basalts	3.5×10^{-6a}	
Dense Basalt	2.8×10^{-10} - 1.8×10^{-8b}	"
Rhyolites Beneath Snake River Plain Aquifer	2.1×10^{-7}	Robertson (1977)
Columbia River Basalt		
Walla Walla, Washington	1.8×10^{-4}	Summers (1978)
Hermiston, Oregon	3.2×10^{-5} - 7.1×10^{-5}	"
Welded Tuff, Nevada Test Site	8.8×10^{-12} - 8.8×10^{-9}	Borg et al. (1976)

^aHorizontal hydraulic conductivity

^bVertical hydraulic conductivity

Reported hydraulic conductivities for the Columbia River Basalt range in the classification of "poor aquifers" to "relatively impermeable aquitards." The upper basalts of the Snake River Aquifer in Idaho represent some of the most permeable aquifers in the United States.

Reported horizontal hydraulic conductivities for deposits overlying the Columbia River Basalt in the Pasco Basin are presented below.

<u>Deposits</u>	<u>Reported Horizontal Hydraulic Conductivity (m/s)</u>	<u>Reference</u>
Glaciofluvial Material	4.2×10^{-9} - 4.2×10^{-2}	Deju and Fecht (1979)
Ringold Conglomerate	3.5×10^{-6} - 7.1×10^{-4}	Deju (1974)
Lower Ringold Conglomerate	3.5×10^{-7} - 2.5×10^{-5}	Deju and Ledgerwood (1976)

For comparison, hydraulic conductivity ranges for other geologic formations are presented in Figure 9.

Reported values of porosity for the Columbia River Basin in the Pasco Basin are presented below.

<u>Formation</u>	<u>Reported Porosity (fraction)</u>	<u>Reference</u>
Saddle Mountains Dense Basalt, Depth >1,000 ft	1×10^{-2} - 3.95×10^{-2}	La Sala and Doty (1970)
Vesicular Basalt	1×10^{-2}	La Sala and Doty (1971)
Fractures, Weathered, or Brecciated Basalt	5×10^{-2}	and Fenix and Scisson (1969)
Basalt Interflow Zones:	1×10^{-1}	"
Sand, clay, and tuff	2×10^{-1}	"

Hydrodynamic Dispersion

Hydrodynamic dispersion is the process that tends to disperse or distribute dissolved substances within a porous media. Hydrodynamic dispersion has two components: molecular diffusion and mechanical dispersion (Bear, 1972). With hydrodynamic dispersion (see Fried and Combarous, 1971), the dissolved substance -- natural groundwater interface does not remain an abrupt one as with advection alone but instead a transitional zone is created across which the concentration varies from that of the dissolved substance to that of the natural groundwater. The parameters and variables involved in this process are shown below.

<u>Parameters</u>	<u>Variable</u>
Diffusion Coefficient	Groundwater velocity
Dispersivity	Concentration

Figure 9. Range of Values of Hydraulic Conductivity
(from Freeze and Cherry, 1979)

The following table presents a summary of the reported values of these parameters for basalts and the degree of certainty in estimating values.

<u>Parameter</u>	<u>Reported Values</u>	<u>Degree of Certainty</u>
Diffusion	$< 10^{-15} - 10^{-10} \text{ cm}^2/\text{sec}$	Uncertain
Regional Longitudinal Dispersivity	0.34 - 30.5 m	Highly uncertain

Values of dispersivities determined from field studies involving well tests and areal models are several orders of magnitude greater than laboratory dispersivities. Where known, field longitudinal dispersivities normally range from 5 to 100 m and field transverse dispersivities normally range from 1 to 35 m (Anderson, 1979). Ratios of longitudinal to transverse dispersivities average 3 (Bredehoeft and Pinder, 1973; Konikow and Bredehoeft, 1974). Well test dispersivities are commonly one-half the values of areal model dispersivities. These discussions of mechanic dispersion are based on the assumption that there is no significant density contrast between the dissolved solids and groundwater and that isothermal conditions exist.

The following table presents a summary of reported values of regional dispersivity for basalts. The degree of certainty in estimating values for this parameter may be classified as highly uncertain.

Basalt	Regional		α_{II}/α_I	Reference
	Longitudinal Dispersivity α_I (m)	Transverse Dispersivity α_{II} (m)		
Columbia River Basalt				
Dense Basalt	0.34			Hill and
Vesicular Basalt	3.35			Grimwood (1978)
Fractured Basalt (Hanford Site)	30.5		0.6	Anderson (1979)
Snake River Plain Aquifer				
Fractured Basalt (Idaho)	91	137	1.5	Anderson (1979)

Reported values of regional dispersivity for other deposits are listed below.

