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426.1/DJB/B0287/85/09/25

SEP 25 1985

Ms. Susan K. Whatley, Manager
Engineering Analysis and Planning
Chemical Technology Division
Oak Ridge National Laboratory
P.O. Box X, Building 4500N, MS 211
Oak Ridge, TN 37830

Dear Ms. Whatley:

SUBJECT: CONTRACT NO. NRC-50-19-03-01, FIN B-0287, ORNL NO. 41-37-54-92-4, "TECHNICAL ASSISTANCE IN GEOCHEMISTRY," AUGUST (1985) MONTHLY PROGRESS REPORT

I have reviewed the August monthly progress report dated September 9, 1985. Based on my review, I have the following comments:

Task 1 - BWIP Technical Assistance

- Progress to date is satisfactory.

- Attachment 1 is for your information. This paper was given at the "International Symposium of Coupled Processes..." held at LBL during the week of September 16.

- Attachment 2 is a draft report concerning numerical modeling of the ground-water flow system at BWIP. It is for your information and may be of some use conceptualizing release pathways at Hanford.

- The agenda for the contract review in October is being finalized. Please consider substituting a summary and discussion of the topical report on BWIP geochemical conditions in the place of BWIP solubility. BWIP expects geochemical conditions to play a major role in the release and migration of radionuclides, thus it is likely that geochemical conditions will be the topic of our next workshop. Solubility, which is influenced by geochemical conditions, can be discussed at another time.

Task 2 - NNWSI Geochemical Technical Assistance

- ORNL Letter Report (LR-287-10), reviewing "Verification and Characterization of Continuum Behavior of Fractured Rock at AECL Underground Research Laboratory-BMI/OCRD-17" has been received. This

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report has been given to Linda Kovach. She will contact you if she has any questions.

- ORNL Letter Report (LR-287-11) reviewing "Petrologic and Geochemical Characterization of the Topopah Spring Member of the Paintbrush Tuff..." has been received. This report has been given to Linda Kovach for review. She will contact you if she has any questions.

- Attachment 3, "Geochemical Sensitivity Analysis for Performance Assessment of HLW Repositories...," is for your information.

Task 3 - Salt Geochemical Technical Assistance

- Progress to date is satisfactory.

- Gary Jacobs' trip report concerning his participation in the DOE/NRC review of drill core from the Polo Duro Basin was received and given to Walt Kelly. Dr. Jacobs' participation was useful and appreciated.

Task 4 - Short-term Geochemical Technical Assistance

- Progress to date is satisfactory.

- The outline for short-term T.A. request number 6 (Letter Report on the Chemistry of Plutonium - See attachment 4) was received. I have distributed it for comment and will discuss it with you during the first week in October.

- The work being done under short-term T.A. request number 10 (catalog of HLW analogs - See attachment 4) appears to be progressing as expected. However, it is my understanding that the types of information to be cataloged include a section describing the application of each analog to problems of radioactive disposal in geomedia (See attachment 5). This section is critical to the catalog. Please discuss with me the progress being made in developing this section prior to our program review (October 16-17).

Task 5 - Project Management

- Progress to date is satisfactory.

- Attachment 6, Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (Final Rule EPA 40 CFR Part 19), is for your information.

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NAME	DJBrooks;mt						
DATE	85/09/						

° The program review for B0287 is scheduled for October 16-17. Attachment 7 is a draft agenda. Please provide comments to me by October 4, 1985.

The action taken by this letter is considered to be within the scope of the current contract NRC-50-19-03-01/FIN B-0287. No changes to cost or delivery of contracted products is authorized. Please notify me immediately if you believe that this letter would result in changes to cost or delivery of contracted products.

Sincerely,

Original Signed By

David J. Brooks
Geochemistry Section
Geotechnical Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosures:
As Stated

OFC	WMGT					
NAME	DJBrooks:mt					
DATE	85/09/25					

See Ltr. dtd. 9/25/85 B0287

BASALT WASTE ISOLATION PROJECT OVERVIEW

David M. Dahlem
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INTRODUCTION

The proposed candidate basalt site for a high level nuclear waste repository is located beneath the Hanford Nuclear Reservation in southeastern Washington State (Figure 1). At this point, the Hanford Reservation has been selected as one of three preferred candidates in the draft Environmental Assessment. Project activities have concentrated on (1) understanding the site location with respect to the 10CFR60, 40CFR191, and 10CFR960, (2) identifying critical parameters for design of waste package and repository seals, and (3) identifying parameters for repository design. This paper describes the program to evaluate the site and identify the natural processes that would effect isolation.

The viability of the reference repository location (RRL) depends on findings in several important areas; (1) the groundwater circulation system, (2) the nature and complexity of the basalt horizons and inhomogeneities, and (3) the structural stability of the repository environment relating to vulcanism and seismicity. Other issues are subordinate.

The Repository Site program has two major testing and data collecting phases: (1) an early reconnaissance activity to locate a site and to assess site suitability, and (2) site characterization to evaluate performance uncertainties. The emphasis in all studies is on identifying system baseline conditions and processes of change. Data collection originally started with surface-based exploration and will continue in in situ measurements in subsurface facilities such as the exploratory shaft facility and in special boreholes to confirm surface work and to collect unique data.

Geologic Program Status

The following sections present the current understanding of the geologic and geophysical properties of the basalt site. Areas that significantly influence the testing program (described in a later section) are highlighted.

Geomorphology

The Hanford site is located within the Columbia Plateau geologic province between the Yakima Fold Belt to the west, the Blue Mountains to the south, and the Palouse. It is at the point where ridges of the Yakima Fold Belt dip east beneath the west dipping Palouse Slope.

The principal geomorphic processes affecting the area during Quaternary time were degradation of bedrock ridges and scouring associated with late Pleistocene cataclysmic floods, and sedimentation associated with wind and water redistribution of glacial outwash of the above materials. The most recent flood was about 13,000 yrs B.P., associated with the last ice advance.

On the basis of paleoclimatic information, only two ice advances are expected in the next 100,000 years; beginning at 15,000 and 35,000 years.

Stratigraphy and Lithology

The Reference Repository area is underlain by three rock sequences (Figure 2): the basalt group is pre-Tertiary epiclastic sedimentary rocks from 6,000 to 18,000 feet thick. This, in turn, is overlain by the Columbia Basalt Group, from 10,000 to 16,000 feet, and by about 500 feet of post basalt sediments.

In the RRL area, the Yakima Subgroup of the Columbia Basalt group is divided into the Grande Ronde, overlain by the Wanapum, and in turn by the Saddle Mountain flow sequences. Within the Grande Ronde sequence, the Cohassett flow is the current reference horizon.

The Cohassett flow is mid-way in the Sentinel Bluffs sequence. From systematic studies of the Cohassett flow, internal or intraflow structural features have been defined allowing a modicum of prediction of mechanical characteristics. Intraflow structural domains differ in strength and mechanical properties, and therefore are of interest in assessment. Fracture (or joint) density has been evaluated for the candidate flows with the Cohassett the most intact, least fractured flow of those studied.

The Grande Ronde, Wanapum, and Saddle Mountains sequences are each separated by sedimentary interbeds of the Ellensburg Formation. The lowest of the interbeds is the Vantage, separating the Grande Ronde and Wanapum basalts. From this point upward in the basalt section, volcaniclastic sedimentary interbeds become an important part of the geohydrologic control. The Mabton interbed is the thickest unit separating the Wanapum from overlying Saddle Mountains basalts, but each flow in the latter two sequences is overlain by an interbed.

The principal uncertainties in the stratigraphy and megascopic lithology are focused on the need to identify and characterize individual flows and to predict variations. Elements in this area consist of flow thickness, intraflow structures, fractures, and textural discontinuities such as zones of vesiculation and brecciation.

Structural Geology and Tectonics

The structural geology of the RRL area is characterized by compressional features comprised of sharp east-west trending anticlines and shallow intervening synclinal valleys. In general the anticlines are asymmetrical and overturned on the north limbs. Second and third-order folds are common on first-order anticlines.

Thrust and high-angle reverse faults are common along the steeper limb of anticlines. Estimated displacements range from several meters to 2.5 km such as along the Saddle Mountains fault at Sentinel Gap. Fault dips vary from 45° to vertical. Northeast- to Northwest-trending cross faults with up to several tens of meters dip-slip and postulated strike-slip displacement transect the anticlined folds. In addition, fold trends commonly display abrupt bends along strike.

Several large-scale features provide the regional structural framework. The Olympic-Wallowa lineament (OWL) and Hog Ranch-Naneum Ridge anticline trend into the Columbia Plateau and transect the Yakima Fold belt. The OWL is 400 km long topographic lineament extending from the Olympic Mountains in northwestern Washington to the Wallowa Mountains of northeastern Oregon. The Cle Elum-Wallula lineament (CLEW) is the central third of the OWL feature, in which area occur northwest-trending faults. In the Pasco Basin, the CLEW is the series of features including Rattlesnake Mountain, and several doubley-plunging anticlines to the southeast. This local feature is referred to as the Rattlesnake-Wallula lineament (RAW). East of Wallula Gap the CLEW is defined by west northwest trending faults of the Wallula fault system.

Evidence for possible Quaternary faulting within the Yakima Fold Belt occurs 75 km west of the site at Toppenish Ridge. Five hundred year old sag ponds at that location are similar to features on Gable Mountain.

The Pasco Basin, in which the site is located, is one of four structural and topographic basins in the Yakima Fold Belt. It is defined on the north by the Saddle Mountains and on the south by the RAW structure. The Hog Ranch structure and Palouse Slope are the western and eastern boundaries. The main trends within the basin are easterly to southeasterly from northwest to southeast. Structural and topographic relief lessens to the southeast, with several of the Yakima folds receding into the subsurface.

Four anticlinal structures define the immediate structural environment of the site: the Saddle Mountains, Umtanum-Gable Mountain, Yakima Ridge and Rattlesnake Mountain, and anticlines along the RAW to the southeast. The intervening synclines are the Pasco Basin on the east, Wahluke syncline, Cold Creek syncline, and Benson Ranch syncline from north to south.

The Cold Creek syncline is a broad southeasterly plunging fold with a relatively steep southern limb toward Yakima Ridge. The structure is interpreted to have been a thick basalt section controlled north and south by anticlinal ridges.

Structural analysis indicates that tectonic forces have been accomodated by folding and closely parallel faulting above the northern limbs of anticlines. These features consist of steep reverse faults and pronounced brecciation parallel to fold axes. Rate of deformation has been assessed from the thinning of flows over ridges and current leveling and trilateration surveys.

The eruption of tholeiitic flood basalts from 7 to 8.5 m yrs B.P. is the most significant volcanic event to effect the Pasco Basin. Feeder dikes for these eruptions have been identified on the eastern basin margin. The only volcanic events subsequent to these are from the Cascade Range, west of the site.

The principal uncertainties in the area of structural geology center around the nature, mechanism, and timing of tectonic deformation effecting long term stability of the site and effect on groundwater circulation in the Pasco Basin.

Seismology

The Columbia Plateau is an area of moderate seismicity based on the historical record. The seismicity of the RRL is low as compared with that of the Columbia Plateau. The seismicity can be grouped into two types of events: deep events and shallow swarms.

The earthquake swarm is the predominant activity of the site area. Swarms typically occur over periods of a few days to several months, are constrained to a rock volume typically 2 km X 5 km X 3-5 km deep, and may contain several hundred earthquakes from magnitude 1.0 to 3.5.

Centers of swarm activity have been recorded near the site at Wooded Island, Coyote Rapids, and northeast of the site between the Saddle Mountain and Frenchman Hills anticlines. The evolution of these events indicates no specific probable structural relation.

The principal uncertainties on the site seismicity include the nature of the mechanism and potential ground motion related to swarm events and the nature of surface wave transmission within the area to the repository rock volume.

Engineering Geology

The engineering properties of concern are those that bear directly on the excavation characteristics of the basalt. The data now available have come from the analysis of outcrops, borehole cores, and in situ measurements from the Near Surface Test Facility (NSTF) constructed in Gable Mountain, northeast of the RRL. A central concern in the data collection effort has been understanding and predicting the in situ response of the rock mass to changes imposed by excavation and from thermal simulations of waste loading.

Intact basalt from the flow interiors is hard, brittle rock that is insensitive to temperature change at 150-200°C and has little definable mechanical change up to 500°C. The intact basalt shows a significant increase in strength with confining stress. Uniaxial comprehensive strength differs between Grande Ronde flows, with typical values for the Cohassett interior and flow top breccias of 290 MPa (42,000 psi) and 1,000 MPa (15,000 psi), respectively.

Jointing is common in the flows and is typically characterized as tight with pervasive filling by secondary minerals. Testing of jointed samples under triaxial loading and direct shear indicates the secondary minerals do not dominate the joint properties. Joint friction angles measured in the NSTF were 35° for the Pomona flow. A value of 42° was obtained for Grande Ronde basalt. Normal and shear stiffness tests on core from the NSTF indicate relatively high stiffness reflecting the competent nature of the joint surfaces and thin joint fillings.

Under low stress conditions, the joint frequency is sufficiently high to significantly influence the rock mass modulus and rock mass strength. Under high stress conditions at the repository depth, joints are expected to be tighter and have less effect on rock mass modulus.

No reliable data on deformation moduli are available at this time.

Thermal properties at the repository horizon probably can be estimated with sufficient accuracy from laboratory tests. This is based on the agreement between lab and NSTF measurements. Thermal properties are expected to be influenced by rock porosity and moisture conditions. Jointing does not appear to have a pronounced effect on thermal or thermomechanical properties and no thermal anisotropy was observed in current testing.

Stress measurements by hydraulic fracturing in three holes within the reference repository location in all four potential repository horizons have produced a consistent pattern of *in situ* stresses that are oriented with the maximum stress essentially north-south and the minimum stress vertical. The maximum horizontal stress does not show any significant increase with depth within the flows or between the four flows tested. The maximum horizontal stress is estimated to be 61.5 MPa (8,900 psi) in the Cohassett flow. In the Cohassett flow, the intermediate horizontal stress is 32.4 MPa (4,700 lb/in^2) with a minimum (vertical) stress of 24.1 MPa (3,500 lb/in^2). These stress levels are high and are compatible with the observed borehole spalling, core disking, and seismic activity in the area.

Rock spalling and small rock bursts can be anticipated given the stress field and brittle nature of basalt, however, the jointed nature of basalt may mitigate the spalling potential by relieving the high stress concentrations around openings.

Geohydrology

Since 1977, reconnaissance hydrologic studies have been conducted in and around the Cold Creek syncline to identify stratigraphic intervals of high and low hydraulic conductivity, areal and stratigraphic hydraulic head distributions, geochemical trends and the influence of geologic structures on circulation patterns. In this program, testing has become progressively sophisticated as new facilities have been constructed. To date, the emphasis has centered on understanding the circulation systems, which in turn requires hydraulic stress testing of discrete horizons. A reference piezometric baseline for this testing is an integral part of the program.

Preliminary studies indicate that basalt flow-brecciated tops and interflow sedimentary units have higher hydraulic conductivity than flow interiors. For flow tops and interbeds, conductivity ranges from 10^{-12} to 10^{-1} m/s with a geometric mean of 7×10^{-6} m/s. For the flow interiors, the range is 10^{-15} to 10^{-8} with a geometric mean of 1×10^{-12} m/s. The hydraulic conductivity of interflow zones differs between basalt sequences and generally decreases with depth. Hydraulic gradient for the Grande Ronde has been estimated to be 2×10^{-4} m/m with direction of flow within the RRL toward the south-southwest. The direction of regional flow appears to be southeast. The local influence of synclinal structural dip is presumed to be the reason for the discrepancy. Vertical hydraulic gradient in the Grande Ronde appears to be upward at 1×10^{-3} m/m.

Hydrochemical data have been used to interpret the circulation systems. These data suggest that two flow systems exist beneath the Hanford site; one in the Grande Ronde and one in the Saddle Mountain and near-surface sediments. Within the Wanapum basalts, limited mixing occurs. Chemical signature data suggests waters of the Grande Ronde are probably part of regional circulation systems in contrast to the more locally circulating waters of the Saddle Mountain basalts.

Possible boundary conditions which may influence geohydrologic conditions at the site are listed below.

- The postulated "Cold Creek Barrier" located just west of the RRL. Hydrologic evidence suggests that this geophysical anomaly may act as an impermeable boundary to groundwater flow.
- The anticlinal ridges to the north and south of the RRL. However, it is not known at this time whether these structures may act as impermeable boundaries, constant head boundaries, or what the extent of such boundaries may be.
- The Columbia River may act as either a source or sink to groundwater in the deep basalts. Hydrologic data collected to date do not confirm either suggestion. The Columbia River is a sink (discharge area) for the unconfined aquifer.

Geochemistry

An understanding of the rock-fluid system environment of the repository is essential to predict repository isolation-containment characteristics. To date, information includes phase definition and distribution of components from petrologic and geologic studies. Reconnaissance geochemical sampling in these studies provides gross system characterization. Limited experimental work identifies the behavior of radionuclides in this system and provides detail on phase stability and reactions.

The major mineral composition of the dense interiors of Grande Ronde basalts ranges from 0 to 35% pyroxene, 25 to 48% plagioclase, 0 to 6% Fe-Ti oxides, 0 to 3% olivine, and 20 to 65% mesostasis. Less abundant phases include apatite, orthopyroxene, pigeonite, and sulfides. The mesostasis is primarily glass.

The concentrations of most major element oxides and trace elements are relatively consistent throughout the Grande Ronde section. The ratio of $FeO/(FeO+Fe_2O_3)$ varies from about 0.76 to 0.79 in the dense interiors of candidate basalt flows. Therefore, the rock mass is highly reduced in the flow interiors. Hematite blebs are disseminated in the groundmass. Secondary phases in fractures, vesicles, and vugs include smectitic clays, zeolites, and silica. Other secondary minerals have been identified but are present in much lower amounts. The presence of secondary pyrite in these basalts provides strong evidence for reducing conditions in the site system.

The sedimentary interbeds consist of tuffaceous siltstone with lesser amounts of quartz sandstone, conglomerate, and well-sorted vitric tuff. Most of these sediments are friable but some are cemented with calcite, clay, opal, and zeolite.

The primary phases of the basalts are not in equilibrium with the present physiochemical environment. They are metastably persistent, however, because the kinetics of alteration are slow at the ambient low temperatures of the basalts. The lack of reliable thermodynamic data on secondary minerals prevents a rigorous evaluation of their stability.

Major inorganic components of deep basalt groundwaters are sodium (50 to 450 mg/L), potassium (4 to 36 mg/L), calcium (2 to 18 mg/L), magnesium (2 to 12 mg/L), silicon (25 to 175 mg/L), chloride, (50 to 550 mg/L), fluoride (5 to 55 mg/L), and sulfate (25 to 250 mg/L). Measured pH values range from 7.2 to 10.8 (most are in the range of 9.2 to 9.8). Alkalinity (as $CaCO_3$) ranges from 75 to 225 mg/L. Both vertical and lateral major element compositional variations are observed.

Methane is the major dissolved gas found in groundwaters. Minor amounts of nitrogen, argon, and carbon dioxide are also present. Estimates of methane concentrations range from 350 to 700 mg/L for groundwaters in Grande Ronde basalts.

RADIONUCLIDES

Sorption of key radionuclides occurs by chemisorption and ion exchange reactions with minerals in the groundwater flow path. Actinides are strongly sorbed by each of the geologic solids studied (basalt, secondary minerals, and interbed materials), as are radionuclides that exist in solution as hydrated metal ions. Non-metallic radionuclides such as iodine-129, carbon-14, and selenium-79 exist only as anions in solution and are weakly sorbed.

Most radionuclide sorption reactions are at least partially irreversible under conditions expected in basalt groundwaters. Sorption and desorption isotherms for a given radioelement are non-single-valued and show a significant degree of sorption hysteresis. This hysteretic effect is important to radionuclide transport calculations since it can lower peak radionuclide concentrations in groundwater and delay transport. Migration of radionuclides as particulates suspended in groundwater must also be considered as a possible transport mechanism.

The chemical species of radionuclides in the site system will influence their retardation behavior. Speciation, in turn, depends on the oxidation state of the radionuclide and on the presence of complexing ligands. The preponderance of evidence indicates that conditions in the site system are reducing. It is expected, therefore, that radionuclides will be present in lower oxidation states.

A large quantity of radionuclide sorption and desorption data have been obtained. A wide range of experimental conditions have been examined in these measurements in an attempt to duplicate the variety of possible conditions expected in the site system. Because of uncertainties in groundwater composition, oxidation states of some radionuclides, and composition of geologic solids in groundwater flow paths, attempts have been made to determine the sensitivity of radionuclide sorption to these parameters. As a result of these efforts, most existing sorption information was obtained at the extremes of expected conditions (oxidation states, groundwater compositions, etc.). Although this may be adequate for certain radionuclides, additional data is needed for radionuclides that are highly sensitive to these sorption parameters.

ENGINEERED BARRIERS

The development of engineered barriers, (i.e., the waste package and repository seals) has been proceeding in parallel with site exploration. The BWIP waste package concept incorporates the waste into a low-carbon steel, thick-walled cylindrical container which is designed for at least 1,000 years containment in accordance with the NRC containment requirement. A six-inch layer of crushed basalt-bentonite clay packing material is placed between the container and host rock to retard groundwater flow and to buffer groundwater oxygen concentrations to extremely low levels, thereby promoting conditions favorable to container life, and lower solubilities and higher sorptivities for many radionuclides. Thus the packing material is expected to play an essential role in meeting the NRC requirement for controlled release and the EPA cumulative mass flux requirement during the isolation period The current waste package program addresses characterization of the waste package environment, testing of waste package components under repository-relevant conditions, waste package design, and performance analyses. In the environmental area, studies include alpha/gamma radiolysis, natural analogs, redox sensitivity, and geochemical modeling. In the testing area, studies include degradation of iron-base and copper-base container materials, static and flow-through release testing of spent fuel and glass waste forms, and a variety of packing material physical and chemical tests. In the design and performance analysis areas, the advanced conceptual design of the waste package and a reliability analysis are nearly complete.

Repository seal development activities involve testing to understand site conditions and material behavior, testing to demonstrate emplacement techniques and component performance, modeling and analysis to assess seal system performance and predict repository conditions which affect performance, and design. All these activities support the selection of materials and evolution of sealing concepts to assure that excavated openings do not become pathways to compromise the ability of the site to isolate wastes.

The principal activities through the initial part of site characterization involve laboratory testing of candidate backfill materials, modeling and performance analysis of alternative shaft and borehole sealing concepts to provide a basis for design optimization relative to performance criteria, and performing conceptual and advanced conceptual design of shaft and borehole seals.

TESTING PROGRAM

The objectives of the testing program include (1) providing a data base for license application, (2) providing assurance on performance issues, and (3) providing data for engineering and design of the repository and dependent operations. At Hanford, the testing effort is oriented toward answering questions on the groundwater system, rock complexities, and stability with respect to demonstrating containment and isolation. (Table 1)

In the event Hanford is selected for site characterization, the testing program will be outlined in the Site Characterization Plan. Central to activities during characterization is providing an understanding of site geologic heterogeneities. As a result, this data collection and testing effort is strongly flavored by classical exploration and engineering geologic studies. Major elements of this program are described below.