Type of Deposit and Location	Regional		Reference
	Longitudinal Dispersivity α_I (m)	α_{II}/α_I	
Alluvial Sediments			
Rocky Mountain Arsenal, CO	30.5	1.0	Anderson (1979)
Colorado	30.5	0.3	"
California	30.5	0.3	"
Lyons, France	12	0.33	"
Barstow, CA	61	0.3	"
Sutter Basin, CA	80-200	0.1	"
Glacial Deposits			
Long Island, NY	21.3	0.2	"
Limestone			
Brunswick, GA	1	0.3	"
Alluvial Sediments			
Barstow, CA	61	1/330	"
Alsace, France	15	0.067	"
Glacial Till over Shale			
Alberta, Canada	3.0 & 6.1	0.3	"
Limestone			
Cutler Area, FL	6.7	0.1	"
Hypothetical	0.003-30	0.2	"
	21.3	0.2	"
	10	--	"
	0.5-100	1-0.05	"

Sorption

Sorption includes the attenuation processes that cause the flow-rate of radionuclides through porous media to be much slower than the flow-rate of the water itself. "Adsorption, colloid filtration, reversible precipitation and irreversible mineralization" (Burkholder, 1976, and Burkholder et al., 1976) are all considered sorption. With respect to the migration of radionuclides through basalts, adsorption and cation exchange are of particular concern.

Sorption encompasses a set of extremely complicated physiochemical processes which are based on many variables. The combined effects of many of the variables with one another are not fully understood and they are beyond the scope of this memorandum. For instance, how will the competition between various radionuclides in the groundwater effect the amount of material that is actually sorbed to any particular porous media? The parameters and variables that were found to be significant with respect to sorption are listed below.

<u>Parameters</u>	<u>Variables</u>
Bulk density	pH
Void fraction	temperature
Cation exchange capacity	nuclide concentration
Distribution coefficient	groundwater velocity
	surface area
Sorption equilibrium constant	pressure
or mass-action constant	particle size

Reported distribution coefficients for selected radionuclides and the Umtanum member of the Columbia River Basalt in the Pasco Basin are provided below.

Type of Test	Radionuclide	Distribution Coefficient, K_d (ml/g)	Reference
Laboratory	^{137}Cs	296 ± 31	Serne (1978)
"	^{90}Sr	151 ± 18	"
"	^{106}Ru	38.0 ± 8.1	"
"	Pu	19.8 ± 4.0	"
"	^{241}Am	231 ± 18	"
"	^{137}Cs	882.1 ± 60.7	Ames (1978)
"	^{85}Sr	120.4 ± 11.6	"
"	^{237}Pu	6.5 ± 2	"
"	^{226}Ra	731 ± 327	"
"	^{60}Co	315 ± 45.8	"
"	U	3.09 ± 15.8	"
"	^{125}I	6.2 ± 2.3	"
"	^{75}Se	11.1 ± 0.8	"

Reported distribution coefficients for selected radionuclides and sediments above the Columbia River Basalt at the Hanford Site are as follows:

Type of Test	Radionuclide	Distribution Coefficient, K_d (ml/g)	Reference
Laboratory	^{90}Sr	5-38	Deju and fecht, 1979
"	^{137}Cs	12-200	"
"	Pu	200	"
"	U	<1	"
"	^{241}Am	$\approx 1,200$	"
"	^{99}Tc	Very low (<<1)	"
"	^{89}Ru	26-750	"
Field	^{90}Sr	5-25	Deju (1974)
Laboratory	^{239}Pu	>1,980	Rhodes (1957)

The distribution coefficient table from Borg et al. (1976) is shown on the next page. It lists the K_d values found for rocks at the Nevada Test Site (NTS). Note that a wide range of values exists even between samples of the same rock type. The large variation

reflects the lack of homogeneity in most formations and the sensitivity of the K_d value to different conditions as well as the problems inherent in measuring K_d values.

Type of Rock and Location	Distribution Coefficient, K_d (ml/g)	
	Sr	Cs
Alluvium		
Central Nevada (Faultless)	48-2454	121-1165
Tuff, Rainier Mesa, NTS	260	1020
Tuff, Rainier Mesa, NTS	2070-3480	12,100-17,800
Tuff, Rainier Mesa, NTS (Area 12b#2)	1700-4300	--
Tuff, NTS (Area 5)	400	5000-8000
Tuff NTS	4000	--
Carbonate, Yucca Flats, NTS	0.19	13.5
Dolomite, Rustler Formation, New Mexico (Gnome)	5-14	--
Granolierite, Climix Stock, NTS (Hardhat and Piledriver)	4-9 11-21	8-9 1030-1810
Granite, Central Nevada (Shoal)	1.7	34.3
Basalt, Buckboard Mesa, NTS (Danny Boy)	16-115	792-9520
Pillow Basalt Amhitka PAE-2	220	39
Basalt, Amhitka, PAE-1 (1741 m)	1220 1.1	280 6.5
Shaley Siltstone, New Mexico (Gasbuggy)	8.32	309
Sandstone, New Mexico (Gasbuggy)	1.37	102
Salt, Tatum Dome, Mississippi	0.19	0.027

Radioactive Decay

According to Schwartz (1975), one of the most important processes to be considered in radionuclide migration is the influence of radioactive decay including decay chains. This process is a natural attenuation mechanism. The parameter of prime interest is the half-life. In terms of waste management, radioactive materials with longer half-lives pose the most serious problem because subsurface confinement must be sufficient to allow decomposition through several half-lives. A table is given below of half-lives of selected radioisotopes.