Geology

Uncertainties in the current knowledge of the site stratigraphy and lithology are based on the paucity of subsurface data, and show up in lower confidence level estimates of basalt flow thickness, variation in intraflow structure, fracture characteristics, and petrology, both of the flows and interbeds. The work to be conducted on surface outcrop and from boreholes will include field mapping, surface and subsurface geophysics, laboratory analysis of chemistry and petrology.

In the area of structural geology, current information concentrates on the geometric characteristics of folds and faults. The data are incomplete and uncertainties exist on the nature, mechanisms, and timing of tectonic deformation. Significant work remains in characterizing the large-scale regional structures like the RAW, and evaluating the possible influence of regional tectonic forces on repository stability.

Groundwater Hydrology

The principal activities in groundwater hydrology include characterizing the regional groundwater flow system, providing a baseline for flow system interpretation, and determining the value of hydraulic properties for the repository rock volume. System uncertainties will be identified through numerical modeling which will require evaluating boundary conditions for the Cold Creek syncline.

Key to the evaluation of the hydrologic system are data obtained from a monitoring system of over 35 monitoring wells at and surrounding the RRL. From these facilities, water level and pressure data are being monitored; first, to establish a baseline and second, in response to formational responses during nearby drilling and pumping activities. A specific phase of testing (large hydraulic stress testing or LHS) will consist of pumping selectively from wells in this system and observing responses in neighboring nested piezometers up to kilometers from the test point.

Pump tests are planned for both local and remote testing, involving scales of hours and days up to a month or more of pumping.

Three types of tests will be conducted from the Exploratory Shaft facility (Table 2): borehole, chamber, and tracer breakthrough between boreholes. Borehole testing procedures will include constant head injection, pulse, and cross hole techniques.

Both surface and subsurface boreholes will be used as monitoring points during all subsequent testing and construction activities.

Rock Mechanics Testing

A key area in demonstrating a viable rock environment is demonstrating stability of underground openings at depth and facility of construction and operations methods. The available data on rock properties provide a basis for evaluating these items but in situ observation, mining, and underground testing are needed. Specific underground tests will be based on the first in situ observations during shaft sinking and facility breakout. Table 2 shows elements in the testing program. Figure 3 shows the exploratory shaft test facility layout with the location of individual tests in the geomechanical testing program. Integrated thermomechanical and hydrological testing may be required to establish that mechanical performance will not impact waste isolation. The nature of such tests can only be proposed at this point. In situ test data will provide guidelines for such tests.

REFERENCES

U. S. Department of Energy, 1982, Site Characterization Report for the Basalt Waste Isolation Project, DOE/RL 82-3, 3 Vols., Rockwell Hanford Operations for the U. S. Department of Energy, Washington, D. C.

U. S. Department of Energy, 1982, Test Plan for Exploratory Shaft Phase I and II Testing, SD-BWI-TP-007

U. S. Department of Energy, 1984, Draft Environmental Assessment for the Basalt Waste Isolation Project, DOE/RW-0017

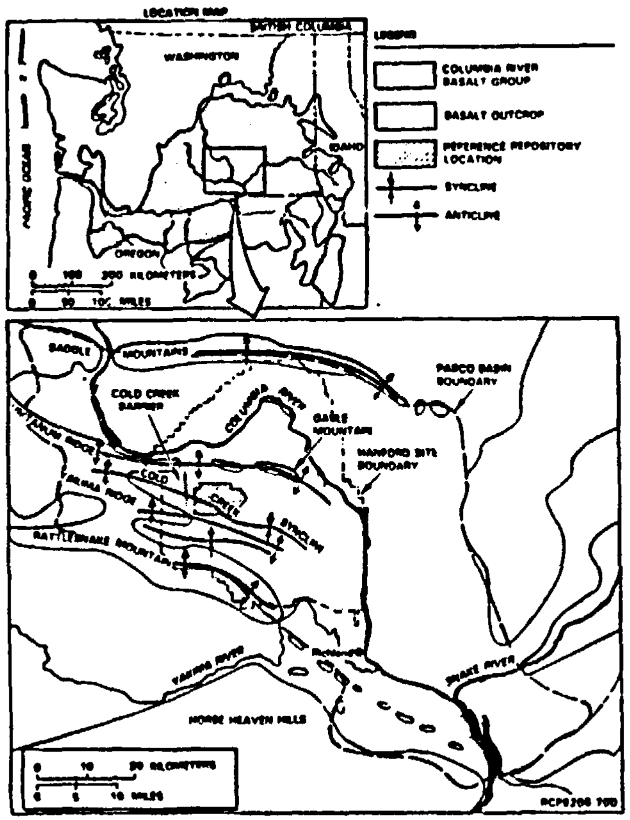

Figure 1. Extent of the Columbia River Basalt Group, the Pasco Basin, and the proposed site for a repository in basalt.

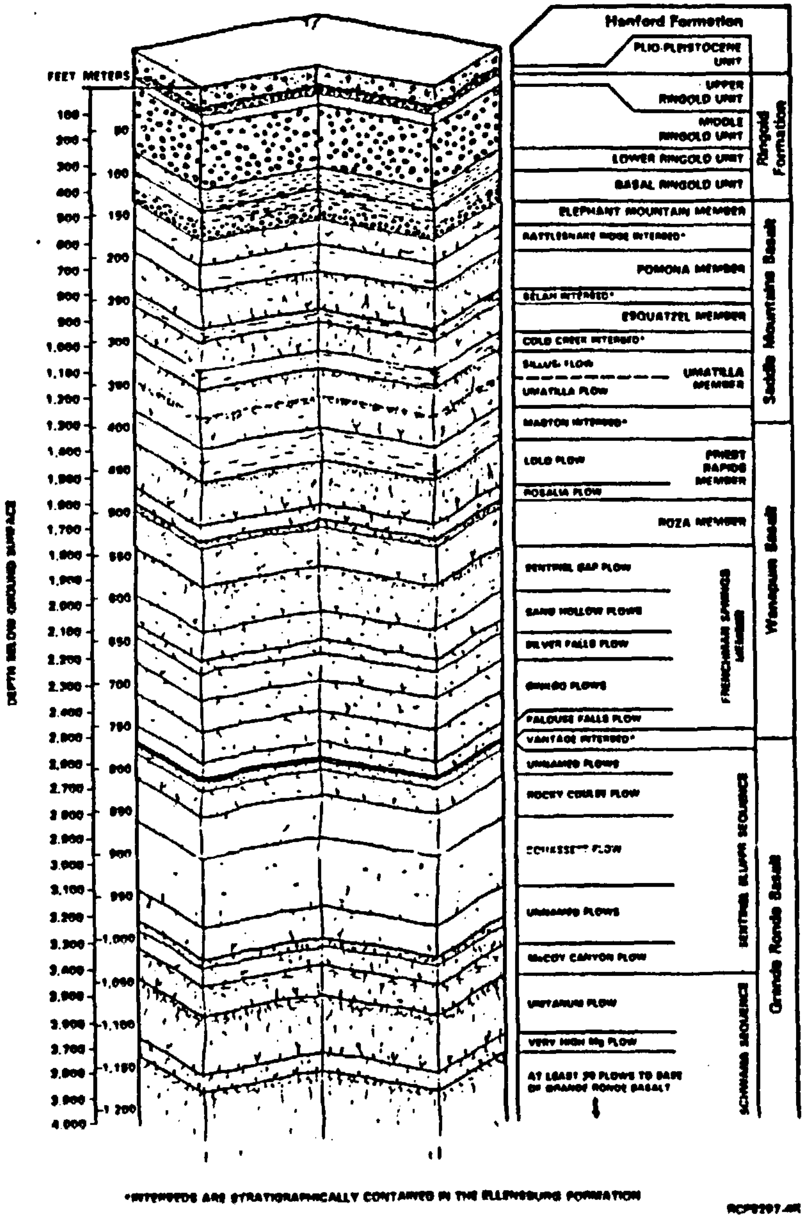

Figure 2. Reference Repository Location Stratigraphy.

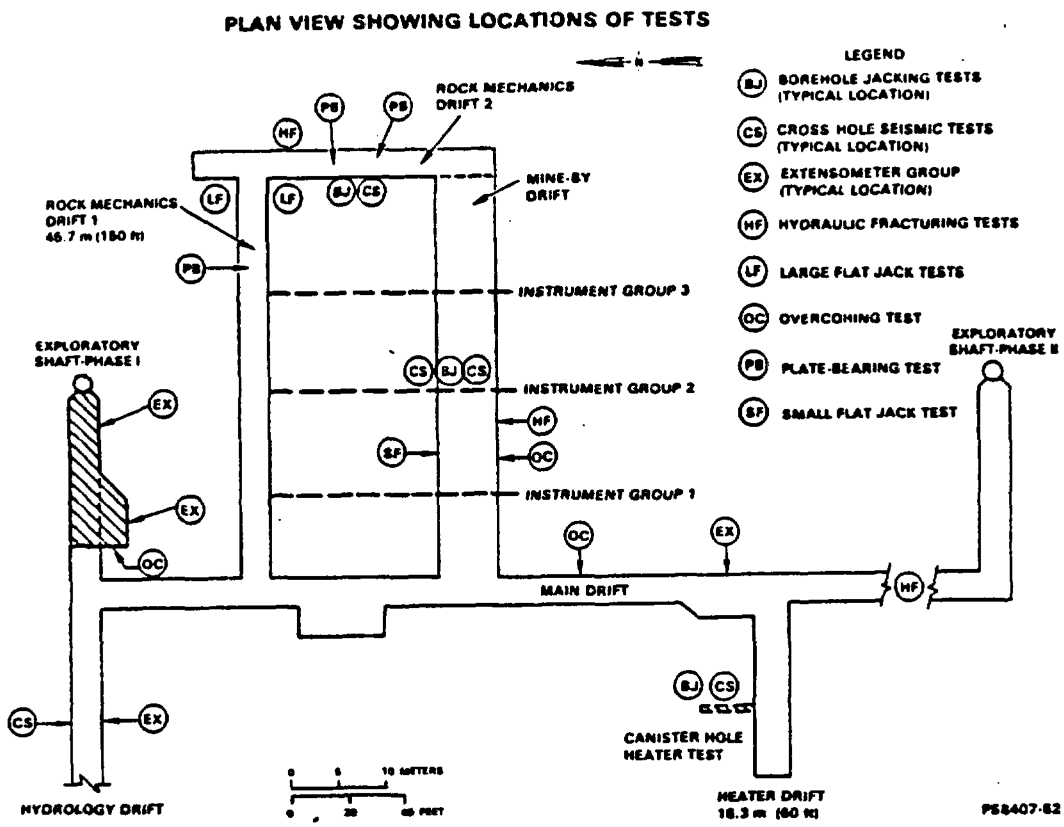

Figure 3. Plan View of ES-II Facility Showing Rock Mechanics Test Location.

TECHNICAL OBJECTIVES / PLANNED TESTS	PHASE I						PHASE II				REFERENCE SECTION	
	I-1 PRINCIPAL BOREHOLE	I-2 SHAFT CONSTRUCTIBILITY	I-3 SHAFT LINER SEALING	I-4 SHAFT STATION GEOHYDROLOGY	I-5 SHAFT STATION GEOMECHANICS	I-6 SHAFT STATION CONSTRUCTIBILITY	II-1 GEOLOGIC CHARACTERIZATION	II-2 HYDROLOGIC CHARACTERIZATION	II-3 GEOMECHANICS CHARACTERIZATION	II-4 UNDERGROUND CONSTRUCTIBILITY	EXPLORATORY SHAFT TEST PROGRAM VOLUME I	PRELIMINARY TEST DESCRIPTION VOLUME II
GEOLOGIC CHARACTERIZATION												
PRINCIPAL BOREHOLE TESTS	●										5.2.4	APPENDIX A
BOREHOLE TESTS				●	○		●	○	○		5.3.1	2.2.1
FACILITY TESTS					○	●	●	○	○	●	5.3.1	2.2.2
HYDROLOGIC CHARACTERIZATION												
PRINCIPAL BOREHOLE TESTS	●										5.2.4	APPENDIX A
BOREHOLE HYDROLOGY TESTS				●				●	○		5.3.2	3.3
CHAMBER TESTS								●			5.3.2	3.4
TRACER TESTS								●			5.3.2	3.6
GEOMECHANICS CHARACTERIZATION												
PRINCIPAL BOREHOLE TESTS	●										5.2.4	APPENDIX A
OPENING DEFORMATION MONITORING					●				●		5.3.3	4.3.2
OPENING SUPPORT MONITORING					●				●		5.3.3	4.3.3
ACOUSTIC EMISSION MONITORING					●				●		5.3.3	4.3.4
BOREHOLE JACKING TEST									●		5.3.3	4.3.5
CROSS HOLE SEISMIC TEST									●		5.3.3	4.3.6
PLATE BEARING TEST									●		5.3.3	4.3.7
LARGE FLAT JACK TEST									●		5.3.3	4.3.8
ROOM SCALE ENLARGEMENT									●		5.3.3	4.3.9
CANISTER HOLE DRILLING TEST									●		5.3.3	4.3.10
HEATER TEST									●		5.3.3	4.3.11
SMALL FLAT JACK TEST									●		5.3.3	4.3.12
OVERCORING TEST					●				●		5.3.3	4.3.13
HYDRAULIC FRACTURING TEST									●		5.3.3	4.3.14
CONSTRUCTIBILITY REPORTING		●	●			●				●	5.4	6.0

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LEGEND: ● PRIMARY DATA ○ SUPPORTING DATA

---- Table 1 - Exploratory Shaft Objectives and Planned Tests.

Table 2

BWIP HYDROLOGIC TEST ACTIVITIES

TEST ACTIVITY	TEST OBJECTIVES	PRIMARY FACILITIES	TEST MECHANICS
PIEZOMETRIC BASELINE MONITORING	• DEFINE WATER-LEVEL TRENDS FOR TESTING PURPOSES • GROUNDWATER FLOW CONCEPTUALIZATION - DIRECTION OF FLOW - HEAD DISTRIBUTION • REGIONAL GROUNDWATER FLOW MODEL CALIBRATION	• DC-19, DC-20, DC-22, RRL-2A, HANFORD MONITORING WELLS (SEE ATTACHMENTS)	• WATER-LEVEL MEASUREMENTS IN ALL AVAILABLE DEEP BOREHOLES • PRESSURE MEASUREMENTS IN DC-19, DC-20, & DC-22 • NO WITHDRAWALS OF GROUNDWATER AT HANFORD FOR A 1-YEAR PERIOD
GRANDE RONDE LARGE-SCALE HYDROLOGIC STRESS TESTS (LHST)	• AREAL HYDRAULIC PARAMETRIC EVALUATION • IDENTIFY BOUNDARIES WITHIN GRANDE RONDE (LIMITED AREA) • VERTICAL CONDUCTIVITY • LITHOLOGIC CONTINUITY • PRESENCE/ABSENCE OF HIGHLY TRANSMISSIVE ZONES	• RL-2B - PUMPING WELL • RRL-2C - MONITORS DENSE INTERIORS OF GRANDE RONDE • DC-19, DC-20, DC-22 • DC-1, DC-2, DC-4, DC-5, DC-7, DC-8, DC-12, DC-15, DC-16, RRL-6B, RRL-14, McGEE	• PUMP SEQUENTIALLY ROCKY COULEE FLOW TOP, COHASSET FLOW TOP, COHASSET FLOW BOTTOM, AND UMTANUM FLOW TOP • MEASURE DRAWDOWN AT NESTED PIEZOMETERS AND OTHER WELLS • "PIGGYBACK" TRACER TESTS • ANALYTICAL AND INVERSE NUMERICAL SOLUTIONS
WANAPUM LARGE-SCALE HYDROLOGIC STRESS TESTS (LHST)	• LARGE-SCALE STRESS OF WANAPUM AQUIFERS TO ADDRESS BOUNDARY CONDITIONS, NEAR TO FAR FIELD	• DC-19, DC-20, DC-22 • DB-1, DB-2, DB-11, DB-12, DB-14, DC-16C, ENYEART, FORD, O'BRIEN, McGEE	• PUMP PRIEST RAPIDS • MEASURE DRAWDOWN • ANALYTICAL AND INVERSE NUMERICAL SOLUTIONS
SMALL-SCALE TESTS	• HYDRAULIC PARAMETER EVALUATION • PRE-LHST EVALUATION TO SIZE TESTS	• AS NEEDED	• PULSE, INJECTION, ETC.

Simulation of Coupled THM Interactions in Fluid Injection into Fracture Rocks

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Introduction

Deformation of fractured rocks in response to fluid pressurization (by fluid injection, for instance) is known phenomena. Re-pressurization of hydraulically induced fractures in hydrofrac experiments, is a common practice to obtain better estimates of insitu stresses. In this process the compressive stress in the fracture is neutralized by the injected fluid pressure leading to complete separation of fracture surfaces. The deformation process in the rock as a whole and in the fracture specifically, is a coupled phenomena. Thus far, lack of data and complexity of analysis has not allowed realistic simulations of fluid injections to be performed. This complexity and the limitations are even greater if one considers nonisothermal injections such as those that arise in hot dry rock experiment or cold water flooding of oil reservoirs. The latter phenomena entails a triply coupled process among the heat flow, fluid flow and the host medium deformability. Theoretical consideration (Nowacki, 1962) and some observations (Stephens, et al., 1982) have pointed to the important role of the thermal stresses in the deformation processes of fractures. As mentioned above, scarcity of data and complexity of the processes make a realistic simulation of the THM phenomena for the cases mentioned almost unattainable. However, availability of numerical procedures (Noorishad et al., 1984) allows scoping analysis of some observations to be made. In the following, such an attempt is made to explain the observations made in a case of cold water flooding of an oil reservoir.

Theoretical Considerations

Field equations of the THM phenomena and the general set up of THM initial boundary value problem along with a numerical solution approach are given in Noorishad, et al. (1984). This work also provides a basis for an understanding of the role of the thermal stresses in the THM phenomena through the inspection of the stress-strain relationships. In these formulations, *temperature* appears in a way similar to *pressure*, with Biot's coupling coefficient (Biot, 1941) replaced by $E\gamma/(1-\nu)$, where E and ν are elastic moduli and γ is the linear thermal expansion coefficient. Solutions of uncoupled thermoelasticity, such as that of thermal stresses in an elastic thick-walled cylinder (Nowacki, 1962) provide a good insight. The variation in the tangential stresses at the inner cylinder boundary, caused by a change in temperature ΔT is given as

$$\Delta\sigma_{\theta\theta}\,|_{r=a} = -\frac{\gamma E \Delta T}{1-\nu} \qquad (1)$$

where a is the inner cylinder radius and tension is assumed positive. A change in temperature of about 10°C can create stress variations from 1-10 MPa depending on the magnitude of the elastic moduli used in the calculation. It is obvious that such stresses could exceed the tensile stress of rocks in certain cases. To investigate the role of thermal stresses in circumstances where transport of energy is helped by fluid flow, and also in conjunction with the mechanical aspect of the flow of fluids, numerical techniques such as the code "ROCMAS" (Noorishad, et al 1984) must be used.

Application

The numerical simulation in this work is motivated by some qualitative information on cold water flooding experiments performed in oil fields. In these experiments, it was noticed that hydrofacing and/or re-opening of existing fractures, in the warm reservoir, consistantly took place at pressure gradients that were 1.5 x 10^{-3} MPa/m less than the expected values. For a reservoir at a depth of about 3000 meters, the above reduction in gradient implies a shot-in pressure reduction of about 5 MPa. Equation (1) shows that this corresponds to a 10°C average cooling of the rocks near the well for a hard host rock. Using the code ROCMAS (Noorishad et al., 1984), a hypothetical 2D (xy) model of the reservoir was constructed to study this problem. Figure (1) shows sketch of the geometry and the initial and boundary data. As shown, the model contains a fracture that spans the geometry. In the field experiments, the wells are pumped at constant rates until well pressure stabilizes and then the rate is increased by a constant amount and the procedure continues for a period of a day or more, during which one or two hydrofracing episodes are observed. A realistic simulation of the experiment is not possible and the purpose of the work is to perform a crude scoping investigation. In our attempt coupled steady state hydromechanical (HM) snapshots of of the system response, at each hour, to constant injection pressures of $P = (27+1.6t_n)$MPa, is coupled to the transient thermal analysis at cumulative time t_n. The approximation is justified because of the large difference between the fluid flow and heat flow time constants. This simplification and the overall modeling simplificaions make the analysis a scoping one suited mainly for phenomenological investigations. The fracture in the model was assumed to be closed initially by assuming that it has a very small aperture (10^{-7}m). Pressurization of the reservoir opens up the fracture elastically while it still sustains compressive stresses. This increase in the aperture allows further penetration of the pressure front until the fracture goes into a tension state and hydrofrac takes place. In the simulations, the occurrence of hydrofrac is marked by instability of the system in the solution. Presence of thermal stresses accelerates this phenomenon. Figure (2) exhibits such behavior which are the results of an isothermal HM calculation and a THM calculation of the model. As can be observed in the figure, the system becomes unstable at an injection pressure close to one order of magnitude less than that of isothermal injection calculations. Figure (3) depicts the advancement of the thermal front in the fracture and Figure (4) displays the calculated TH and THM pressure distributions in the fracture as they separates from each other with the advancement of time.

Conclusion

A hypothetical THM modeling of a cold water flooding experiment of an oil reservoir is attempted. Preliminary calculations with this model shows that hydrofrac with thermal effect occurs an order of magnitude earlier in time than the case where thermal effects are ignored.

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Stephans, G., B. Voight, Hydraulic Fracturing Theory for Conditions of Thermal Stress, *Int. J. Rock Mech. Min. Sci.*, B. Gesmoch, Abstr., 19, 279-284, 1982.

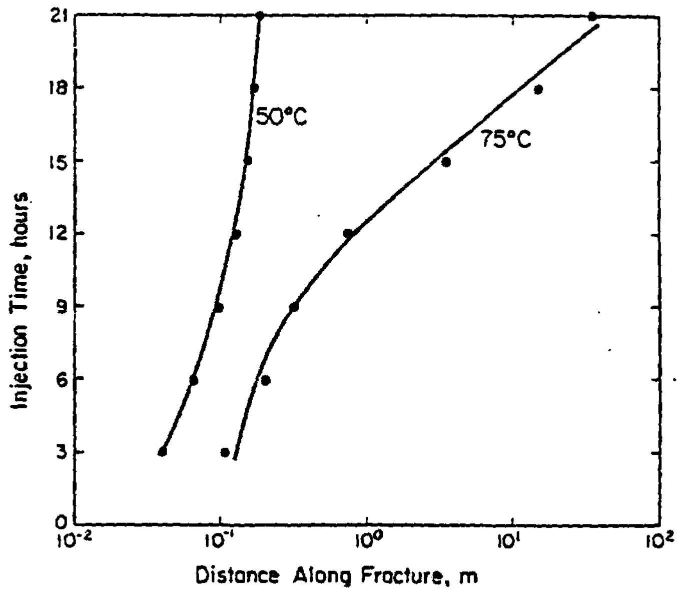

Fig. 3. Thermal front advancement in the fracture.

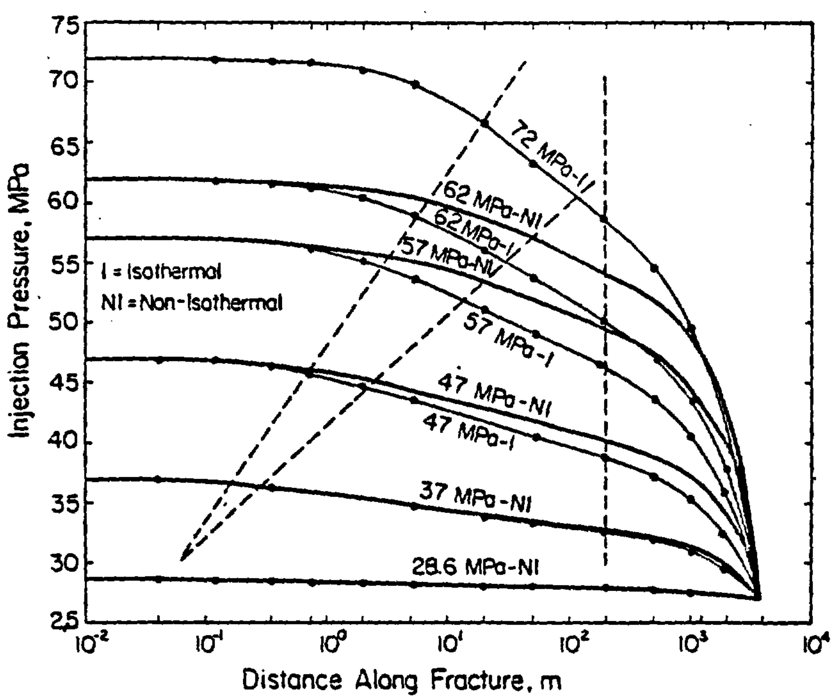

Fig. 4. Pressure profile in the fracture for isothermal and nonisothermal injection episodes.

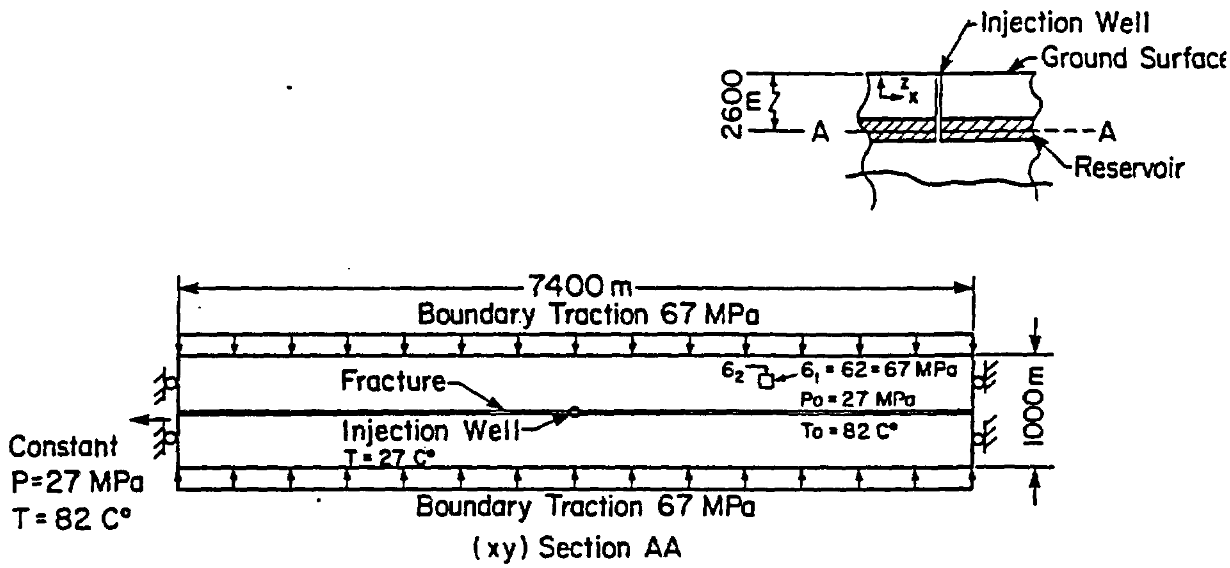

Fig. 1. Schematic geometry of the model and initial and boundary data.

Table 1.
Data Used for Nonisothermal Fluid Injection into Fractured Rocks

Material	Property	Value
Rock	mass density, ρs	$2.5 \times 10^3 Kg/m^3$
	porosity, ϕ	2.0×10^{-1}
	Young's modulus, E_s	50.0 GPa
	Poisson ratio, ν_s	0.25
	solid thermal expansion coefficient, γ	$8.0 \times 10^{-6} C^{\circ -1}$
	specific heat, C_{vs}	2.1×10^{-1} KJ/Kg C°
	thermal conductivity, K_M	7.65×10^{-4} KJ/ms C°
	permeability, k	$2.5 \times 10^{-13} m^2$
	Biots storativity constant, $\frac{1}{M}$	5.0 GPa
	Biots coupling coefficient, α	1.0
Fracture	initial aperture, 2b	10^{-7}m
	Biot storativity constant, $\frac{1}{M}$	1.0 GPa
	initial normal stiffness, k_n	100 GPa
	initial stiffness, k_s	10 GPa
	friction angle, ψ	30°
	cohesion, C	0.0
	porosity, ϕ	1.0

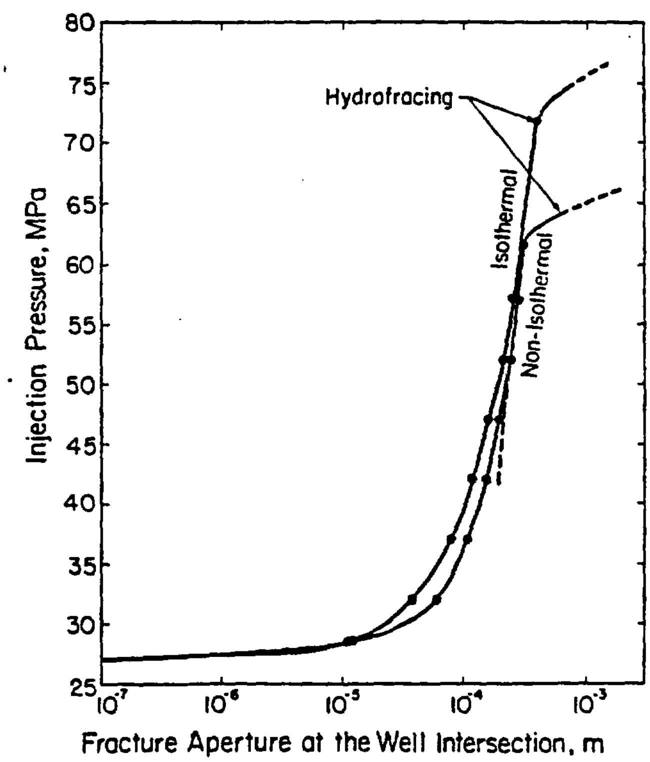

Fig. 2. Variation of fracture aperture in response to pressurization.

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NUMERICAL MODELING OF THE GROUND-WATER FLOW SYSTEM AT THE LOCATION, HANFORD SITE, WASHINGTON

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) has identified the Reference Repository Location (RRL) at the Hanford Site, Washington, as one of nine potentially acceptable sites for a mined geologic repository for spent nuclear fuel and high-level radioactive waste. This report will provide the NRC staff with assessments of groundwater modeling studies that have been performed to date of the area in and around the RRL. In this report the geologic and hydrologic setting are characterized as a framework for evaluating hydrogeologic conceptual models of the flow system(s) at the Hanford Site.

2.0 REGIONAL GEOLOGY

2.1 LOCATION

The RRL is in DOE's Hanford Reservation near Richland, Washington. The RRL is in the central portion of the Cold Creek Syncline within the Pasco Basin, a structural and topographic basin located within the Columbia Plateau (Figure 1).

Major surface features of significance in the area include:

The Columbia River, Umtanum Ridge, Gable Butte, and Gable Mountain to the north;

Yakima Ridge to the west;

Rattlesnake Mountains to the south;

The Columbia River to the east and Yakima River to the south-east (Figure 2).

2.2 GENERAL GEOLOGY

The Columbia Plateau coincides with the distribution of Miocene flood basalts of the Columbia River Basalt Group. The Plateau is a large structural and topographic depression, with its low point near the location of the RRL. The maximum thickness of the Columbia River Basalt Group, including its interbedded sediments, is approximately 5,000 meters (Mitchell and Bergstrom, 1983). The flood basalts, underlain by metamorphosed sedimentary and volcanic units, were erupted from a series of north-northwest-trending linear vents (e.g., Waters, 1961). Individual flows range in thickness

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from a few centimeters to approximately 100 meters, with most flowsbetween 20 and 40 meters thick. The basic disposal concept for the Hanford Site is that the HLW would be placed in a repository that would be excavated within the dense interior of one of the Columbia River Basalt flows.

The Columbia River Basalt Group has been divided inot 5 formations and 19 members (Swanson and others, 1979; Camp, 1981) (Figure 3). The areal distribution of the Columbia River Basalt Group is shown on Figure 4. Because the Imnaha and Picture Gorge Basalts do not crop out in the area of interest and because they are well below the repository level, they will not be discussed further.

The Grande Ronde Basalt, extruded 17 to 15.6 mybp, is the most areally extensive and volminous of the Columbia River Basalt Group. The known thickness rages from tens of meters along the Plateau margins to over 1,000 meters in the Pasco Basin. The obly regional (i.e., at the scale of the Plateau) subdivisions are four magnetostartigraphic units, indicated on Figure 3. However, at a subregional scale, there are a number of "through-running" flows that extend over areas of at least 250 square kilometers (Long and Landon, 1981). Four of these through-running flows within the Pasco Basin are currently being considered as candidate horizons for the geologic repository (see Section 3.2.1, below).

The Grande Ronde Basalt is overlain by the Wanapum Basalt, extruded 14 to 13.5 mybp. The Wanapum Basalt has been subdivided into four recognized members regionally (Figure 3).

The youngest formation of the Columbia River Basalt Group is the Saddle Mountains Basalt, which has been divided into at least 10 members (Figure 3). The extrusion period, 13.5 to 6 mybp, was characterized by declining volcanism, the deposition of interbedded sediments (Ellensburg Formation), folding and canyon cutting.

The stratigraphy of the suprabasalt sedimentary formations is shown in Figure 5. The Ellensburg Formation is primarily weakly lithified clastic and volcanoclastic sediments derived from the Cascades. Units of the Ellensburg Formation are interbedded with and overlie Wanapum and Saddle Mountains Basalts. Fluvial deposits of the Mio-Pliocene Ringold Formation overlie the Columbia River Basalt Group. Pleistocene and Holocene deposits of alluvium, colluvium, eolian loess overlie Ringold sediments.

The Cold Creek Snycline is one of a series of eastward-trending folds that comprise the Yakima Fold Belt. The anticlines in the fold belt are typically narrow, linear and somewhat assymetrical; the synclines are typically broader than the anticlines. The ridges, buttes and mountains listed in Section 2.1 are the surface expression of the anticlines adjacent to the Cold Creek Syncline. Major faults are generally associated with the anticlines. Fault plane solutions for shallow swarm earthquakes suggest that the faults are reverse faults parallel to the axial planes of the anticlines. A generalized structure cross-section is presented in Figure 6.

Internal structures that formed during the emplacement and subsequent cooling of the lava are termed "intraflow structures" (DOE, 1984). Particularly important are the cooling joints that produce polygonal columns are hackly blocks. In general, three major intraflow structures are regognized: Vesicular or brecciated flow tops; irregular and discontinuously jointed entablature near the middle of a flow; and more regularly jointed colonnade near the bottom of the flow (Figure 7). The bottom of a flow is typically a thin (approximately 0.5 meter) zone of fractured, glassy basalt. The three major intraflow structures may vary in thickness, be absent from a given flow, or occur repeatedly within a single flow. The orientation of joints and fractures is typically nearly vertical, but occasionally approach horizontal. Radiating Columnar joints have been observed in surface exposures of basalt flows. Limited core data indicates that there is secondary mineralization in fractures.

3.0 GEOLOGY OF THE PASCO BASIN AND RRL

3.1 PHYSIOGRAPHY AND GEOMORPHOLOGY

The RRL is located in the west-central portion of the Pasco Basin, near the boundary between the Yakima Folds and the Central Plains morphologic sections of the Columbia Intermontaine province. Shown in Figure 8 are the major landform systems of the Pasco Basin. The basin-and-valley terrain in which the RRL is located consists of low-relief, sediment-filled portions of the Central Plains and synclinal valleys of the Yakima Folds.

Four geomorphic units are defined within the RRL (Figure 9). The Umtanum Ridge Bar and the 200 Areas Bar are gravel bars formed during catastrophic Pleistocene flooding. The Central Hanford Sand Plain was formed by the deposition of finer grained sediments on the lee of the Umtanum Ridge Bar. The predominant materials are granules of fine grained sand and silt. Holocene alluvium along Cold Creek is superimposed on the western portion of the Central Hanford Sand Plain.

3.2 STRATIGRAPHY

The stratigraphic units present in the Pasco Basin are illustrated in Figure 10. The Columbia River Basalt Group is represented by the Grande Ronde, Wanapum and Saddle Mountains Basalts. Interbedded Miocene sediments are referred to the Ellensburg Formation. The basalt sequence is overlain by semiconsolidated to unconsolidated sediments of the Ringold and Hanford Formations and by unconsolidated surficial deposits.

3.2.1 Grande Ronde Basalt

In the Pasco Basin the Grande Ronde basalt comprises at least 56 flows. The basalt is typically fine grained a aphyric or sparsely microphyric with few consistent textural differences. Flows are correlated on the basis of magnetostratigraphy and chemical composition. Two informal "through-runner" units identified in the basin are termed the Schwana and Sentinel Bluffs sequences. Four flows in the Grande Ronde have been identified as potential candidate horizons: the Umtanum Flow of the Schwana Sequence and the McCoy Canyon, Cohassett and Rocky Coulee Flows of the Sentinel Bluffs Sequence. Figure 11 is a generalized geologic section through the RRL illustrating the subsurface distribution of the major stratigraphic units of interest.

3.2.1.1 Umtanum flow

The Umtanum flow is the lowermost candidate horizon; the top of the flow lies at approximately 1059 to 1135 meters below ground surface in the RRL. The Umtanum appears to be thicker to the northwest and southeast of the RRL than it is in the center of the Cold Creek syncline area. In the RRL, the Umtanum varies in thickness, ranging from about 60 to about 70 meters (figure 12). The dense interior of the flow also varies in thickness (Figure 13), but appears to be everywhere greater than about 24 meters thick, based on current borehole informaton. Within the RRL the brecciated flow top appear to be quite thick and highly variable, apparently similar to the exposed section at Emerson Nipple, based particularly on the results from Borehole RRL-2.

3.2.1.2 McCoy Canyon flow

The McCoy Canyon flow is the lowermost of the Sentinelle Bluffs flows; top of the flow lies from approximately 1025 to 1090 meters below ground surface. The flow generally thins from northwest to southeast, ranging from about 45 meters to about 34 meters thick across the RRL (Figure 14). Multitiered intraflow entablature and colonnade structures give a total dense interior of about 30 meters across the RRL, but the dense interior has sporadic vesicular zones that reduce the potentially available dense interior volume for a repository.

3.2.1.3 Cohassett flow

The Cohassett flow is stratigraphically near the middle of the Sentinel Bluffs sequence; top of the flow lies 896 to 943 meters below the ground surface. The flow is thickest in the central Pasco Basin, is relatively constant near 80 meters in thickness across the RRL, and thins to the southeast (Figure 15). Although the Cohassett flow is the thickest candidate flow within the RRL, the multitiered entablature/colonnade structures cannot be correlated from borehole to borehole, and there is a laterally continuous vesicular zone of

3 to 8.5 meters thickness about 30 meters from the top of the flow that divides the dense interior into an upper and a lower zone (Figure 16 and 17). The dense interior below the vesicular zone ranges from 36 to 46 meters in thickness.

3.2.1.4 Rocky Coulee flow

The Rocky Coulee flow is the uppermost candidate horizon, occuring in the upper third of the Sentinel Bluffs Sequence. The Rocky Coulee flow thins from about 55 meters thick to about 43 meters thick from west to east across the RRL (Figure 18). The dense interior of the flow ranges in thickness from about 27 to about 47 meters, thinning significantly to the northwest across the RRL as a result of vesiculation beneath the flow top (Figure 19).

3.2.2 Wanapum Basalt

Within the Pasco Basin the Wanapum Basalt consists of three members: Frenchmen Springs, Roza and Priest Rapids. The Vantage interbed separates the formation from the undelying Grande Ronde; the Mabton interbed separates the formation from the overlying Saddle Mountains Basalt. The total thickness of the Wanapum Basalt in the RRl is about 335 meters.

3.2.2.1 Frenchman Springs Member

The Frenchman Springs is the oldest Wanapum member and consist of 7 to 9 flows or lobes within the Cold Creek syncline. The flows or flow lobes cannot be consistently correlated from hole to hole. In the RRL it is about 215 meters thick, but thins abruptly onto the Rattlesnake Mountain structure south of the Cold Creek Syncline.

3.2.2.2 Roza Member

The Roza Member is comprised of one to two flows or flow lobes in the RRL, where it is about 53 meters thick. The Roza thins across Rattlesnake Mountain and the Umtanum Ridge-Gable Mountain structure.

3.2.2.3 Priest Rapids Member

The Priest Rapids Member comprises the distinct Rosalia and Lola flows, which appear to be present throughout the Cold Creek snycline. The Priest Rapids is about 46 meters thick in the RRL, thinning across the Rattlesnake Mountain and Umtanum Ridge-Gable Mountain structures.

3.2.3 Saddle Mountains Basalt

In the RRL the Saddle Mountains Basalt is represented by four members: Umatilla, Esquatzel, Pomona, and Elephant Mountain Members.

3.2.3.1 Umatilla Member

The Umatilla Member comprises the Sillusi and Umatilla flows, which together total about 70 meters thickness in the RRL. The member has a wedge-shaped geometry, thinning to the north and pinching out north of the Umtanum Ridge-Gable Mountain structure and east of the Cold Creek syncline.

3.2.3.2 Esquatzel Member

The Esquatzel Member consists of one to two flows or flow lobes, locally separated by a vitric tuff; total thickness in the RRL is about 70 meters. The member is confined to the southern and eastern parts of the Pasco Basin, pinching out on the Rattlesnake Mountain and Umtanum Ridge-Gable Mountain Structures.

3.2.3.3 Pomona Member

Although one to two flows are present in the Pasco Basin, within the RRL the Pomona member is represented by only one flow, approximately 80 meters thick. As with the other members of the Saddle Mountains Basalt, the Pomona thins over the anticlinal structures that bound the Cold Creek syncline.

3.2.3.4 Elephant Mountain Member

Within the Pasco Basin the Elephant Mountain Member consists of two flows, but in the RRL only the Elephant Mountain flow is present. The flow is about 25 meters thick in the RRL. The member is thickest in the eastern part of the Cold Creek syncline, thinning both toward the Rattlesnake Mountain anticline and to the northwest within the syncline. The Elephant Mountain defines the top-of-basalt over most of the Cold Creek syncline on the Hanford reservation.

3.2.4 Ellensburg Formation

The Ellensburg Formation is a Miocene fluvial sequence with volcanoclastic sediments, interbedded primarily with the Wanapum and Saddle Mountains Basalts. There are two distinct lithologies, representing distinct provenance: volcanoclastic sediments deposited as ashfalls and as fluvial sediments derived from the Cascade Range and clastic plutonic and metamorphic sediments deposited by westward flowing fluvial systems draining the Rocky Mountains. Nomenclature of the Ellensburg Formation is given in Figure 20.

3.2.5 Suprabasalt Stratigraphy

The Columbia River Basalt Group (including the interbedded Ellensburg Formation) is overlain across the Pasco Basin by Miocene the Holocene sediments. The suprabasalt stratigraphy is summarized in Figure 21

3.2.5.1 Ringold Formation

The Columbia River Basalt Group (and interbedded Ellensburg Formation) are overlain over most of the Pasco Basin by the Ringold Formation, dominantly fluvial sediments with some lacustrine and fanglomerate facies (Figure 22). Within the RRL the Ringold Formation is 105 to 215 meters thick.

Within the RRL the Ringold unconformably overlies the Elephant Mountain Member of the Saddle Mountains Basalt. The basal Ringold represents a fining-upward fluvial cycle, capped by a paleosol formed on the fine grained uppermost materials of the cycle. Laminated silt and clay of the lower Ringold disconformably overlie the basal Ringold paleosol. Up to several meters of local erosional relief separate the sandy gravels (with some intercalated sand and mud) of the middle Ringold from the lower Ringold. The upper Ringold, bedded and laminated sand and mud, conformably overlies the middle Ringold. Shown in Figure 23 is an incised paleochannel in the Ringold across the RRL, illustrating that the variation in thickness of the formation is probably due primarily to erosion.

3.2.5.2 Plio-Pleistocene Unit

The Ringold Formation is unconformably overlain across the RRL by a Plio-Pleistocene unit that consists of a fanglomerate and a paleosol. The fanglomerate probably represents mass wastage of material from the surrounding ridges. The fanglomerate is thickest (up to 24 meters) beneath the Cold Creek Valley and thins and fines to the northeast, where it grades into a paleosol formed after the incision of the Ringold.

3.2.5.3 Hanford Formation

Catastrophic late Pleistocene floods deposited coarse-grained (Pasco Gravels) and fine-grained (Touchet Beds) facies sediments across much of the Pasco Basin. The gravels are present at the Umtanum Ridge Bar and itrs extension, the 200 Areas Bar (see Section 3.1). The slackwater flood facies were deposited away from the gravel bars and are most common in the southern and western parts of the RRL and beneath the gravels of the 200 Areas Bar.

3.3 Structure

The Pasco Basin is located along the eastern margin of the Yakima Fold Belt. Structures in the area are characterized by long, narrow anticlines and broad snyclines trending generally eastward from the western part of the Columbia Plateau to the Pasco Basin, where they die out (Figure 24). Most of the major faulting is associated with the anticlinal folds. Most of the faults are reverse faults (including thrust faults) that are parallel or subparallel to the axial planes of the anticlines; it is likely that these faults formed during the deformation that resulted in the folding. Structural relief on the anticlinal basalt ridges is up to approximately 1200 meters, and the wavelengths of the folds are typically 5 to 10 kilometers. Anticlines are typically concentric, gentle to tight and upright to inclined. The tighter, inclined folds are usually asymmetric, with the steep limb up to vertical or even overturned. The asymmetric folds usually verge to the north.

Significant characteristics of major structures in the Pasco Basin are summarized below.