RADIOACTIVE DECAY RATES
(Deju and Fecht, 1979)

<u>Isotope</u>	<u>Half-life (years)</u>
^{241}Am	432
^{14}C	5,730
^{135}Cs	2.3×10^6
^{137}Co	30.17
^{60}Co	5.27
^{244}Cm	18.11
^3H	12.33
^{129}I	1.59×10^7
^{237}Np	2.14×10^6
^{239}Pu	2.4×10^4
^{241}Pu	14.7
^{226}Ra	1,600
^{79}Se	10,000
^{90}Sr	29
^{99}Tc	2.13×10^5
^{234}U	2.44×10^5
^{238}U	4.47×10^9

Thermal

Several types of gradients may be involved in groundwater movement including hydraulic pressure, density induced, and geothermal gradients. In thick aquifer/aquitard systems, interaction of these gradients induce gravity convection currents which may cause entrained wastes to migrate in unanticipated directions.

This report section primarily concerns discussion of the geothermal processes related to groundwater movement. Since many groundwater parameters, such as density and viscosity, are temperature-dependent, one must realize that there is a great deal of coupling of other processes described in this report.

According to Bear (1972), heat is transported in a fluid-porous medium by the three modes -- conduction, convection, or radiation. The parameters and variables involved in this process are as shown below:

<u>Parameters</u>	<u>Variables</u>
specific heat of fluid	velocity
specific heat of solid/fluid complex	temperature
density of fluid	pressure
density of solid/fluid complex	time
thermal conductivity of solid/fluid complex	
porosity of solid	
viscosity of fluid	
coefficient of thermal dispersion	

Bear (1972) gives specific heat values for various dry rocks as follows:

<u>Dry Rock Material</u>	<u>Temperature ($^{\circ}\text{C}$)</u>	<u>Specific Heat (cal/g - $^{\circ}\text{C}$)</u>
Basalt	20 - 100	0.20
Chalk	20 - 100	0.214
Clay	20 - 100	0.22
Granite	12 - 100	0.192
Quartz	12 - 100	0.188

Other values of specific heat from Carslaw and Jaeger (1959) are given below.

<u>Substance</u>	<u>Specific Heat (cal/g - $^{\circ}\text{C}$)</u>
Limestone	0.22
Sandstone	0.23
Soil (average)	0.20
Soil (sandy, dry)	0.19

Typical density values of solids taken from Carslaw and Jaeger (1959) and Dames and Moore (1978), and the Handbook of Chemistry and Physics (1970) are as follows:

<u>Material</u>	<u>Density (g/cm³)</u>	<u>Reference</u>
Basalt	2.4 - 3.1	Handbook of Chemistry and Physics (1970)
Chalk	1.9 - 2.8	"
Clay	1.8 - 2.6	"
Coal, anthracite	1.4 - 1.8	"
Coal, bituminous	1.2 - 1.5	"
Dolomite	2.84	"
Granite	2.64 - 2.76	"
Limestone	2.68 - 2.76	"
Quartz	2.65	"
Rock salt	2.18	"
Sandstone	2.14 - 2.36	"
Soil (average)	2.5	Carslaw and Jaeger (1959)
Soil (sandy, dry)	1.65	"
Air	0.00129	"
Rock salt	2.08 - 2.44	Dames and Moore (1978)

Thermal properties of the Columbia River Basin reported by Board (1978) are given below.

<u>Property</u>	<u>Unit</u>	<u>Average</u>	<u>Range</u>
Grain density	gm/cm ³	2.87	2.4 - 3.1
Thermal conductivity	cal/cm-sec-°C)	3.6×10^{-3}	$3.35 - 10 \times 10^{-3}$
Specific heat	$\frac{\text{cal}}{\text{gm-}^\circ\text{C}}$	.35	.23 - .25
Thermal expansion coefficient	/°C	6.6×10^{-6}	$2.9 - 11.6 \times 10^{-6}$

The process of hydrodynamic dispersion is taking place along with the thermal process.

Media Deformation

The only media deformation processes in basalt suspected of having a possible effect on regional hydrogeology are faulting and fracturing. Fracturing is the process by which rock is broken, generally along a plane. The break in the rock serves as a potential channel for groundwater flow. A fault is a fracture along which movement has taken place. The parameters and variables important with respect to basalts are as follows.

<u>Parameters</u>	<u>Variables</u>
Rock strength	temperature
Radiation level	pressure
	radiation level

Unlike the other processes discussed in this section, media deformation is not expected to have an effect on the hydrogeologic regime of a basalt repository unless certain catastrophic events take place such as meteor impact, volcanicism, or major faulting activity.

Piper (1975) concludes that a repository deep in sound basalt beneath the Hanford Site would face only minimal prospective hazard from future tectonic or seismic activity. Excepting a possible slow, progressive deepening of the structural Pasco Basin, stratigraphic evidence indicates that present tectonic forms have been sensibly stable for at least 12,000 years, and probably have been

stable for 100,000 years longer. Considering the low frequency and small magnitude of perceptible earthquakes during the past century, the expectable recurrence interval of a severe earthquake within the Hanford Site, say of magnitude VII or greater, may be several centuries. No evidence has been found of contemporary movement of the land surface, vertically or horizontally, that correlates with the geographic pattern of known local or regional tectonic forms. Microseismic evidence that has been summarized appears also not to correlate with the geographic pattern of tectonic forms, and so does not suggest incipient rejuvenation of tectonic activity.

Some mechanical properties of Columbia River Basalt reported by Board (1978) are provided below.

<u>Property</u>	<u>Units</u>	<u>Average</u>	<u>Range</u>
Young's Modulus	GPa	77	61 - 112
Poisson's Ratio	--	.25	.22 - .28
Uniaxial Compressive Strength	MPa	284	0 - 400
Angle of Internal Friction (intact)	χ^0	55	45 - 60
Tensile Strength	MPa	21	0 - 23

Difficulty of Predicting Parameter Values

Measurement techniques, such as pumping tests, drill stem tests, and laboratory tests for determining the horizontal hydraulic conductivity and porosity of basalts are fairly well established. Some mechanical problems arise when measurements of relatively impermeable rocks are attempted but the theory and practice are known. On an areal basis, the spatial distribution of measurements is seldom adequate and always needs improvement.

On the other hand, great difficulty is encountered in evaluating basalt vertical hydraulic conductivity and its variation in space. The list of vertical hydraulic conductivity values for basalts determined with available measurement techniques is short. In a few cases, vertical hydraulic conductivity has been estimated in connection with the calibration of areal digital models. There has been little or no application of the long-term pumping test methods outlined by Witherspoon et al. (1967) for determining vertical hydraulic conductivity with aquitard observation wells. At this time, only the general order of magnitude of vertical hydraulic conductivity is known and the confidence limit is probably $\pm$ two orders of magnitude. Vertical hydraulic conductivity is one of the weakest links in the chain of predictable parameters.

Vertical hydraulic gradients are most difficult to identify and quantify especially those in relatively impermeable basalt rocks. Sampling techniques often significantly disturb artesian pressure heads and re-establishment of static conditions may require excessively long periods of recovery.

Anderson (1979) provides a critical review of the difficulties experienced in predicting parameter values to simulate the movement of radionuclides through groundwater flow systems. The velocity distribution and dispersivities are needed to solve the transport equation. However, currently used techniques for acquiring these critical data have recently been called into question. Groundwater velocity is usually determined indirectly with measurements of head and hydraulic conductivity and often the results of flow model analysis.

Unless heterogeneity and anisotropy are fully recognized and simulated as dominant factors controlling velocity distribution and magnitude, meaningless conclusions regarding radionuclide transport may be reached.

There is no standard technique for measuring longitudinal and transverse dispersivities or the other components of the basalt anisotropic dispersion tensor. Regional dispersivities are generally determined in connection with the calibration of transport digital computer models by adjusting dispersivities and sometimes porosity until the model simulates the observed concentrations. In light of complex heterogeneous and anisotropic conditions existing in most groundwater systems, on a macroscopic basis dispersivity can not be precisely defined. The magnitude of dispersivity changes depending on the scale of interest. Very little is known at this time concerning the dispersivities of basalts at any scale or degree of complexity. In predicting meaningful dispersivity parameter values, the problem of determining hydraulic conductivities of individual layers rather than spatial averages must be faced. Studies of radionuclide migration under field conditions require dispersivity measurements in the field. Although this premise is generally accepted, there is little agreement on the types of field dispersivity tests or methods of test analysis that are most appropriate.

To date, only chemical processes such as adsorption and radioactive decay have been incorporated into most transport models. Emphasis has been placed on the use of the distribution coefficient

in simulating ion exchange. Distribution coefficients are commonly determined in the laboratory where it is difficult if not impossible to maintain or simulate the physical and chemical field integrity of a sample. The use of the distribution coefficient approach is limited because it takes into account only relatively fast mass transfer processes. In general, knowledge of hydrogeochemical processes is primitive.

MODELING COMPUTATIONAL AND OUTPUT REQUIREMENTS

The following discussion concerning model computational and output requirements is based on a regional point of view. The ultimate objective of model computation is to assess the risk of siting a radioactive waste repository in a basalt. The information given in the preceeding sections of this memorandum are aimed at identifying the basic input parameters and boundary and initial conditions of groundwater flow and transport models that will serve as the basis for the assessment of risk from a basalt repository. The parameter requirements and general flow chart for these models are shown in Figure 10. Flow models probably can be uncoupled from transport models based on the assumption that regional movement of wastes from a repository will not significantly change the hydrogeologic properties of basalt. Flow models are input to transport models, inasmuch as the flow field is responsible for moving radionuclides.