3.3.1 Wahluke Snycline

The Wahluke Syncline is broad (up to 13 Kilometers), Asymmetric trough lying between the Saddle Mountains structure and the Umtanum Ridge-Gable Mountain structure; the southern limb is steeper than the northern limb. In the lowest part of the syncline, the top-of-basalt is approximately 61 meters below mean sea level.

3.3.2 Umtanum Ridge-Gable Mountain Structure

The eastward-trending structure extends 110 kilometers from Ellensburg, Washington, to Gable Mountain. Within the Pasco Basin, the anticline is flanked by the Wahluke syncline to the north and the Cold Creek syncline to the south. Maximum structural relief is approximately 880 meters. The eastern Umtanum Ridge segment is a complex structure: an asymmetric, overturned, eastward-plunging anticline whose crestal surface splinters into several en echelon folds along trend. Structural relief and complexity decrease toward the center of the Pasco Basin, where the structure appears to be an asymmetric, eastward-plunging anticline with a steeply dipping north limb. Thrust faulting observed in the Priest Rapids Dam area to the west is believed to die out as structural relief decrease to the east.

Gable Mountain and Gable Butte are surface expressions of en echelon, eastward-trending, second-order anticlines and synclines that are a structural segment of the large, first-order northward-verging anticline. Three significant eastward-trending reverse faults and one north-trending normal fault has been described on Gable Mountain. It is likely that these tear faults are associated with second-order folds, and therefore have likely lengths of about 1.6 kilometers or less. Fractures in fluvioglacial sediments are continuous with reverse faults in the underlying basalts.

3.3.3 Cold Creek Syncline

The Cold Creek syncline is a broad, open, asymetric, eastward-plunging, almost flat-bottomed syncline that occupies the structural low between the Umtanum Ridge-Gable Mountain structure and the Yakima Ridge structure.

3.3.4 Yakima Ridge Structure

A group of topographic ridges are the surface expression of the plunging anticlines, monoclines and faults that comprise the Yakima Ridge Structure. Within the Pasco Basin, the dominant structure is a northward-verging asymmetric, southeastward-plunging anticline (Cairn Hope Peak anticline), whose southern flank includes two monoclines, one of which may extend into a major fault zone of uncertain geometry (Silver Dollar fault). The major structure plunges into the basin as a series of second-order folds and associated, probably reverse faults. There is a buried structural high along the trend of the Yakima Ridge structure to the southeast of the surface expressions. A saddle or shallow syncline with possible faulting are believed to separate the two segments.

3.3.5 Benson Ranch Syncline

The shallow Benson Ranch syncline lies between the Yakima Ridge and the Rattlesnake Hills structures on the western side of the Pasco Basin. The syncline plunges to the east and apparently dies out toward the Wye Barricade depression.

3.3.6 Pasco Syncline

The Pasco syncline is a broad, low amplitude depression with a sinuous trend in the southeast part of the Pasco Basin. Overall the syncline plunges to the north, dying out against the Wye Barricade depression.

3.3.7 Rattlesnake - Wallula Alignment

The Cle Elum - Wallula lineament is a 200 kilometer - long, 40 kilometer - wide deformed belt that parallels the western and southern boundaries of the Pasco Basin. Along the southwestern boundary of the basin, the Rattlesnake Hills - Rattlesnake Mountain segment is a major anticlinal structure. Geomorphic continuity along strike to Wallula Gap is considered to reflect continuity of deformation, probably as a right lateral strike slip or oblique slip fault.

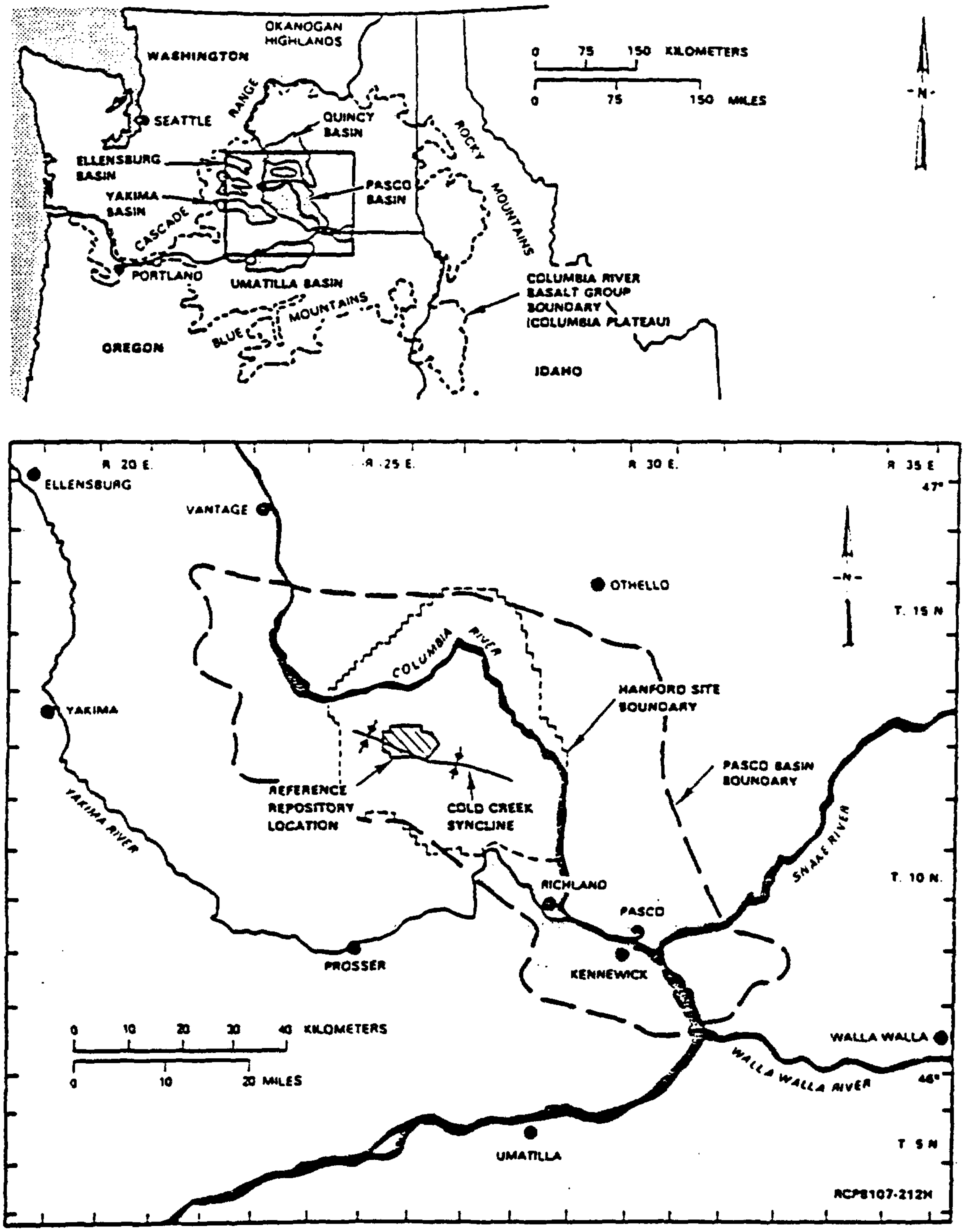

Figure 2-1. Location of the Hanford Site, southeastern Washington State.

Figure 1

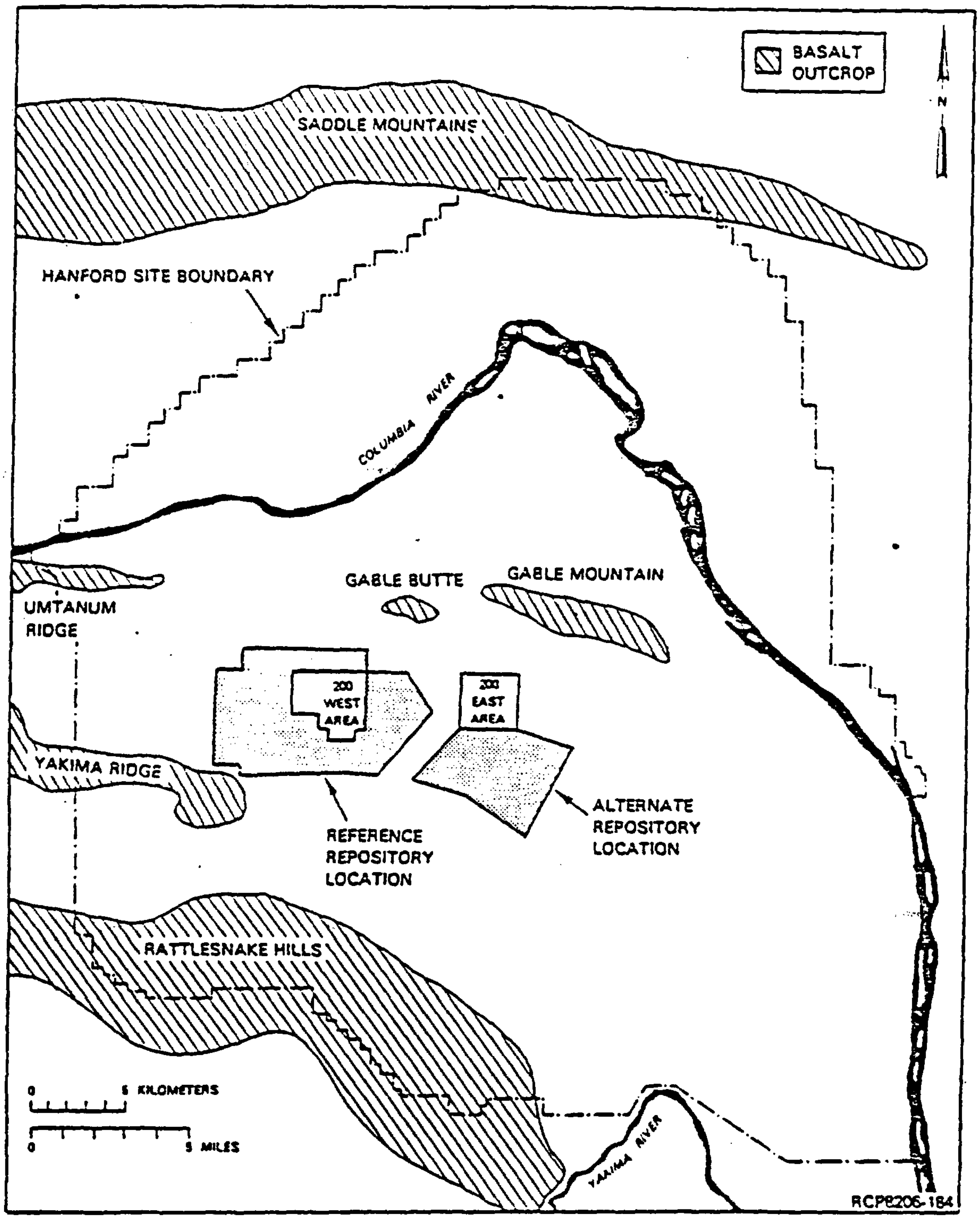

Figure-2-26. Location of the reference repository location and alternate repository location.

Figure 2

vesicular and brecciated basalt can form up to half the thickness. The flow interior consists of entablature and colonnade. The entablature is composed of jointed rock with relatively small columns (approximately 0.2- to 1.0-meter (0.7- to 3.0-foot) diameter). The orientation of columns ranges from vertical to horizontal. The colonnade consists of relatively well-formed columns (approximately 0.5- to 2-meter (1.6- to 6.5-foot) diameter) with fewer fractures than the entablature. Columns are normally upright but radiate locally and exhibit a variety of internal features. In some flows, the entablature overlies a single colonnade; in other flows, colonnade and entablature zones may be repeated in the flow interior (Long and Davidson, 1981). The basal portion of a basalt flow is usually a thin (approximately 0.5-meter (1.6-foot)) zone of fractured, glassy basalt. Spiracles (zones of fissured glassy rock) may extend a few meters (feet) into the lower portion of a flow.

Fracture logging of basalt flows indicates that fracture abundances in core samples range from approximately 1 to 40 fractures per meter (less than 1 to 12 fractures per foot) (Long and WCC, 1984, p. I-69). Most of these fractures have narrow widths (less than 0.5 millimeter (0.02 inch)) now filled with multiple generations of secondary minerals. The exact mineral distribution in fractures will differ among basalt flows in response to varying depths of burial, fracture widths, and basalt flow composition. Dominant secondary minerals are clay, zeolite, silica, and pyrite (Long and Davidson, 1981, pp. 5-38 to 5-40). The volume of unfilled fractures, particularly in the dense interior of basalt flows, is typically small, less than 0.4 volume percent.

2.1.1.1 Stratigraphy

Regional geologic maps at a scale of 1 to 250,000 define the stratigraphy and structure of the Columbia River Basalt Group that is generally coincident with the Columbia Plateau (Swanson et al., 1979a, 1981). A compilation of these maps shows a plateau-wide basalt stratigraphy. Figure 2-4 gives the stratigraphic nomenclature for the Columbia River Basalt Group of the Columbia Plateau. Basalt flows throughout the region can be correlated through a combination of chemical, paleomagnetic, and field techniques.

The Columbia River Basalt Group has been divided into 5 formations, 19 members, and 4 informal paleomagnetic subdivisions (Swanson et al., 1979b, pp. 6 and 7; Camp, 1981, pp. 669 through 678). The oldest formation (approximately 17 million years old), the Imnaha Basalt, crops out only within the extreme southeastern portion of the Columbia Plateau where it is conformably overlain by flows of the Grande Ronde Basalt. The Picture Gorge Basalt that is 15.8 to 14.6 million years old crops out only in the southwestern portion of the plateau and is considered partly equivalent in age to the Grande Ronde Basalt.

The Grande Ronde Basalt is the most areally extensive and voluminous unit of the Columbia River Basalt Group underlying most of the Columbia Plateau (Fig. 2-5). The basalt comprising this formation was extruded

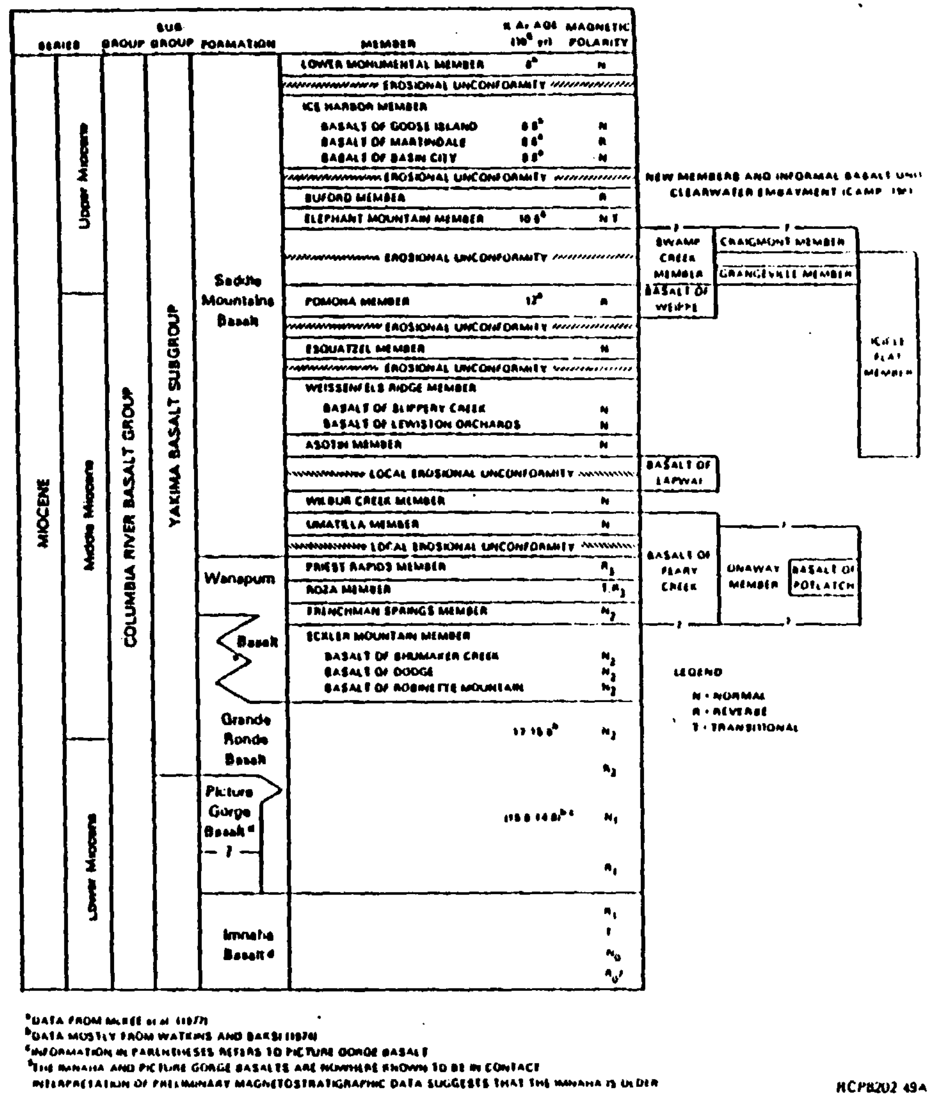

Figure 2-4. Stratigraphic nomenclature for the Columbia River Basalt Group of the Columbia Plateau (after Swanson et al., 1979b).

Figure 3

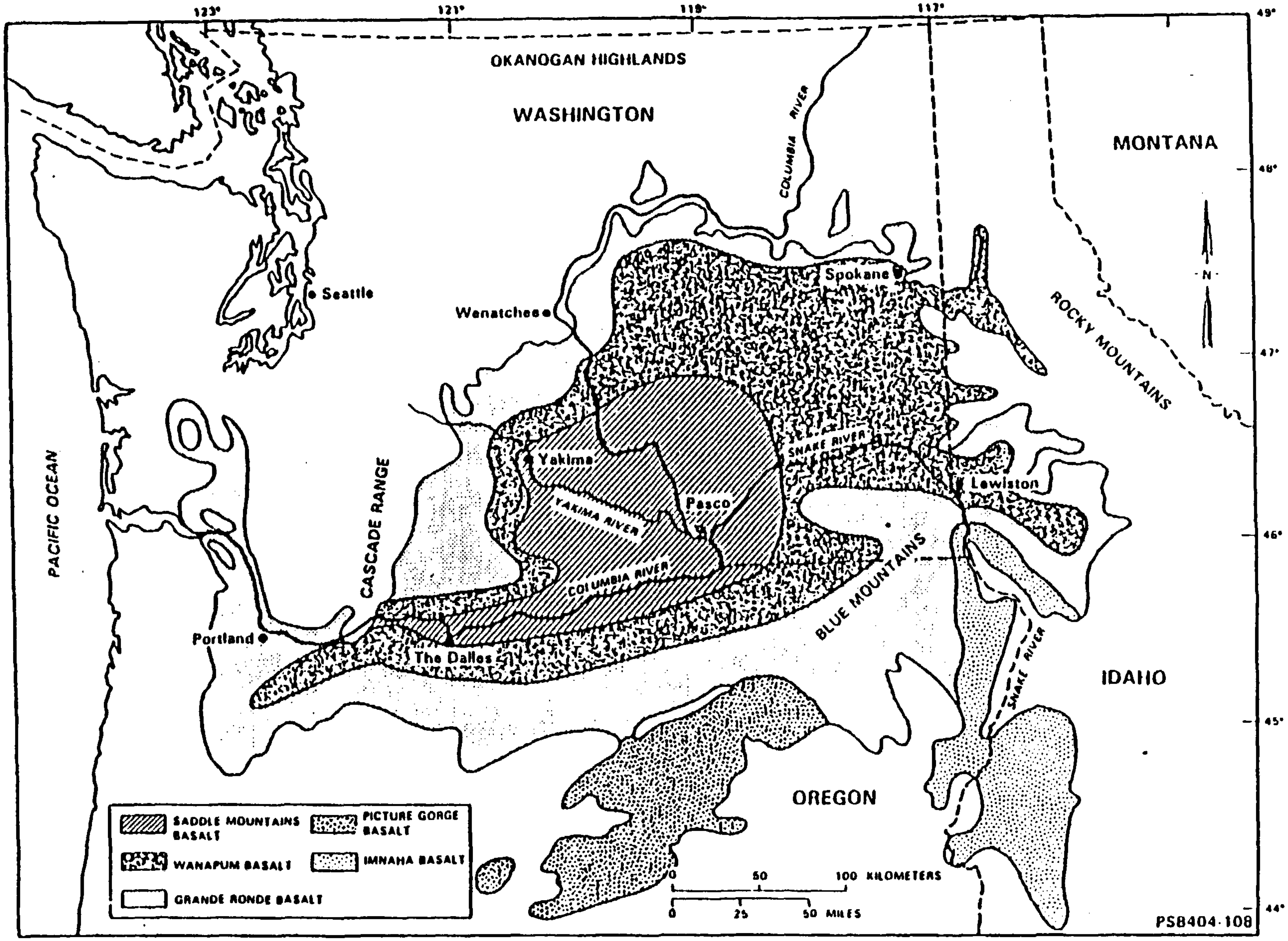

Figure 2-5. Distribution of Columbia River Basalt Group (after Wright et al., 1973).

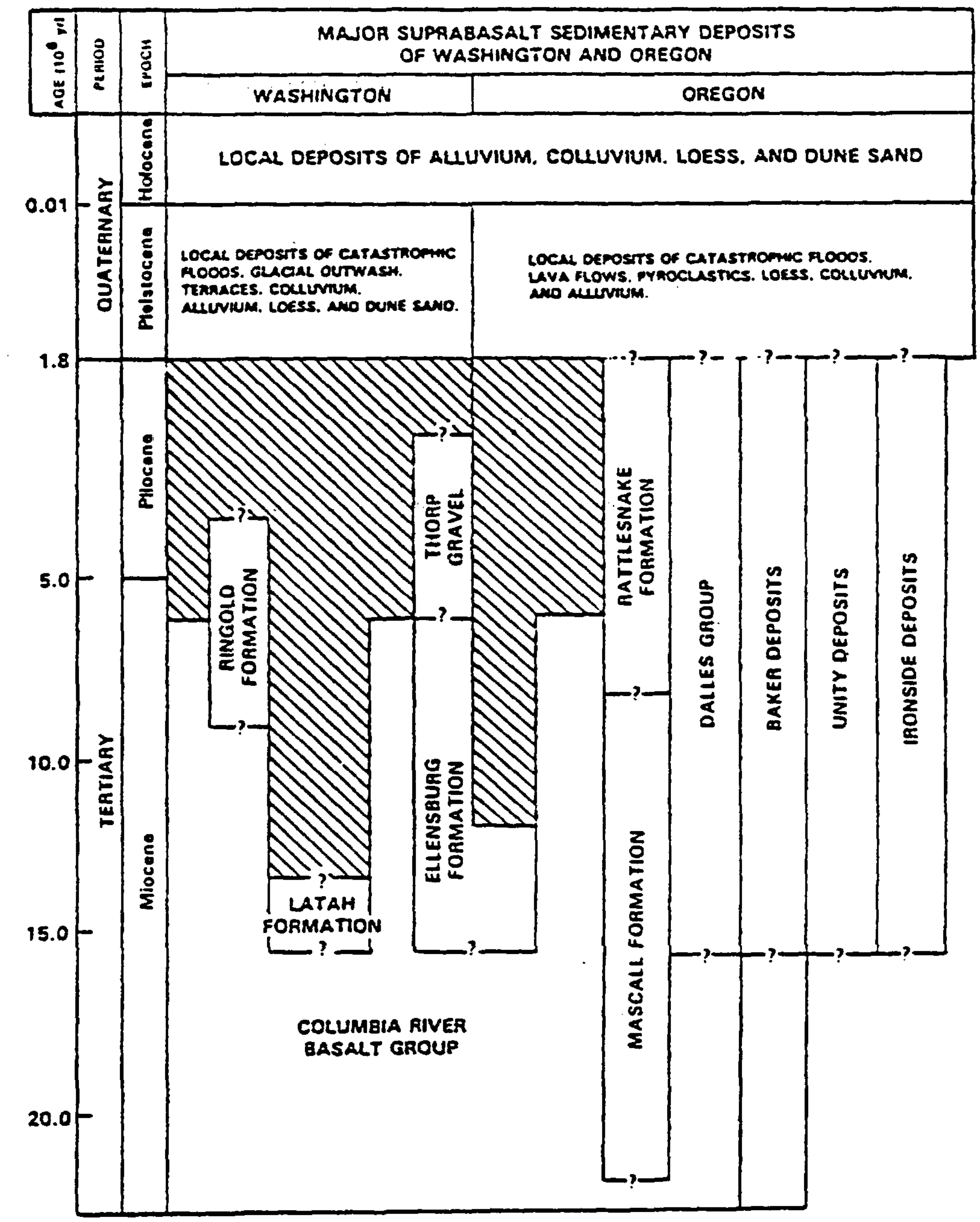

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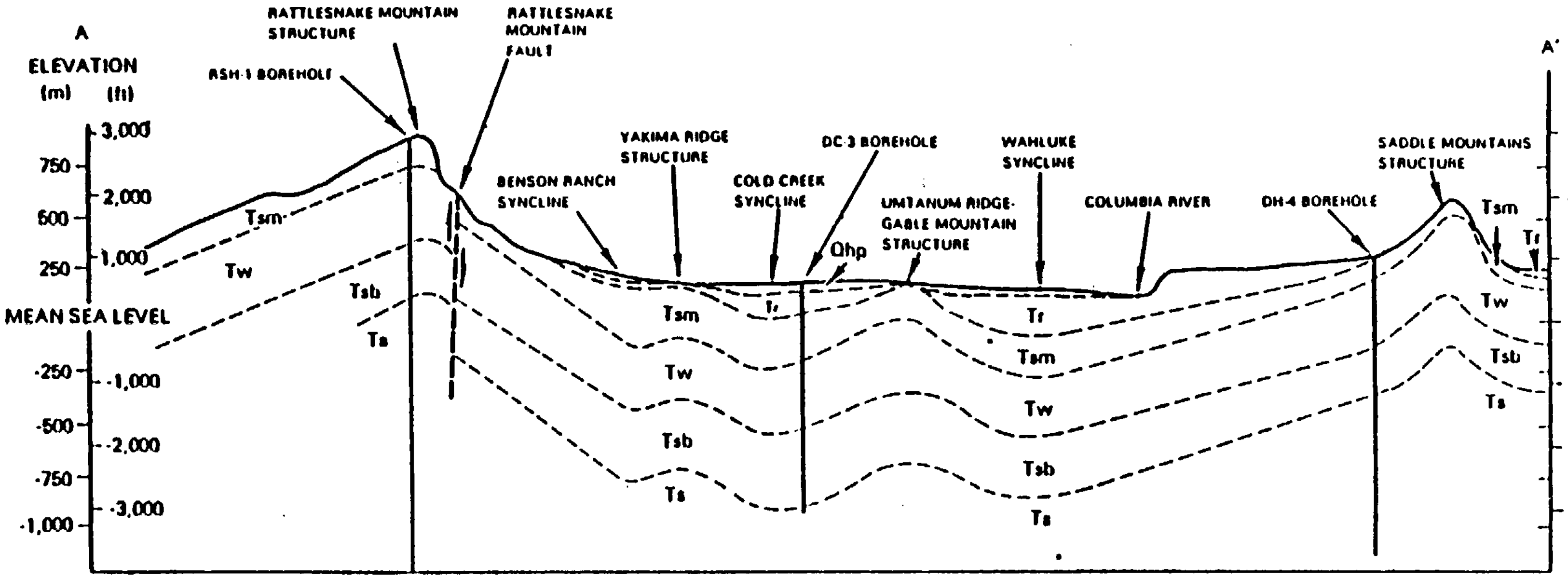
Figure 2-6. General stratigraphic relationship of suprabasalt sediments.

Figure 5



Qhp-HANFORD FORMATION-PASCO GRAVELS
Tr- RINGOLD FORMATION
Tsm-SADDLE MOUNTAINS BASALT
Tw-WANAPUM BASALT
Tsb-SENTINEL BLUFFS SEQUENCE } GRANDE RONDE
Ts-SCHWANA SEQUENCE } BASALT

0 5 10 KILOMETERS
0 5 MILES

VERTICAL EXAGGERATION = 125X

Figure 2.2 Generalized structure cross section

2-7

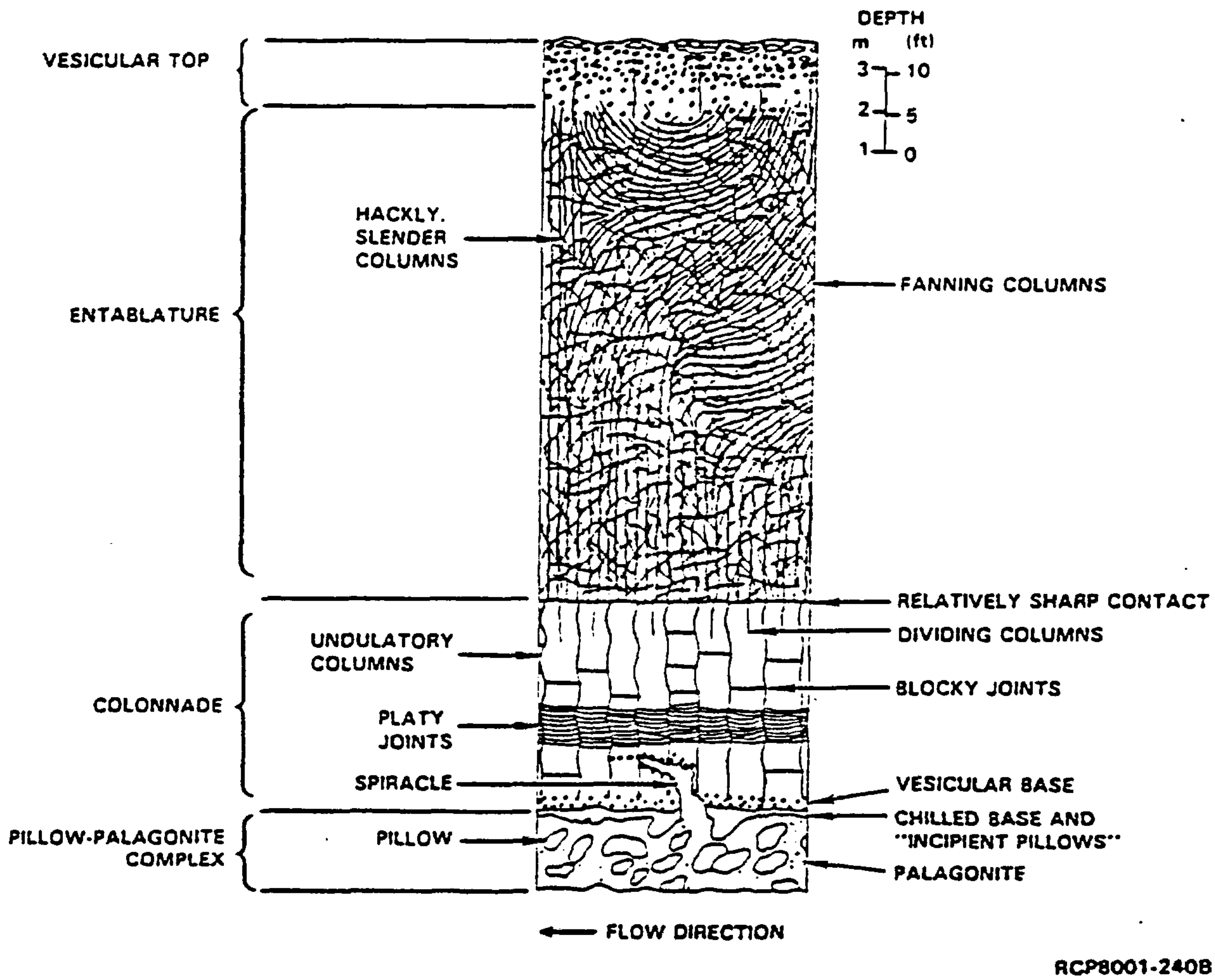


Figure 2-3. Cross section of a typical flow in the Columbia River Basalt Group illustrating, in idealized form, jointing patterns and other structures (from Swanson and Wright, 1976).

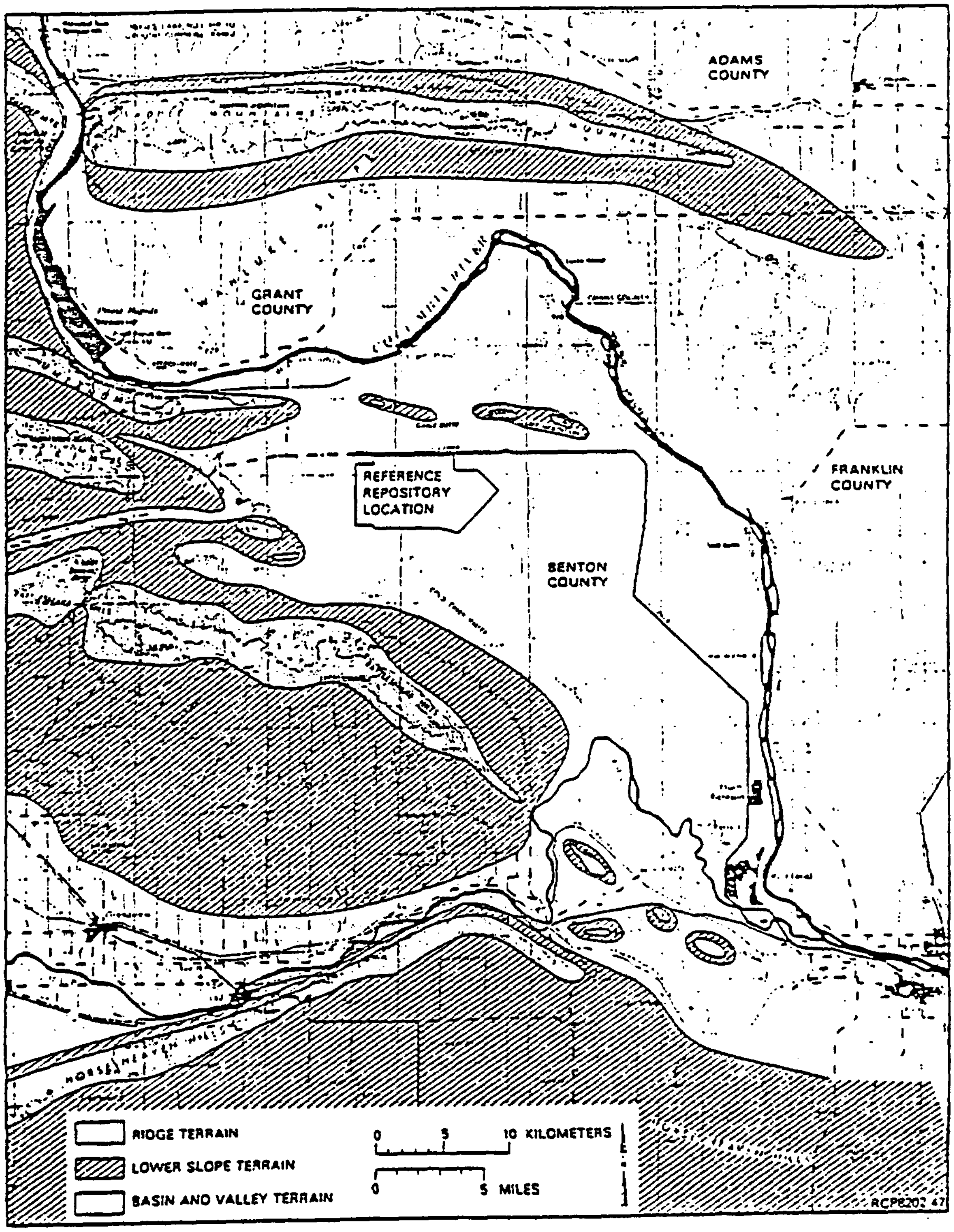


Figure 3-4. Map of major landform systems of the Pasco Basin.

Figure 8

3-7
Figure 9

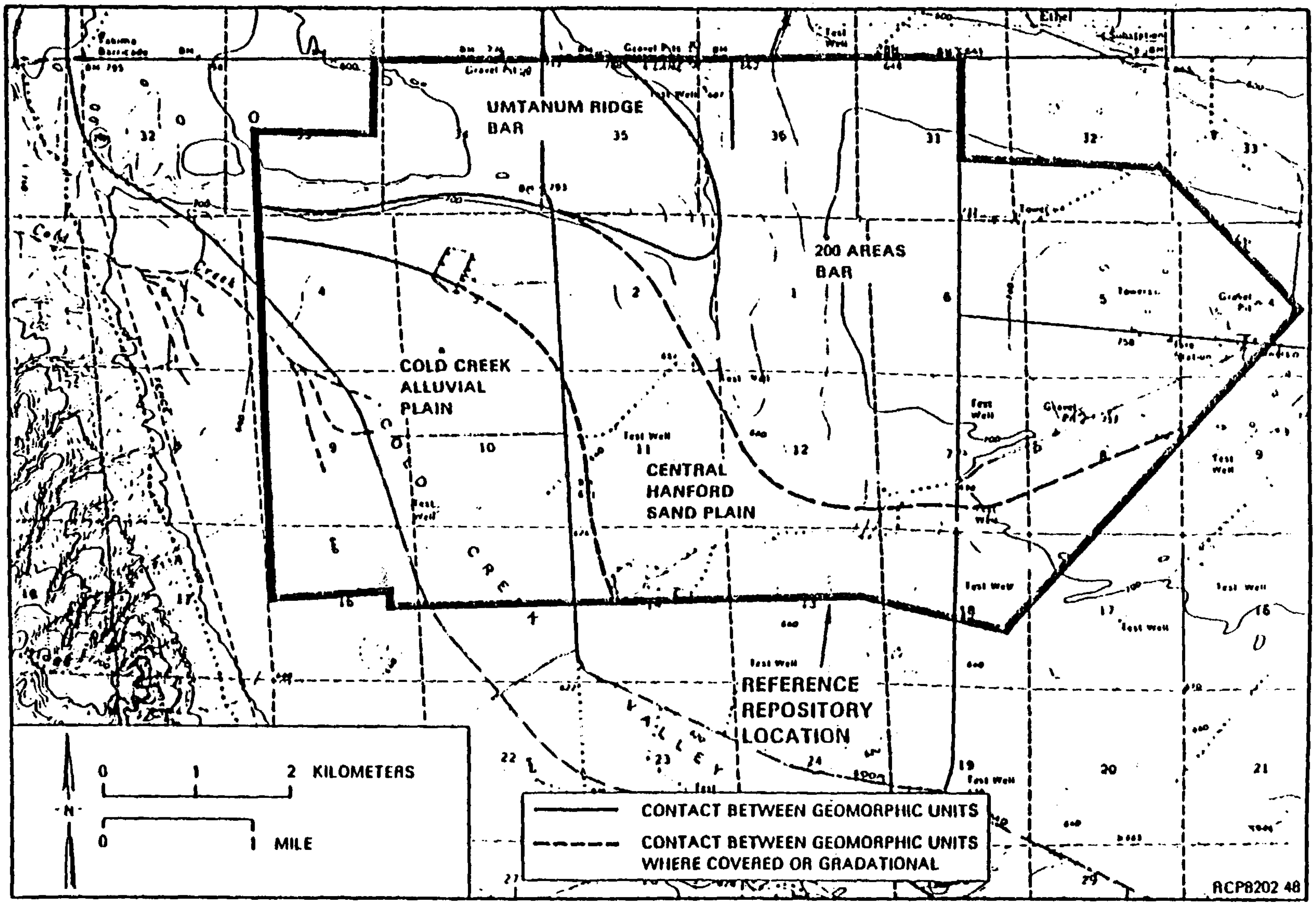


Figure 3-5. Geomorphic map of the reference repository location.

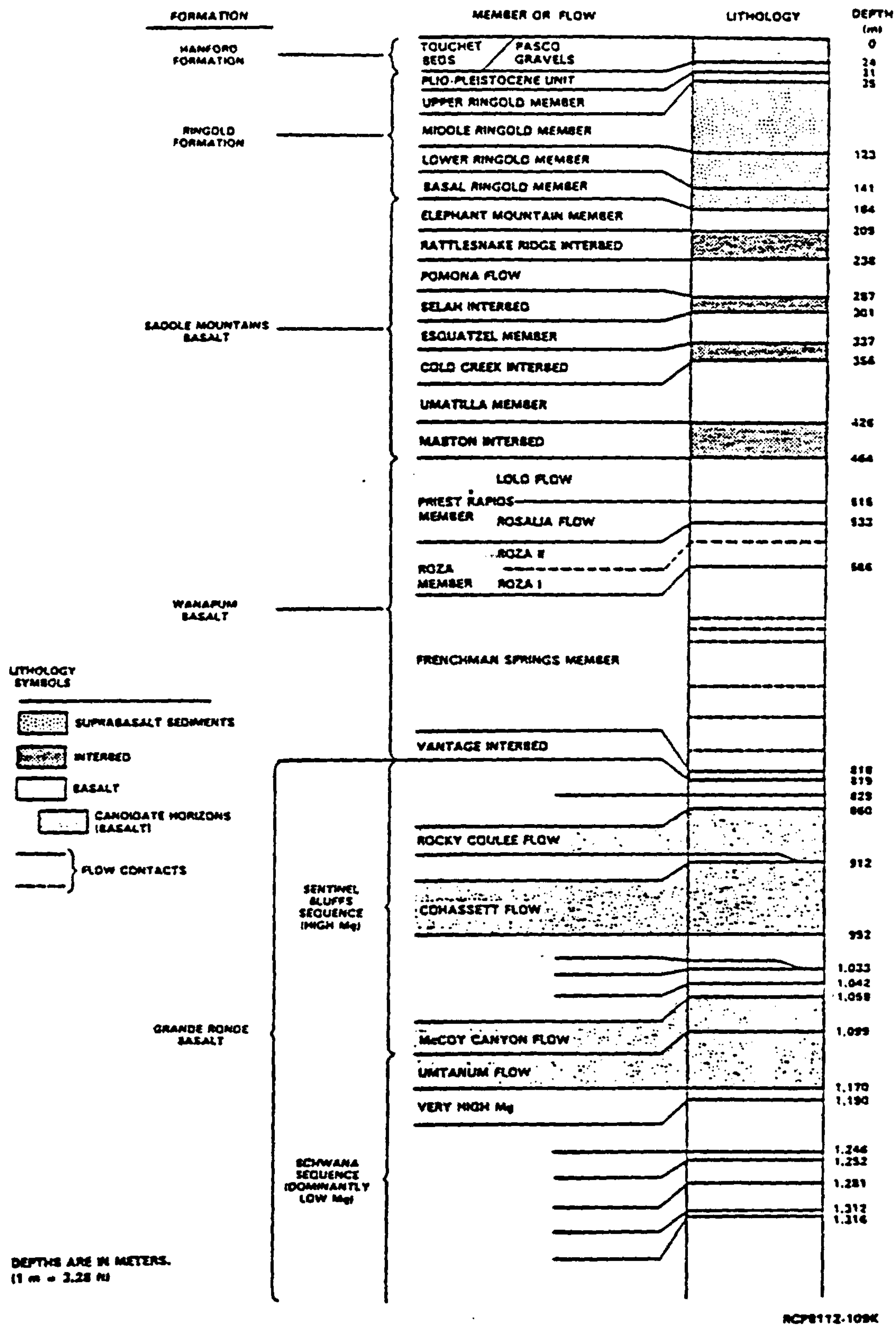


Figure 2-29. General stratigraphy of the reference repository location showing position of the candidate horizons. Depths are from borehole RRL-2.

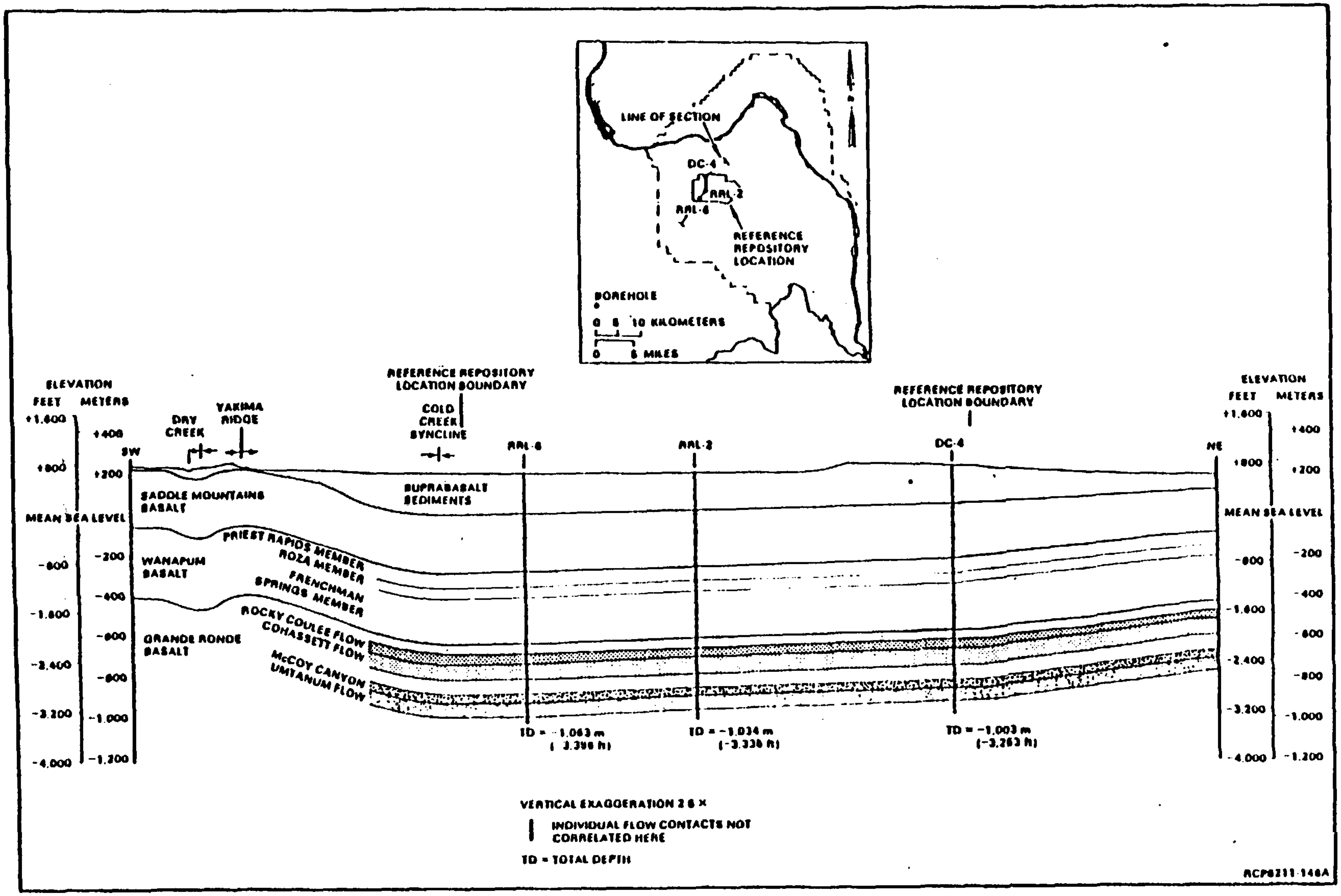


Figure 3-8. Geologic cross section through the reference repository location.