The large areal and profile extent and complex hydrogeologic conditions dictate that numerical digital mathematical models be employed in assessing risk. Reflecting upon the conceptual model described in a preceeding section of this memorandum, the models should be three-dimensional because horizontal and vertical flow and mass transport in several stacked and hydraulically connected layers must be analyzed. Coupled two-dimensional models of individual basalt and sediment layers (quasi three-dimensional models) also might adequately simulate possible radionuclide migration.

Figure 10. Generalized Parameter Requirements And Flow Chart For Models.

Available digital mathematical models are based on a wide variety of techniques for predicting migration of radioactive wastes (Anderson, 1979). In each case they are essentially alternative methods of solving simultaneous equations which represent flow and transport processes. Chosen techniques should be amenable to verification, calibration, sensitivity analysis, and prediction. Both water and mass balance calculations should be possible and the models should have the capability of simulating chemical processes such as sorption. Numerical errors should be minimal.

It may be necessary to employ both areal and profile models if a 3-D model is not used. Either finite difference or finite element methods could be employed with success. Some experience has been gained in the application of finite difference methods involving the method of characteristics or random walk technique to solve the dispersion equation (Anderson, 1979). However, the application of advection-dispersion models is still in the developmental stage. Chosen models should be as simple as possible both conceptually and operationally commensurate with the adequacy and accuracy of available data.

Examples of typical computational requirements are given by Prickett (1975) for flow models and by Konikow and Bredehoeft (1978) for transport models. Fortran IV programs developed for these models can include over 2,000 statements. Total core storage requirements can be several hundreds of thousands of bytes which can be met by commonly available computers.

Output requirements include the groundwater head distribution in the basalt at the end of selected predictive time steps. Hydraulic gradients determined from head elevations are used to compute velocities of groundwater flow. Changes in concentration due to transport of dissolved solids during predictive time steps are then computed on the basis of groundwater velocity and concentration gradients. The results can be reduced to maps and graphs by existing computer equipment. Desirable output items are: radionuclide location and concentration with time, radionuclide flux at point of discharge, and travel times and paths.

Additional information concerning modeling computational and output requirements has been provided by Prickett (1980).

REFERENCES CITED

- Agapito, J. F. T., M. P. Hardy, and D. R. St. Laurent. 1977. Geo-Engineering Review and Proposed Program Outline for the Structural Design of a Radioactive Waste Repository in Columbia Plateau Basalts. Rockwell Hanford Operations, RJO-ST-6, Richland, Washington.
- Ames, L. L. 1978. Radionuclide Batch K_d Values on Basalt, Heulandite, and Nontronite. In Basalt Waste Isolation Program Annual Report -- Fiscal Year 1978. Rockwell Hanford Operations, RHO-BWI-78-100, Richland, Washington.
- Anderson, M.P. 1979. Using Models to Simulate the Movement of Contaminants through Groundwater Flow Systems. Critical Reviews in Environmental Control. Volume 9, Issue 2.
- Bear, J. 1972. Dynamics of Fluids of Porous Media. American Elsevier, New York.
- Benson, L. V. 1978. Secondary Minerals Oxidation Potentials, Pressure and Temperature Gradients in the Pasco Basin of Washington State. Lawrence Berkeley Laboratory. RHO-BWI-C-34.
- Board, M. P. 1978. The Thermal and Mechanical Properties of Columbia Plateau Basalt. In Basalt Waste Isolation Program Annual Report -- Fiscal Year 1978. Rockwell International, Rockwell Hanford Operations, Richland, Washington. RHO-BWI-78-100.
- Borg, I. Y., R. Stone, H. B. Levy, and L. D. Ramsdottir. 1976. Information Pertinent to the Migration of Radionuclides in Ground Water at the Nevada Test Site. Part 1: Review and Analysis of Existing Information. Lawrence Livermore Laboratory UCRL-52078, Part 1.
- Bredehoeft, J. D., and G. F. Pinder. 1973. Mass Transport in Flowing Groundwater. Water Resources Research, Volume 9.
- Bredehoeft, J. D., A. W. England, D. B. Stewart, N. J. Trask, and I. J. Munograd. 1978. Geologic Disposal of High-Level Radioactive Wastes -- Earth Science Perspectives. U. S. Geological Survey Circular 779.
- Burkholder, H. C., J. A. Stottlemire, and J. R. Raymond. 1977. Safety Assessment and Geosphere Transport Methodology for the Geologic Isolation of Nuclear Waste Materials. In Risk Analysis and Geologic Modelling in Relation to the Disposal of Radioactive Wastes into Geological Formations. Proceedings of workshop organized jointly by the OECD Nuclear Energy Agency and the Commission of European Communities, Ispra, Italy, pp. 216-229.