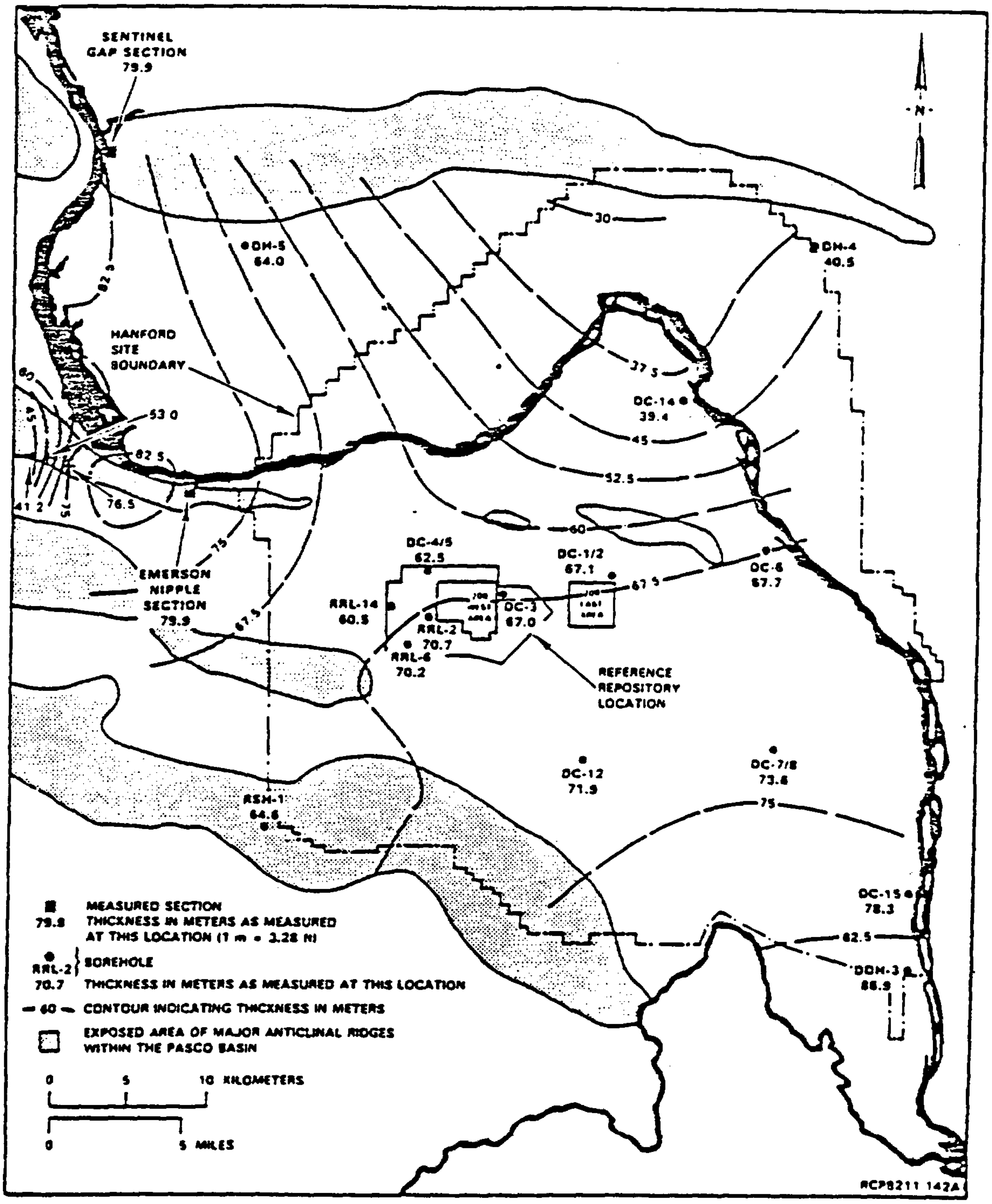


Figure 3-12. Umtanum flow isopach map.

Figure 12

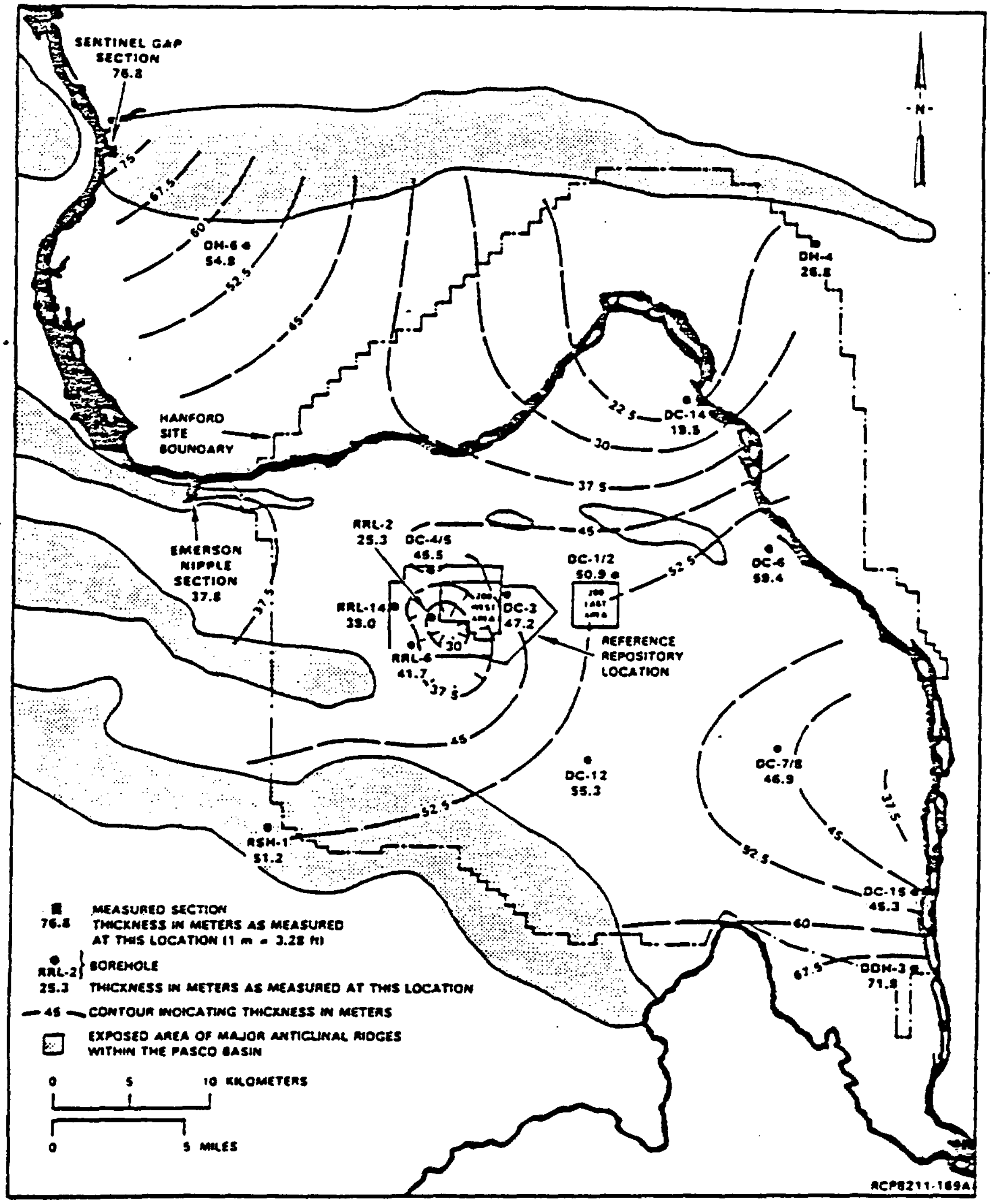


Figure 3-11. Isopach map of the dense interior of the Umtanum flow.

Figure 13

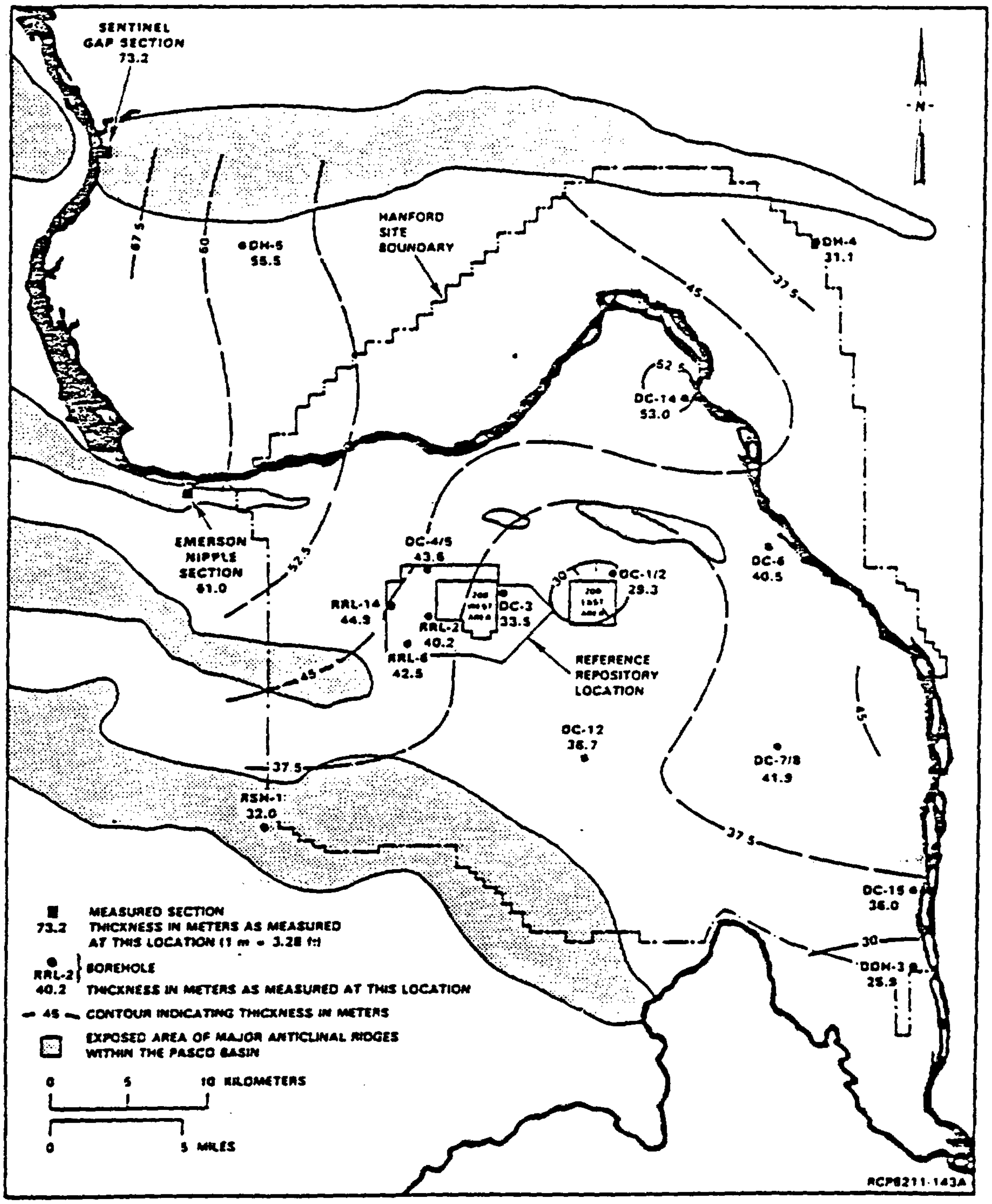


Figure 3-13. McCoy Canyon flow isopach map.

Figure 14

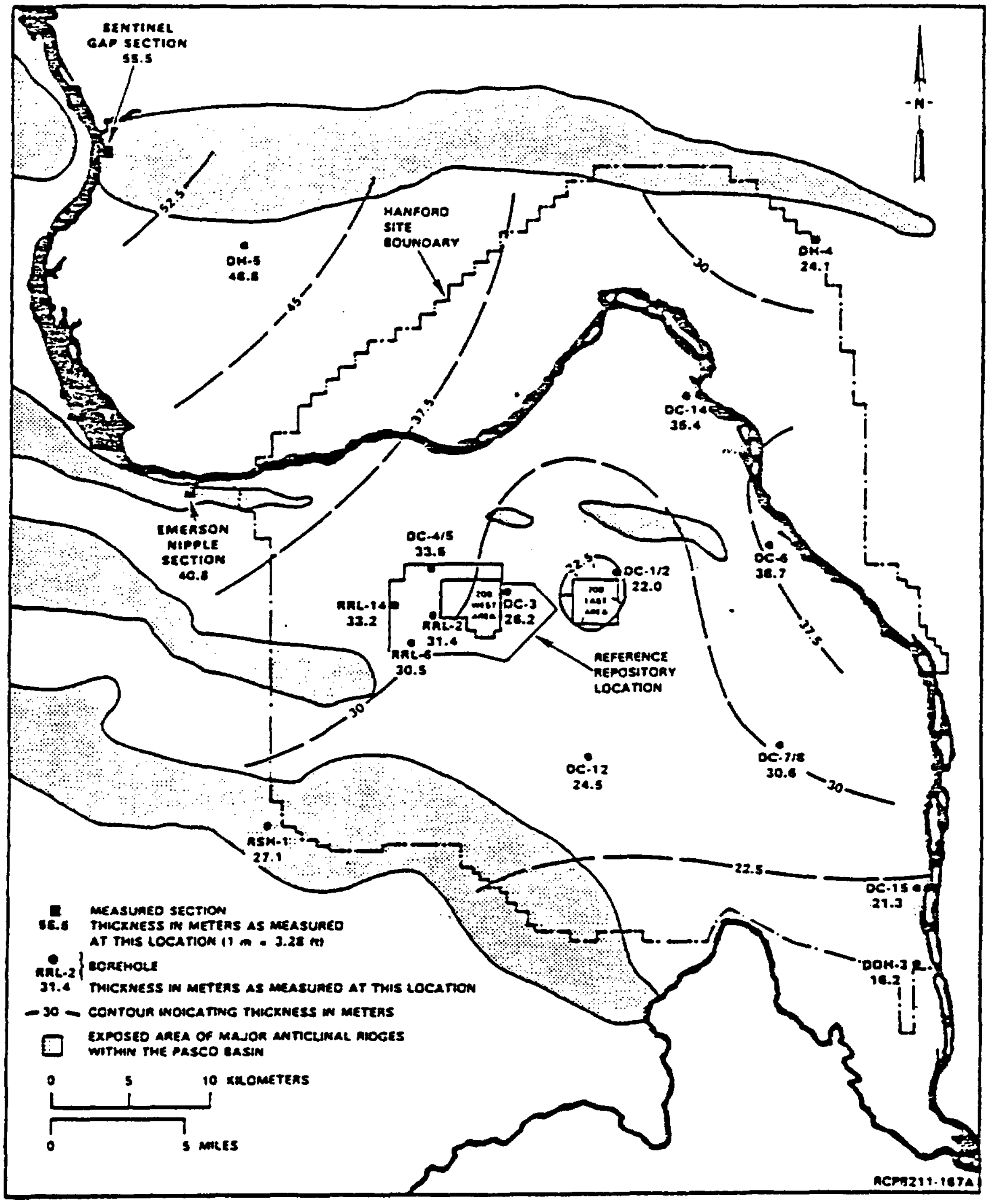


Figure 3-14. Isopach map of the dense interior of the McCoy Canyon flow.

Figure 15

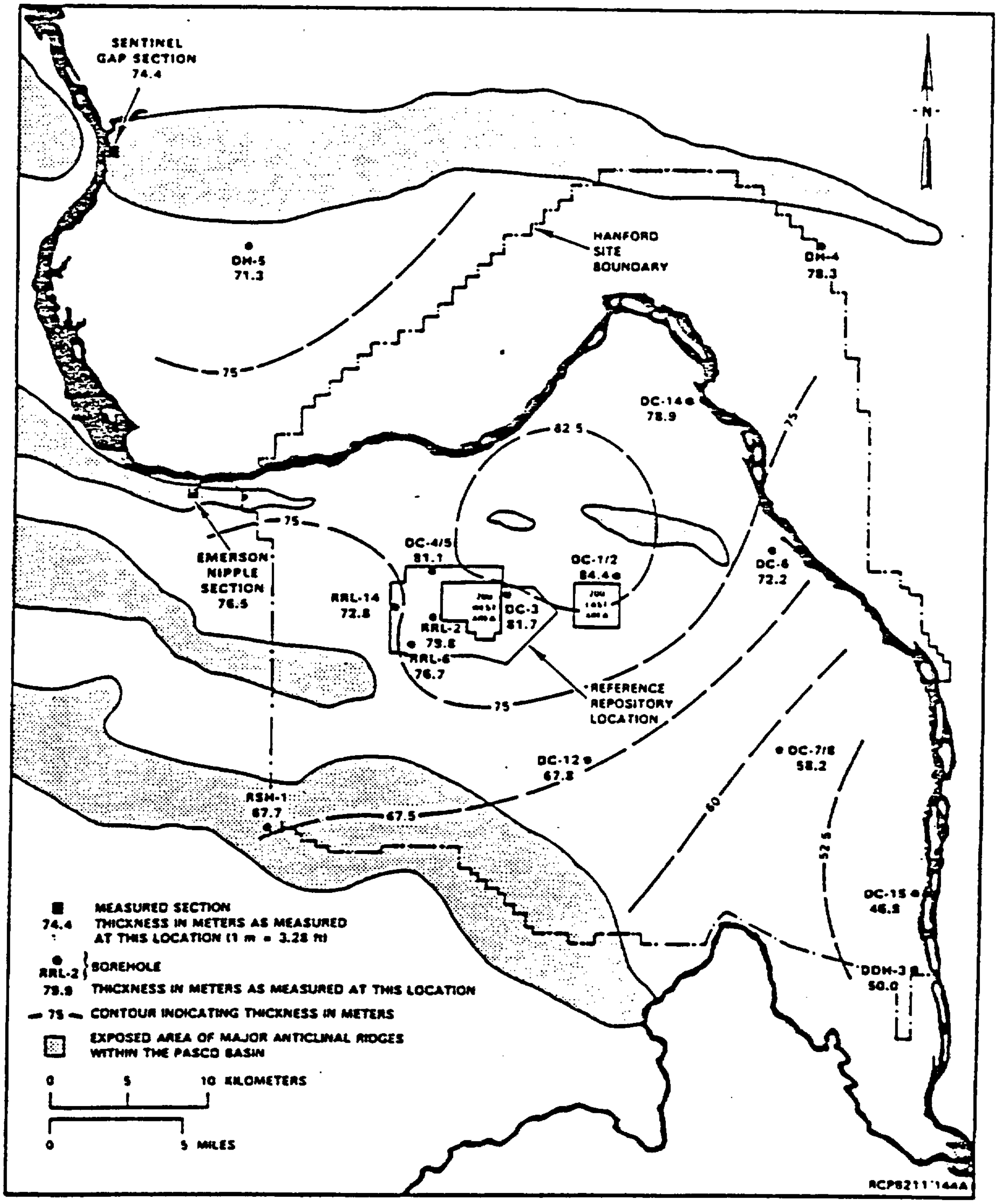


Figure 3-15. Cohassett flow isopach map.

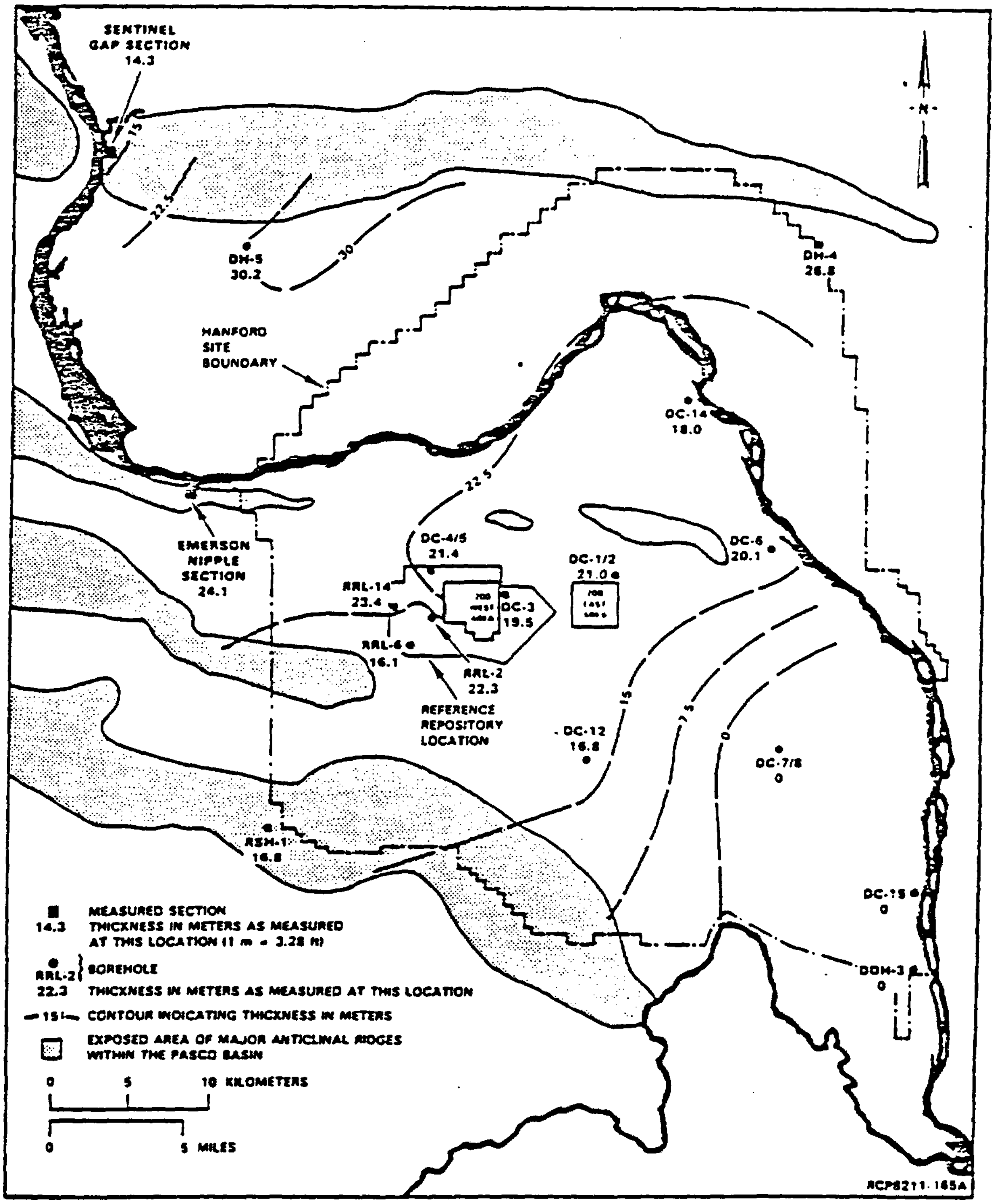


Figure 3-16. Isopach map of the dense interior of the Cohassett flow above the vesicular zone.

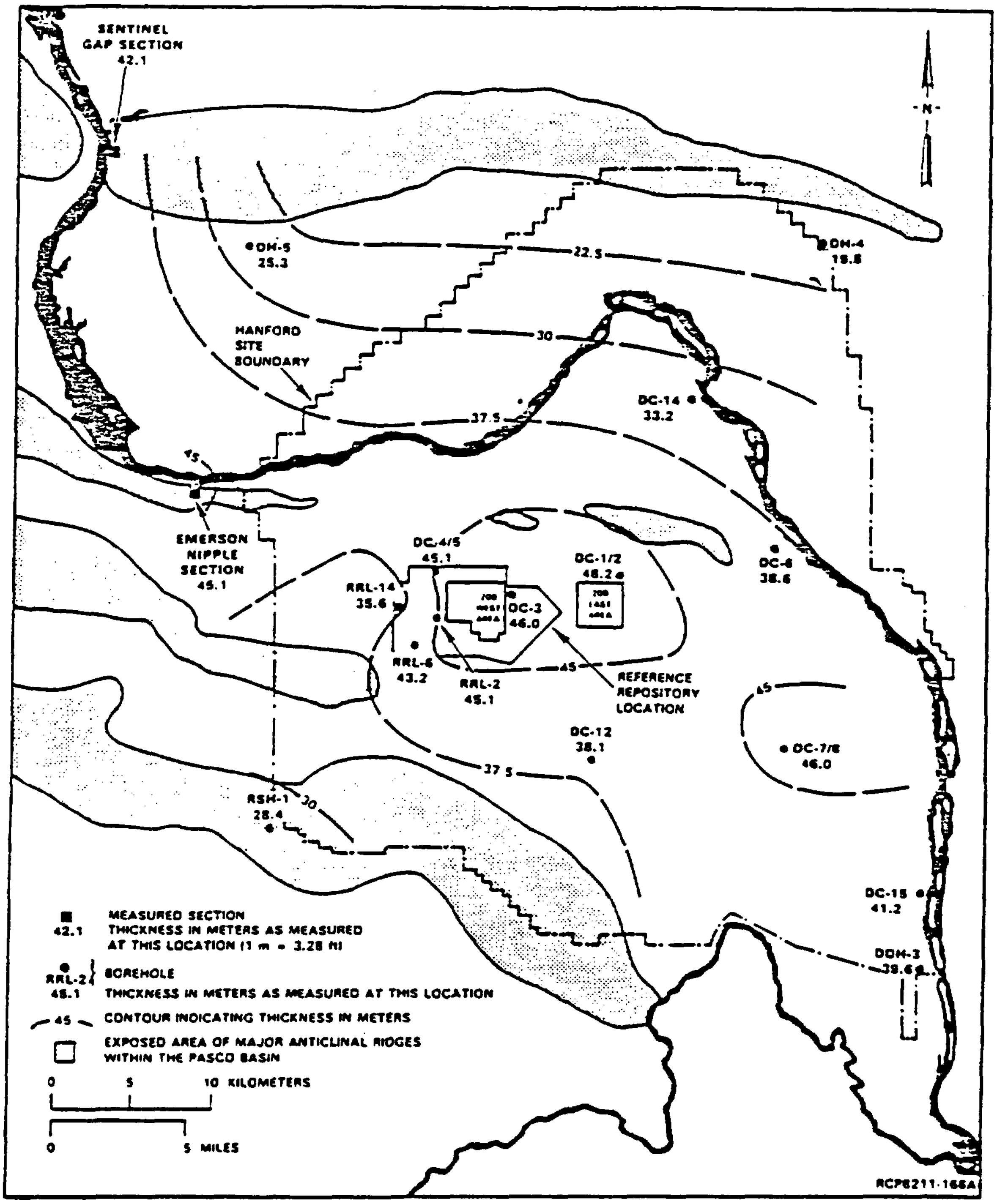


Figure 3-17: Isopach map of the dense interior of the Cohassett flow below the vesicular zone.

Figure 18

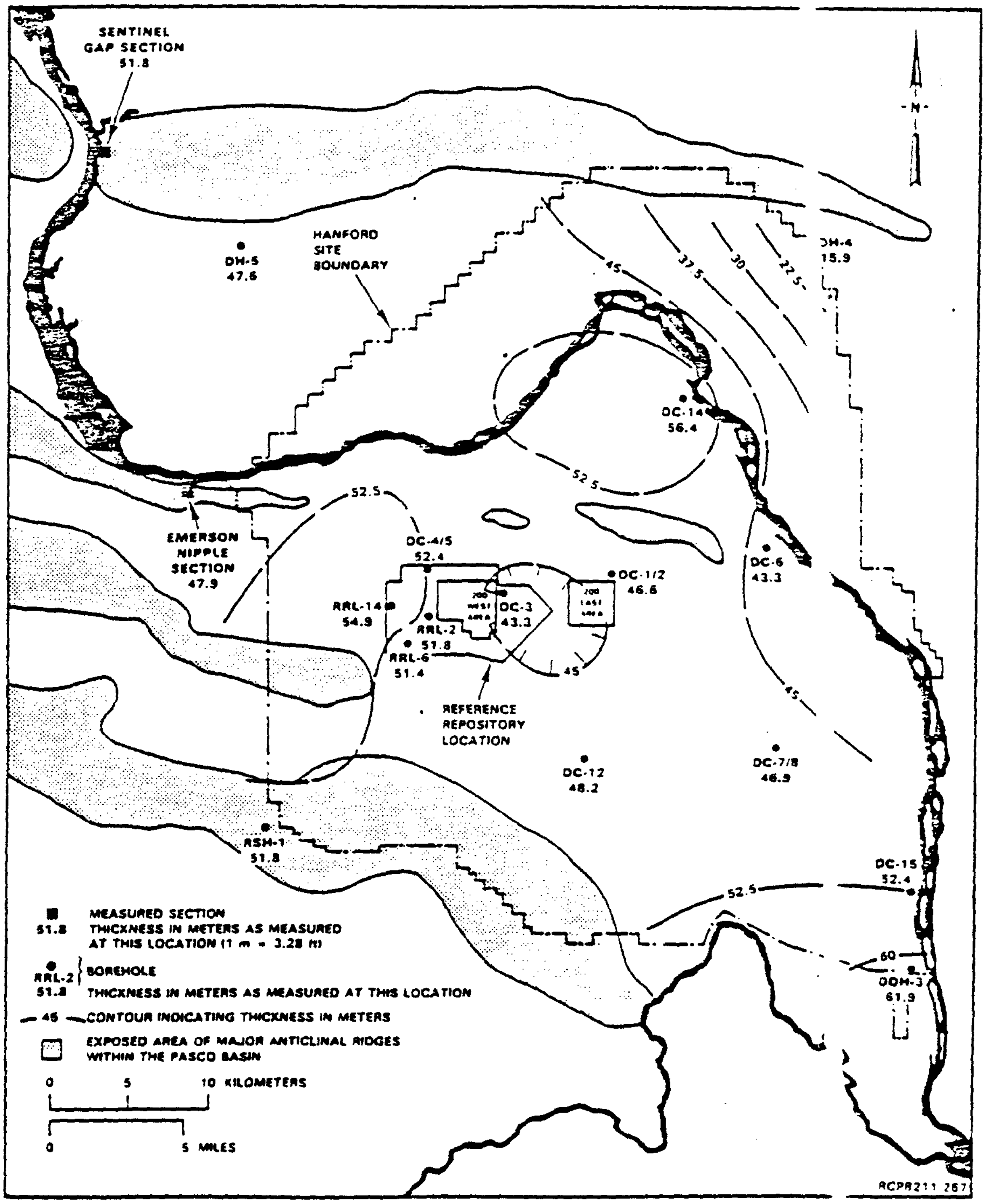


Figure 3-18. Rocky Coulee flow isopach map.

Figure 19

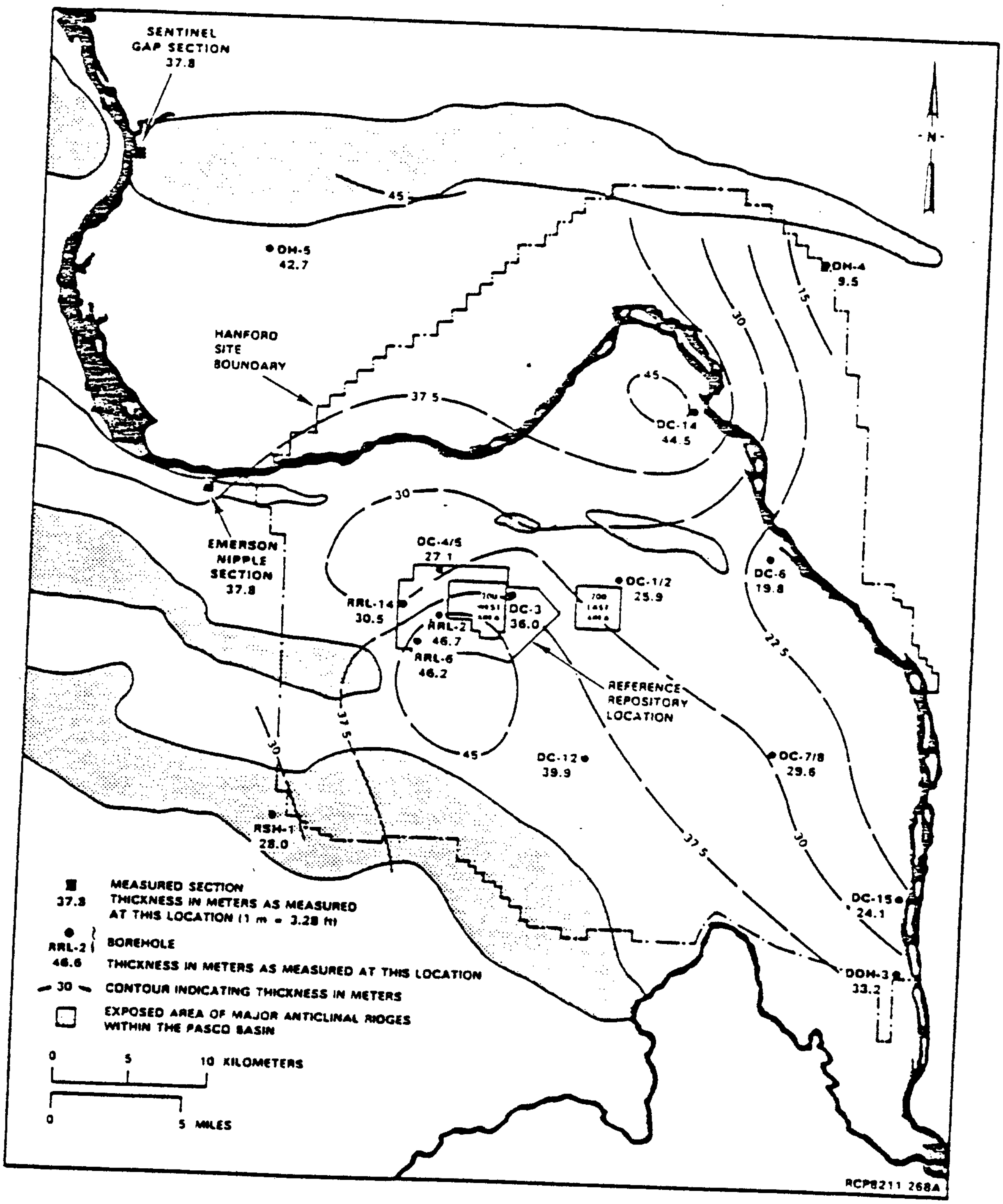


Figure 3-19. Isopach map of the dense interior of the Rocky Coulee flow.

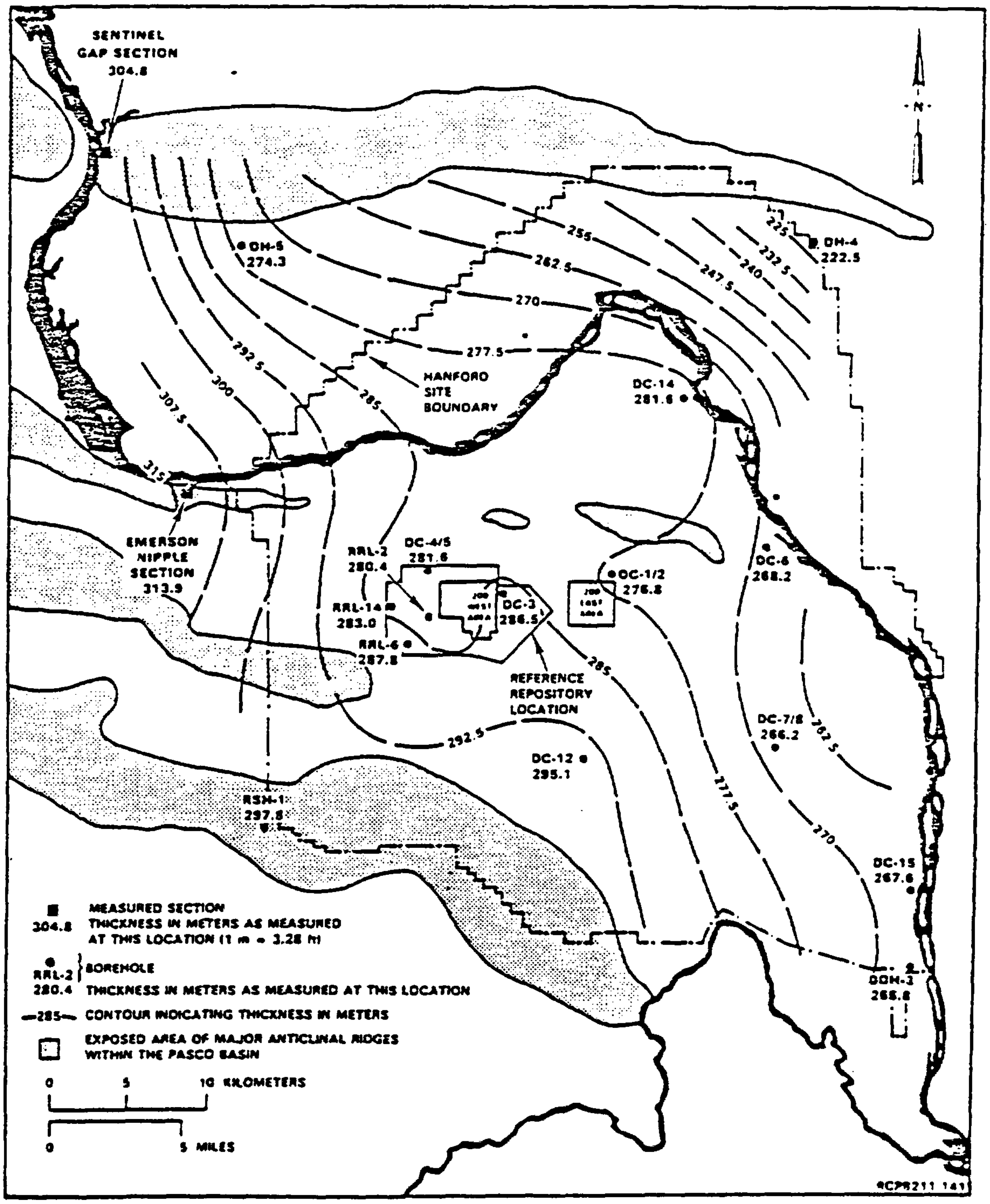


Figure 3-9. Sentinel Bluffs sequence isopach map.

Figure 21

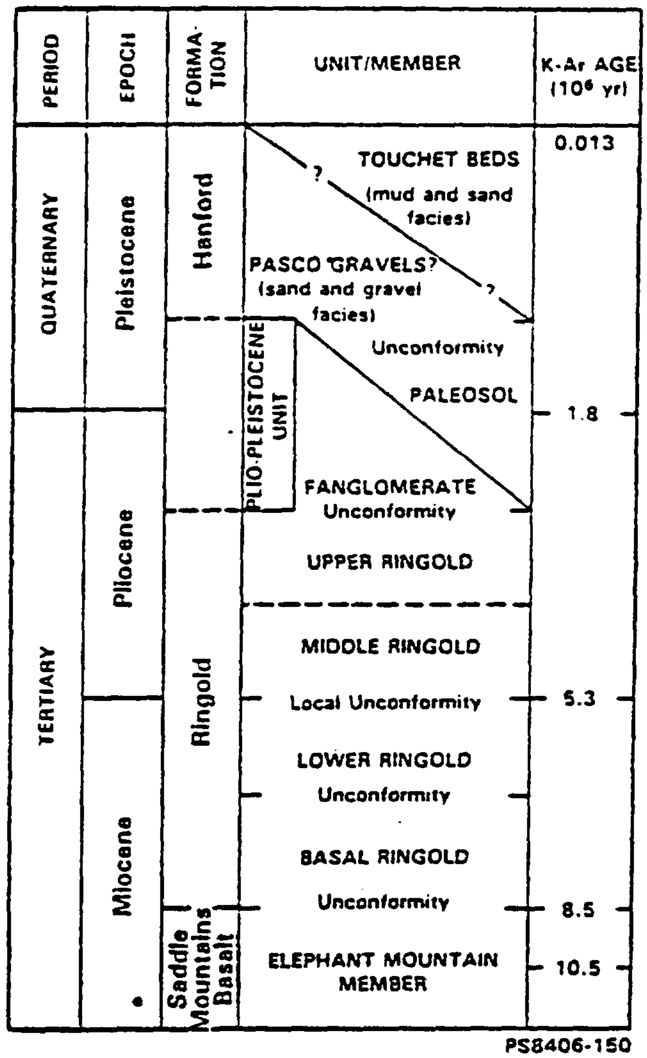


Figure-3-21. Suprabasalt stratigraphy in the reference repository location.

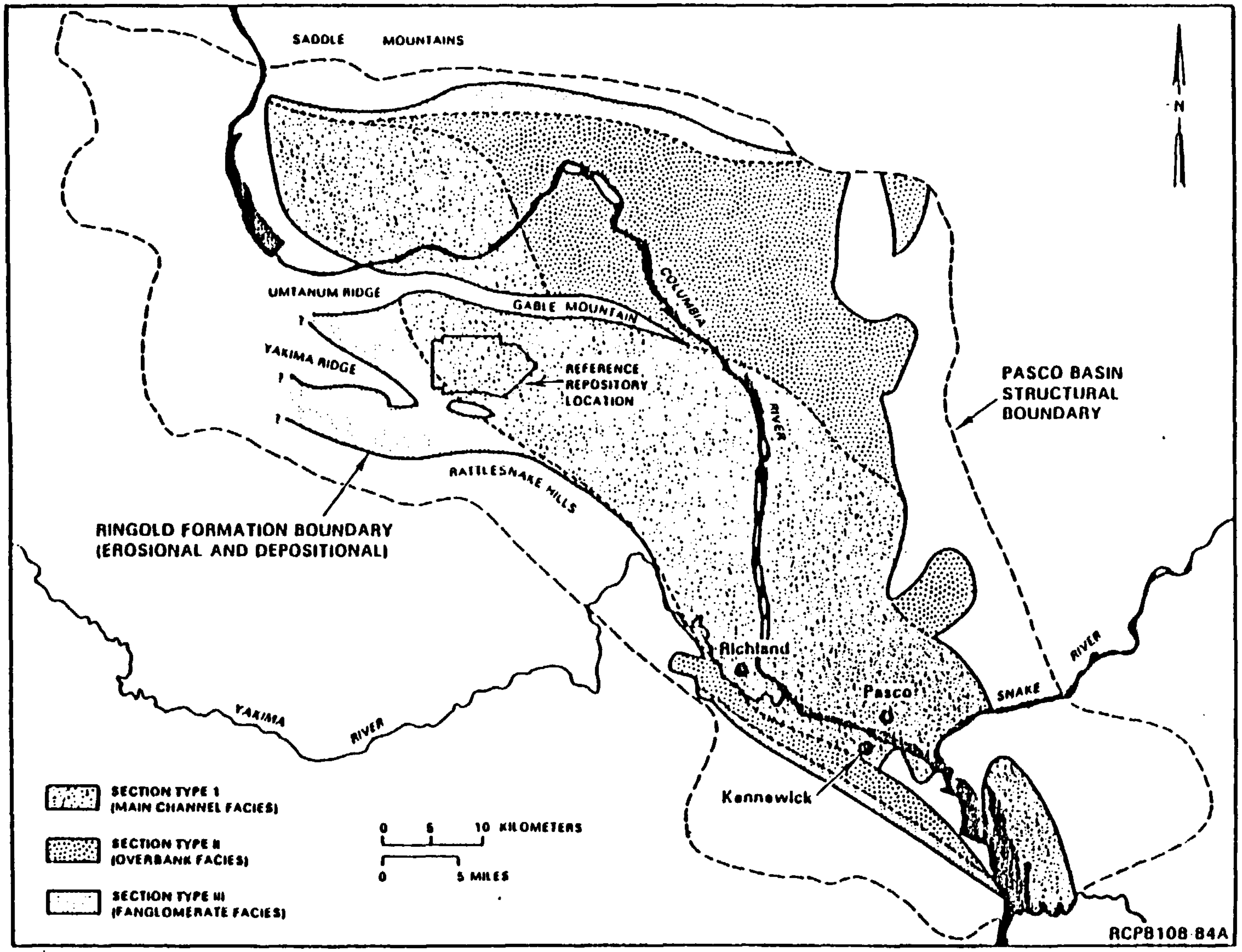


Figure 3-20. Distribution of Ringold Formation section types.