- Burkholder, H. C. 1976. Methods and Data for Predicting Nuclide Migration in Geologic Media. International Symposium on Management of Wastes from the LWR Fuel Cycle. Denver, BNWL-SA-5523, Battelle Pacific Northwest Laboratories.
- Burkholder, H. C., et al. 1976. Incentives for Partitioning High-Level Wastes. Nuclear Technology, Volume 31.
- Carslaw, H. S., and J. C. Jaeger. 1959. Conduction of Heat in Solids. Oxford at Clarendon Press, Second Edition.
- Camp Dresser & McKee. 1979. Processes and Parameters Involved in Modelling Radionuclide Transport from Bedded Salt Repositories. Technical Memo.
- Crosby, J. W., III, and R. M. Chatters. 1965. Water-Dating Techniques as Applied to the Pullman-Moscow Ground-Water Basin. Washington State University Research Division Bulletin 296.
- Dames and Moore. 1978. Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations. Volume 4, Baseline Rock Properties - Salt. Prepared for Office of Waste Isolation, Union Carbide Corporation.
- Davis, S. N. 1969. Porosity and Permeability of Natural Materials. In Flow through Porous Media. R. J. M. De Wiest (Ed.). Academic Press. New York.
- Deju, R. A., and K. R. Fecht. 1979. Preliminary Description of Hydrologic Characteristics and Contaminant Transport Potential of Rocks in the Pasco Basin South-Central Washington. Rockwell International, Rockwell Hanford Operations, Energy Systems Group, Richland, Washington, RHO-BWI-LD-20.
- Deju, R. A., and R. K. Ledgerwood. 1976. Hydrogeology of the Uppermost Confined Aquifers Underlying the Hanford Reservation. ARH-SA-253, Atlantic Richfield Hanford Company, Richland, Washington.
- Deju, R. A., and W. K. Summers. 1975. Transmissivity and Hydraulic Conductivity of Saturated Sedimentary Rocks in the Hanford Reservation. ARH-C-00007, Atlantic Richfield Hanford Company, Richland, Washington.
- Deju, R. A. 1974. A Comprehensive Review of Mathematical Models Construction to Describe the Hydrology of the Hanford Reservation. Atlantic Richfield Hanford Company, Richland, Washington ARH-C-00003.
- Deju, R. A. 1974. The Hanford Field Testing Program. Atlantic Richfield Hanford Company, Richland, Washington. ARH-C-00004.

- Fenix and Scisson. 1969. Completion Report, Explatory Hole. ARH-DC-1, Hanford Works, Richland, Washington.
- Freeze, R. A., and J. A. Cherry. 1979. Groundwater Prentice-Hall, Inc., Englewoods Cliffs, New Jersey.
- Freeze, R. A., and P. A. Witherspoon. 1968. Theoretical Analysis of Regional Groundwater Flow, Three Quantitative Interpretations. Water Resources Research, Volume 4, No. 3.
- Fried, J. J., and M. A. Combarous. 1971. Dispersion in Porous Media. In Advances in Hydrosience. Ven Te Chow (Ed.), Volume 7, Academic Press, New York.
- Gephart, R. E., R. A. Deju, and P. A. Eddy. 1979. Geophysical Logging and Hydrologic Testing of Deep Basalt Flows in the Rattlesnake Hills Well Number One. RHO-BWI-ST-1. Rockwell Hanford Operations and Pacific Northwest Laboratory.
- Goldstein, P., G. O. Hultgren, and R. W. Nelson. 1978. A Model of Contaminant Diffusion from a Finite Line Source in a Dense Basalt Stratum to an Overlying Permeable Interbed. BCS Richland, Inc., Richland, Washington. RHO-BWI-C-3.
- Handbook of Chemistry and Physics. 1970. 51st Edition. Chemical Rubber Publishing Company, Cleveland, Ohio.
- Heiken, G. 1979. Pyroclastic Flow Deposits. American Scientist, Volume 67, No. 5, Sept.-Oct. ISSN0003-0996.
- Hill, M. D., and P. D. Grimwood. 1978. Preliminary Assessment of the Radiological Protection Aspects of Disposal of High Level Waste in Geological Formations. National Radiological Protection Board Report, United Kingdom, R69.
- Kibbe, R. K., and A. L. Boch. 1978. Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations. Volume 21. Ground Water Movement and Nuclide Transport. Office of Waste Isolation, Oak Ridge, Tennessee.
- Konikow, L. F., and J. D. Bredehoeft. 1978. Computer Model of Two-Dimensional Solute Transport and Dispersion in Ground Water. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 7, Chapter C2.
- Konikow, L. F., and J. D. Bredehoeft. 1974. Modeling Flow and Chemical Quality Changes in an Irrigated Steam-Aquifer System. Water Resources Research Volume 10, No. 3.
- La Sala, A. M., Jr., and G. C. Doty. 1971. Preliminary Evaluation of Hydrologic Factors Related to Radioactive Waste Storage in Basaltic Rocks at the Hanford Reservation, Washington. U. S. Geological Survey Open File Report.

- La Sala, A. M., Jr., and G. C. Doty. 1970. Preliminary Evaluation of Hydrologic Factors Related to Radioactive Waste Storage in Basaltic Rocks at the Hanford Reservation. Washington Open File Report, U. S. Geological Survey in Cooperation with the U. S. Atomic Energy Commission.
- Liverman, J. L. 1975. Final Environmental Statement -- Waste Management Operations -- Hanford Reservation, Richland, Washington. ERDA-1538. U. S. Energy Research and Development Administration, Washington, D. C.
- MacDonald, G. A. 1967. Forms and Structures of Extrusive Basaltic Rocks. In Basalts the Poldervaart Treatise on Rocks of Basaltic Composition. Eds., H. H. Hess and A. Poldervaart. Volume 1, Interscience Publishers, John Wiley & Sons, New York.
- MacKish, R. D., and R. A. Barker. 1973. Digital Simulation of a Basalt Aquifer System, Walla Walla River Basin, Washington and Oregon. Washington State Department of Ecology, Olympia.
- McClain, W. C., and C. D. Zerky. 1976. Waste Isolation in Geologic Formations in the United States. In Proceedings of the International Symposium on the Management of Wastes from the LWR Fuel cycle. Oak Ridge National Laboratory.
- Meinzer, O. E. 1923. The Occurrence of Ground Water in the United States. USGS Water Supply Paper 489.
- Mundorff, M. J., E. G. Crosthwaite, and C. Kilburn. 1964. Ground-water for Irrigation in the Snake River Basin in Idaho. U. S. Geological Survey Water Supply Paper 1654.
- Mundorff, M. J., D. J. Reis, and J. R. Strand. 1952. Progress Report on Ground Water in the Columbia Basin Project, Washington. U. S. Geological Survey Open-File Report.
- National Academy of Sciences, Division of Earth Sciences, Committee on Waste Disposal. 1957. The Disposal of Radioactive Waste on Land. National Academy of Sciences Research Council Pub. 519.
- Newcomb, R. C. 1969. Effect of Tectonic Structure on the Occurrence of Ground Water in the Basalt of the Columbia River Group of the Dalles Area, Oregon and Washington. U. S. Geological Survey Professional Paper 383-C.
- Newcomb, R. C., J. R. Strand, and F. J. Frank. 1972. Geology and Ground Water Characteristics of the Hanford Reservation of the U. S. Atomic Energy Commission, Washington. U. S. Geological Survey Professional Paper 717.
- Newcomb, R. C., J. R. Strand, and F. J. Frank. 1970. Geology and Ground-Water Characteristics of the Hanford Reservation of the U. S. Atomic Energy Commission, Washington. U. S. Geological Survey Open-File Report.

- Norvitch, R. F., C. A. Thomas, R. J. Madison. 1969. Artificial Recharge to the Snake Plain Aquifer: An Evaluation of Potential and Effect. Water Information Bulletin No. 12, Idaho Department of Reclamation, Boise, Idaho.
- Piper, A. M. 1975. Hypothetical Prototype Sites of Repositories for Radioactive Wastes: Flood Basalt. Office of Waste Isolation, Oak Ridge, Tennessee. Y/OWI/SUB-3725/6.
- Piper, A. M. 1975. Hypothetical Prototype Sites of Repositories for Radioactive Wastes; Certain Metamorphic Rocks and Mudstone. Unpublished Report to Union Carbide Corporation.
- Piper, A. M. 1974. Rock Types, Also Geologic and Hydrologic Settings, Favorable to Deep Placement of High-level Radioactive Wastes. Unpublished Report to Union Carbide Corp.
- PNL. 1977. Multicomponent Mass Transport Model: Theory and Numerical Implementation. Battelle, Pacific Northwest Laboratory, Richland, Washington BNWL-2127.
- Price, C. W. 1960. Artificial Recharge of a Well Tapping Basalt Aquifers, Walla Walla Area, Washington. Water-Supply Bulletin 7, Washington State Department of Ecology.
- Prickett, T. A. 1975. Modeling Techniques for Groundwater Evaluation. In Advances in Hydroscience. Ven Te Chow (Ed.) Volume 10, Academic Press.
- Prickett, T. A. 1980. Specifications for the Development of a Fully Three-Dimensional Numerical Groundwater Model for Regional Mass Transport of Radionuclides from a Deep Water Repository. Technical Memorandum. Camp Dresser & McKee.
- Raymond, J. R., and D. D. Tillson. 1968. Evaluation of a Thick Basalt Sequence in South-Central Washington. Battelle, Pacific Northwest Laboratories, Richland, Washington. BNWL-776.
- Rhodes, D. W. 1957. The Effects of pH on the Uptake of Radioactive Isotopes from Solution by a Soil. In Soil Science Society of America Proceedings, Volume 21.
- Robertson, J. B. 1977. Numerical Modeling of Subsurface Radioactive Solute Transport from Waste-Seepage Ponds at Idaho National Engineering Laboratory. U. S. Geological Survey Open-File Report 76-717.
- Robertson, J. B., R. Schoen, and J. T. Barraclough. 1974. The Influence of Liquid Waste Disposal on the Geochemistry of Water at the National Reactor Testing Station, Idaho: 1952-70. IDO-22053.

- Rockwell. 1977. The Basalt Storage Program. Staff Department of Waste Isolation Research and Engineering, Rockwell Hanford Operations, Richland, Washington.
- Rockwell. 1978. Basalt Waste Isolation Program Annual Report -- Fiscal Year 1978. Rockwell Hanford Operations, Richland, Washington, RHO-BWI-78-100.
- Routson, R. C. 1973. A Review of Soil-Waste Relationships on the Hanford Reservation from 1944 to 1967. BNWL-1464, Battelle, Pacific Northwest Laboratory, Richland, Washington.
- Routson, R. C., G. Jansen, and A. V. Robinson. 1975. Sorption of ^{99}Tc , ^{237}Np , and ^{241}Am on Two Subsoils from Differing Weathering Intensity Areas, BNWL-1889, Battelle, Pacific Northwest Laboratories, Richland, Washington.
- Schmalz, B. L. 1972. Radionuclide Distribution in Soil Mantle of the Lithosphere as a Consequence of Waste Disposal at the National Reactor Testing Station. U. S. Atomic Energy Commission, Idaho Falls, Idaho. IDO-10049.
- Schneider, K. J., and A. M. Platt (Eds.) 1974. High-Level Radioactive Waste Management Alternatives. BNWL-1900, Volume 1, Battelle, Pacific Northwest Laboratory, Richland, Washington.
- Schwartz, F. W. 1975. On Radioactive Waste Management: An Analysis of the Parameters Controlling Subsurface Contaminant Transfer. Journal of Hydrology, Volume 27.
- Silar, J. 1969. Ground Water Structures and Ages in the Eastern Columbia Basin, Washington. Bulletin 315, College of Engineering, Washington State University, Pullman, Washington.
- Spitsyn, V. J., and V. D. Galukova. 1967. Investigation of Sorption and Migration of Radioisotopes in Soils and Rocks of Different Composition. Proceedings on Disposal of Radioactive Waste into the Ground. International Atomic Energy Agency, Vienna. Paper SM 93/13.
- Streltsova, T. D. 1976. Advances and Uncertainties in the Study of Groundwater Flow in Fissured Rocks. In Advances in Groundwater Hydrology. (Ed.) Z. A. Saleem. American Water Resources Association.
- Summers, W. D., and Associates. 1978. A Survey of the Ground-Water Geology and Hydrology of the Pasco Basin, Washington. RHO-BWI-C-41, Rockwell Hanford Operations, Richland, Washington.
- Summers, W. K., and R. A. Deju. 1974. Final Report, A Preliminary Review of the Regional Hydrology of the Hanford Reservation Atlantic Richfield Hanford Company, Richland, Washington ARH-C-5.

- Swanson, D. A., T. L. Wright, P. R. Hooper, and R. D. Bentley. 1978. Revisions in Stratigraphic Nomenclature of the Columbia River Basalt Group. U. S. Geological Survey Bulletin 1457.
- Tamura, T. 1971. Sorption Phenomena Significant in Radioactive-Waste Disposal. Underground Waste Management and Environmental Implications, Proceedings of the Symposium, Houston, Texas, American Association of Petroleum Geologists.
- Tanaka, H. H. 1977. Aquifer Test of Well 18/25/15F in Grant County, Washington. Washington State Department of Ecology, Olympia.
- Tanaka, H. H., A. J. Hansen, and J. A. Skrivan. 1974. Digital-Model of Ground-Water Hydrology, Columbia Basin Irrigation Project Area, Washington. Washington State Department of Ecology, Olympia, Washington. Water-Supply Bulletin 40.
- Toth, J. A. 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Journal Geophysical Research, Volume 68, No. 16.
- U. S. Atomic Energy Commission. 1974. Draft Environmental Statement: Waste Management Operations. Hanford Reservation, Richland, Washington. Report WASH-1538, Volume 1.
- U. S. Geological Survey. 1967. Tectonic Features. National Atlas.
- Wilson, C. R. 1970. An Investigation of Laminar Flow in Fractured Porous Rock, Ph. D. Thesis, Civil Engineering Department, Inst. Transp. Engineering, University of California, Berkeley.
- Witherspoon, P. A., I. Javandel, S. P. Neuman, and R. A. Freeze. 1967. Interpretation of Aquifer Gas Storage Conditions from Water Pumping Tests. American Gas Association, New York.