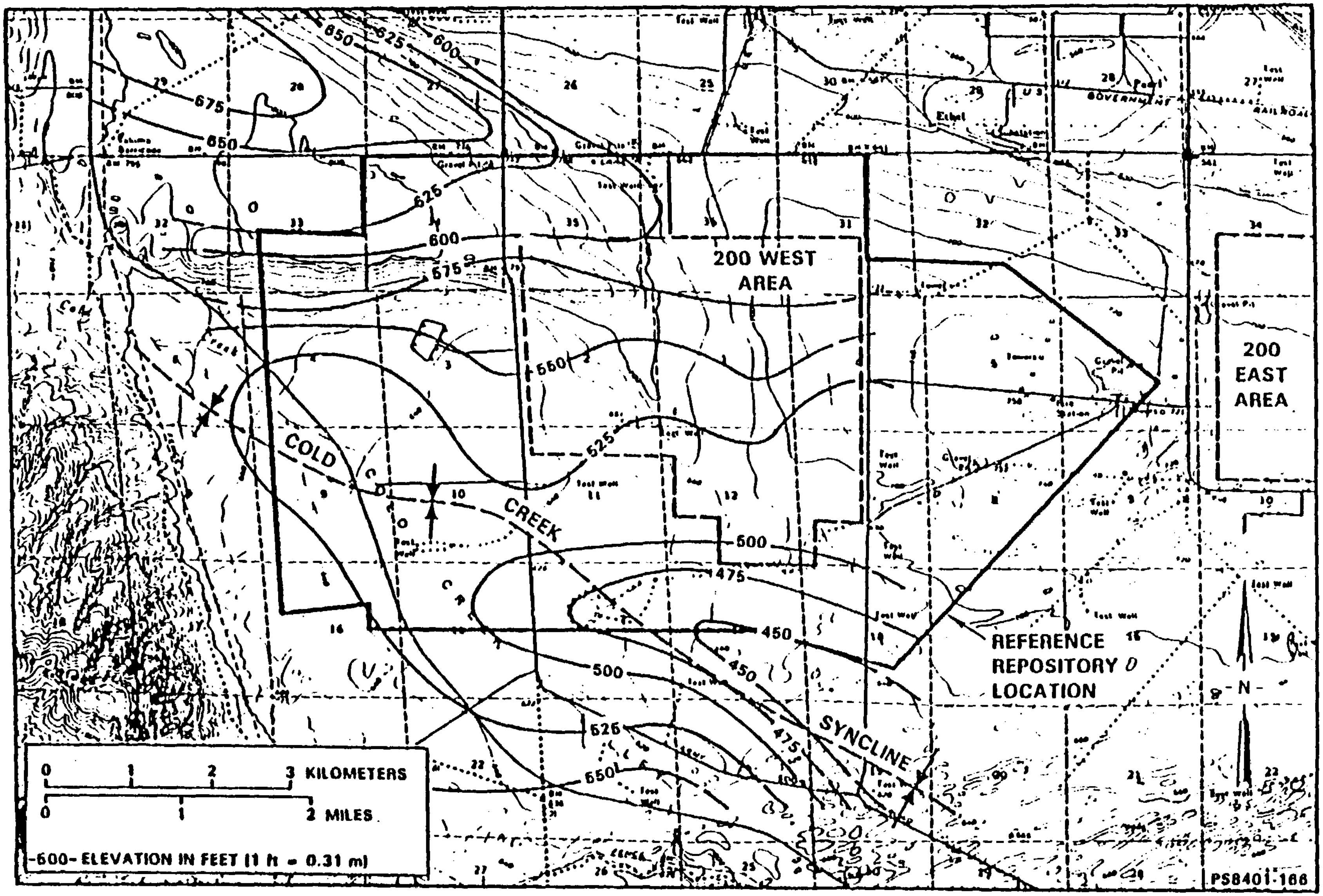


Figure 3-22. Top of the Ringold Formation. Contour pattern indicates maximum post-Ringold incision occurred near the trend of the present Cold Creek Valley.

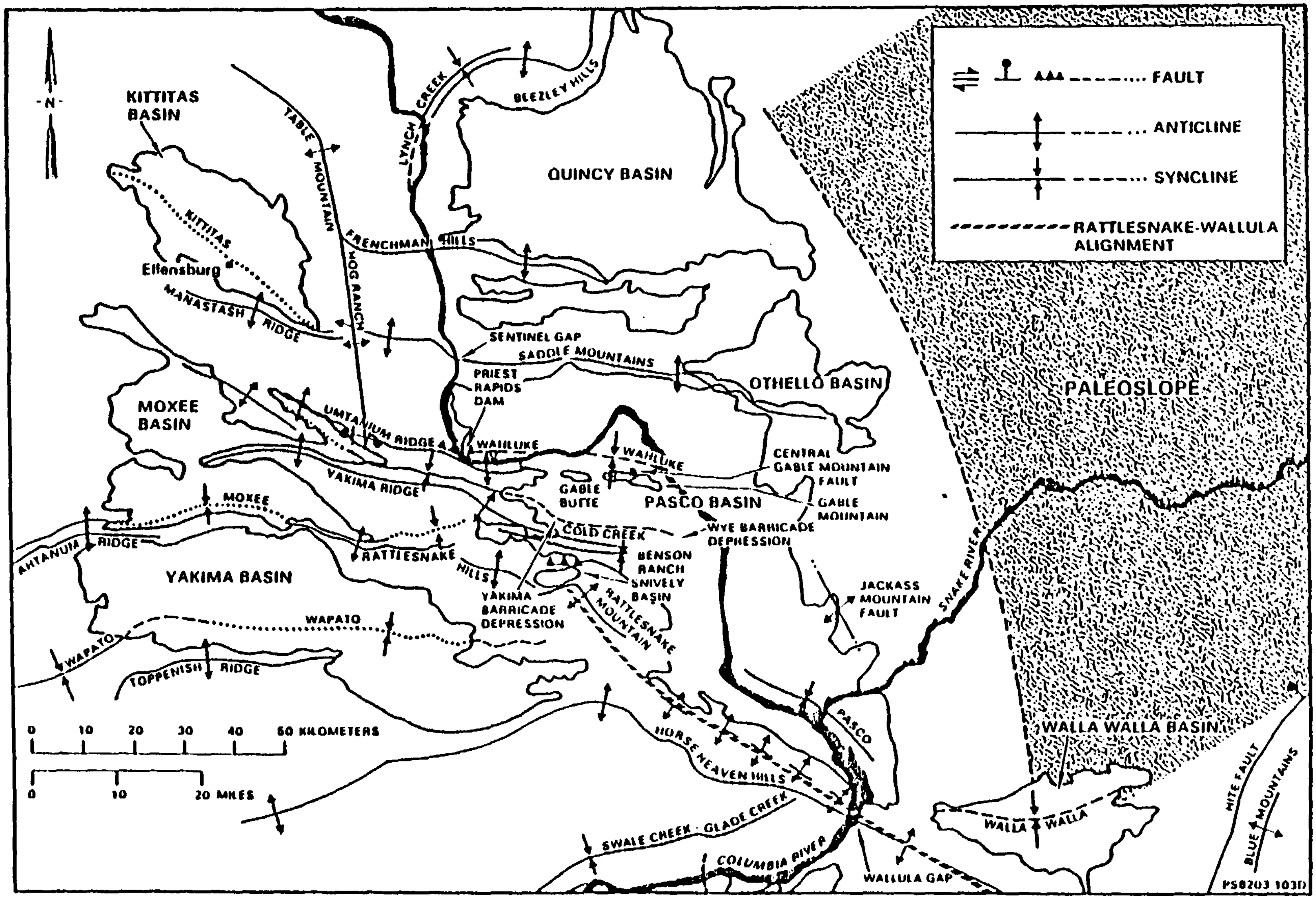


Figure 3-23. Generalized geologic structure map of central Columbia Plateau.

3.0 HYDROLOGY

The Pasco Basin hydrologic system consists of four parts: surface waters, unsaturated (vadose) zone, confined aquifers, and unconfined aquifers. The confined and unconfined aquifers will be discussed in this paper and the surface waters and vadose zone will be only discussed in the context of discharge and recharge.

Ground-water movement in the Pasco Basin occurs in the dense interiors, at the flow contacts, in the interbeds of the basalt flows, and in the alluvium at the surface. Shown in figure 1 are the stratigraphic units of the study area. There are over fifty basalt flows and associated rubble zones and interbeds in the Pasco Basin.

3.1 PREVIOUS INVESTIGATIONS

A good general review of the Pasco Basin hydrology and geology prior to 1972 was done by Newcomb, and others (1972). The report contains a general description of the geologic and hydrologic units in the Pasco Basin and a review of the tectonic history of the area. The report also contains a discussion of the history of ground disposal of radioactive wastes. Gephart and others (1979) have summarized existing hydrogeologic reports pertaining to the Pasco Basin with emphasis on the deeper basalt flows. Meyers and others (1979) have provided a compilation of borehole studies, geophysical surveys, and tectonic studies.

3.2 GROUND-WATER FLOW

3.2.1 Unsaturated Zone

The unsaturated zone varies in thickness from several inches at the Columbia River to over 300 feet thick in the 200 Areas plateau (Gephart, and others 1979). The role of the unsaturated zone in this analysis of waste disposal in the deep basalts is restricted to its effect on ground-water recharge.

3.2.2 Unconfined Aquifers

Unconfined aquifers in the Pasco Basin are mostly restricted to the Hanford and Ringold Formations. Unconfined conditions may be found in the Saddle Mountain and Wanapum Basalts in areas where the alluvium is absent and the basalts are exposed at the surface. The unconfined aquifer in the aluvium ranges from very thin up to 250 feet thick along the eastern edge of the repository site. The Hanford Formation extends below the water table and is composed of coarse sand, gravel, and cobbles with occasional finer grained sediments.

The Ringold Formation is dominated by a middle unit composed of sorted sands and gravel with various degrees of cementing which directly affects hydraulic conductivity. The lateral boundaries of the unconfined aquifer include the Saddle Mountains to the north, Umtanum and Yakima Ridges on the west, Rattlesnake and Horseheaven Hills on the south and a broad monocline on the east. The bottom boundary is a thick relatively impervious relatively extensive layer of silts and clays above the Saddle Mountain basalts.

3.3.3 Recharge and discharge in the unconfined layer

Precipitation in the Pasco Basin ranges from less than 7 inches in the area of the proposed repository to around 15 inches in the Rattlesnake Mountain area. Gephart and others (1979) estimate the precipitation over the entire basin at 800,000 acre feet annually or less than 8 inches.

Jones (1978) estimated that precipitation in the Pasco Basin did not penetrate the soil deeper than 12 meters (39 feet) at any time of the year. This limit would indicate there would be no recharge due to precipitation. Consequently, recharge must occur at the basin periphery, through inter-basin flow, through stream loss mechanisms, or through artificial mechanisms such as irrigation.

Most of the recharge for the unconfined aquifer probably originates at the margins where runoff infiltrates the basalts and alluvium and by the Columbia and Yakima Rivers losing water during high stages. Some recharge occurs where the upward hydraulic gradient from the underlying basalts is sufficient and conditions exist where water can move upward. About 20 to 40 percent of water put on fields during irrigation becomes recharge (Gephart and others, 1979).

Liquid waste disposal ponds from ordinary industrial plant and radioactive waste disposal has caused "mounding" of the water table at two sites and produced minor changes in the water table elsewhere in the area (Newcomb and others, 1972). The widespread effects of the mounds shows a rise of 80 feet below U Pond in the 200 East area, a rise of 20 feet below B Pond, and 10 feet below Gable Mountain Pond (Figure 4).

Discharge in the Pasco Basin is principally to the Columbia River with some of the water going to the Snake and Yakima rivers. A net discharge from the basin of about 2.657 million acre-feet per year is shown in Figure 5.

3.3.4 Hydrologic Parameters

In the Pasco Basin, and in particular, the Hanford Reservation, the principle hydrologic parameters tested for are storage coefficient (specific yield), transmissivity, and hydraulic conductivity. These parameters are obtained from aquifer tests while outside the reservation the principle test is the production test on irrigation wells. Gephart and others (1979) and Guzowski (1982) have compilations of tables of tests of the unconfined unit and lists of calculated conductivities (K), transmissivities (T), and storage (S). Shown in Table 2 are representative hydraulic parameters of the unconfined aquifer.

Most hydrologic parameters listed in Table 2 show an obvious difference between the Hanford and Middle Ringold Formations. The Hanford Formation has a hydraulic conductivity between 1000 and 10000 feet per day and the Ringold is a lot lower averaging about 130 feet per day. Figure 4 is a plot indicating a correlation between hydraulic conductivity and the unit. Consequently, a unit composed of Ringold sediments, such as in the area 699-31-31, that has a high conductivity indicative of Hanford sediments may be showing the result of reworking Ringold sediments with the fines removed and cementation dissolved.

Representative hydraulic parameters of the unconfined aquifer are shown in Table 3. The results indicate that permeable Hanford Formation gravels occur along the northern and southern flanks of Gable Mountain trending southeast to the Columbia River. The Ringold Formation with its moderate to low permeabilities is found throughout the Pasco Basin.

3.3.5 Hydro Chemistry

The major ion geochemistry of the ground water in the Pasco Basin basalts has been summarized in Smith and other (1980) and Guzowski (1981) summarized the major ion similarities in all the Hanford waters in Piper (trilinear) diagrams (Figure 6). A table listing the trace element concentration in ground water at the Hanford Reservation is also provided (Table 4). Figure 6 will also be referred to in the discussion of the Saddle Mountains, Wanapum, and Grande Ronde water chemistry.

3.4 CONFINED HYDROSTRATIGRAPHIC UNITS

3.4.1 Previous Investigations

Before 1960, most hydrologic testing was done in the Hanford and Ringold Formations because developed wells were mainly for water supply. Because of the complex morphology of the rock units in the Pasco Basin, determination of hyydraulic conductivity is difficult. Hydraulic parameters within a unit are affected horizontally and vertically by flow morphology, erosion, alteration, and the infilling of fractures (Guzowski, 1982).

In the mid 1960's a drillstem test was conducted of the Grande Ronde and pre-Grande Ronde basalts in well RSH-1 across seven 76-foot long intervals with multiple tests carried out for each run. Permeabilities and hydraulic heads were obtained from the flow data and shut-in pressure data (Raymond and Tillson, 1968).

Borehole RSH-1 was re-tested by Gephart and others (1979) with 11 additional production and injection tests that were conducted opposite specific zones. Summarized in Table 5 are the basalt hydrologic tests prior to 1980 and the principal organizations involved. Since 1979 many aqufier tests have been performed at the Hanford site. Some of them are discussed below and many others remain in the form of "interval reports" that have not been compiled or summarized.

3.4.2 Ground Water Occurance

As described in the geology section, ground-water flow in basalt is ultimately governed by the genesis of basalt. The movement of a lava flow has a definite effect on its permeability. In the study area, the basalts are composed of successive layers of basalt interbedded with stream gravels and interflow rubble that forms a high permeability layer. Older flows have been compacted and undergone recrystalization. Weathered flows have a high porosity but low permeability. Sedimentary interbeds in the Pasco Basin consist of silts and clays with intermitant sand and gravel lenses. The interbeds are thickest in the center of the basin and thinning toward the basin margin. Flow in the interbeds is poor to moderate (Gephart and others, 1979).

Ground water moves through entablature and colonade fractures in the dense interior basalt to the interbed material, flow contacts, and bedrock structures (Figure 7). Shown in Table 5 is the percentage of dense basalt compared to interflow and sedimentary interbeds. Three trends are shown:

1) Percentage of sedimentary interbeds decreases with depth.
2) Percentage of dense basalt remains nearly the same with depth.
3) Percentage of interflow material increases with depth.

3.4.3 Flow Interiors

Horizontal hydraulic conductivities from ten hydrologic tests of flow interiors using pulse and constant head injection test methods at depths ranging from 350 m to 1190 m were less than or equal to 10e-11 m/s (10e-6 ft/d) (Gephart, 1983). Lasala and Doty (1971) and Newcomb (1984) also reported low conductivities. Vertical conductivity tests are rare, but one suggests a vertical conductivity of less than 10e-10 m/sec (10e-5 foot/day) (Spane and others, 1983).

3.4.4 Flow Contact and Sedimentary Interbeds

Flow tops have a higher conductivity than flow interiors and may extend over many square kilometers (several thousand). Nearly 200 single hole hydrologic tests in about 35 wells indicate hydraulic conductivities in the Saddle Mountains and Wanapum basalts range from 10e-4 to 10e-7 m/s (10 to 10e-2 ft/day) with a geometric mean of about 10e-5 m/s (1 ft/day). The Grande Ronde has a range of conductivities of 10e-5 to 10e-9m/s (1 to 10e-4 ft/s) and a geometric mean of about 10e-7 m/s (10e-2 ft/day) Gephart and others, 1983. Hydraulic conductivities are consistent within a flow top and may vary spatially only slightly. Also, ground-water flow in basalt flow tops may occur in intervals less than one meter thick which results in a high local permeability but a low transmissivity.

3.4.5 Bedrock Structures

Pasco Basin bedrock structures, as discussed in the geology section of this report, have areas where high conductivities result in high anisotropy rations due to fractures. These zones of high conductivity may provide potential pathways between flow systems above and below a repository.

Zones of tectonic breccia occur along the limbs of the gently dipping anticlines and synclines. The zones are generally about 1 meter thick and have an unknown lateral extent. A thick zone (5 meters) in the Frenchman Springs member of the Wanapum was tested using a pulse technique and yielded conductivities of approximately 10e-11 m/s (10e-6 ft/day).

Synclinal troughs, such as the Cold Creek Syncline, are difficult to assess as to the amount of fracturing that occurs but it is assumed that less strain occurs on the nearly flat lying strata. Nevertheless, observations of cliffs and roadcuts indicate a network of tectonic fractures occur and may extend tens of hundreds of meters (tens to hundreds of feet). The genesis of the fractures is doubtful but may be the result of cooling or related to deposition.

West of the repository site (Figure 8) is a bedrock "structure" referred to as the "Cold Creek Barrier" (DOE, 1984). The barrier is almost normal to the Cold Creek Syncline and is an impediment to ground-water flow as indicated by a hydraulic head drop of 150 meters (500 Feet) across the "structure".

3.4.6 Alternative Flow Concepts

Sometimes data are too scarce to reach conclusions about a particular flow system, consequently, alternative concepts may be developed in order to concentrate efforts in the direction of a narrow range of models suitable for detailed study. Gephart and others (1983) have conceptualized four types of ground-water movement (Figure 7). The concepts (quoted freely from Gephart and others, 1983) are as follows:

- CONCEPT A: This concept illustrates ground-water moving principally within heterogeneous, permeable flow tops separating flow interiors of relatively low vertical and horizontal permeability. Upward movement into shallower systems occurs as a result of (1) the positioning of flow where the front of one basalt flow of limited extent terminates atop a more continuous flow creating a direct conduit between two flow tops, or (2) ground-water movement across low permeability flow interiors over large areas. In concept A, local features of relatively high permeability (such as thickening of flow top breccia atop a spiracle) are not commonly juxtaposed. Basically, Concept A depicts an anisotropic, heterogeneous flow system undisturbed by major folds and faults.

- CONCEPT B: In this concept, basalt flows are crossed by bedrock structural discontinuities having potentially larger vertical permeabilities than the aquitards. On a local scale of several square kilometers, such discontinuities might represent individual tectonic fractures or shear zones. Regionally, these features could depict major fault zones. If rock movement has occurred, such structures could depict zones where the lateral continuity of flow contacts is disrupted causing a flow contact to terminate against a flow interior of permeability. In this concept, structural discontinuities are heterogeneities having the potential for vertically connecting shallow and deep flow systems. Dependent upon the extent of fracture mineral infilling and/or fine gouge material, these discontinuities could act as high permeability conduits or ground-water barriers. Overall, this concept depicts rock volumes of relatively low vertical leakage bounded by structural discontinuities.

- CONCEPT C: This concept represents a flow system characterized by lateral ground-water movement in flow tops bounded by basalt interiors of relatively high leakage. The anisotropy between flow top and interior is considerably less than in Concept A. In this concept, ground-water movement between deep and shallow systems occurs as a result of stratigraphic positioning/inter-section of flow contacts and vertical leakage through unfilled or partially filled cooling fractures and other relatively high permeability primary features that are juxtaposed.

• CONCEPT D: This concept superimposes bedrock structural discontinuities on Concept C. As described under Concept B, such discontinuities might act as vertical conduits and/or low permeability barriers. This concept depicts rock zones of relatively high vertical leakage bounded by structural discontinuities.

3.4.7 Hydraulic Heads

Hydraulic head data from selected wells (Figure 9) can be used to determine horizontal flow direction in a particular hydrostratigraphic unit and the direction and magnitude of potential vertical flow. In the Pasco Basin, values of the hydraulic head gradient tend to be related to depth. Head values in the Saddle Mountains Formation are erratic but seem to increase with depth (Table 7). In the Wanapum (Tables 8 and 9), values are uniform or decrease with depth. The Grande Ronde Formation has head values that decrease with depth. In the area of well DC-15, Grande Ronde values increase with depth. Shown in Figures 10, 11, 12, 13, and 14 are the available data on potentiometric levels on the Hanford Reservation. The arrows indicate the direction of flow. Gephart and others (1979) provide a summary which shows a comparison of Hydraulic heads for boreholes DC-1, DC-6, and DC-8 (Tables 10-12).

3.4.8 Additional Hydraulic Properties

The following is a discussion of additional hydraulic properties at the respostory site:

Transmissivity

Transmissivity is the rate water is passed through a given width of aquifer under a hydraulic gradient. Transmissivity values in the Pasco Basin are from mostly unconfined aquifers. The scarcity of data is the result of poor records, the method of well construction, and the large intervals tested.

Storage Coefficient

The storage coefficient of confined aquifers is the volume of water released from storage per unit surface area per unit change in head. Storage coefficients for the confined aquifer in the Hanford area range from about 1.0e-5 to 1.0e-3.In the Pasco Basin, storage coefficient values from 2 wells penetrating the Wanapum and Grande Ronde Basalts range from 1.4e-6 to 3.0e-3 (Lasala and Doty, 1971). Higher permeability zones along flow contacts have storage coefficient values of 1.0e-4 to 1.0e-3 which are within the range typically reported for confined aquifer systems (Gephart and others, 1979). The storage coefficients at the lower end are probably characteristic of columnar basalts which are denser and hydraulically tighter.

Porosity

Porosity is expressed quantitatively as the ratio of the volume of pore space to the total volume. Effective porosity is the volume percentage of connected pores through which flow can occur. Basalts have many large isolated voids, consequently, the total porosity is much greater than the effective porosity. The basalt porosities are from the Columbia Plateau (Table 13). The measurements are made on disturbed samples in the laboratory and the effective porosities do not reflect the actual effective porosity. Total porosity in the study area ranges from less than 1% in the dense interior basalts to greater than 30% in the scoriaceous zones and effective porosities range from 0 to about 2.5% (Guzowski, 1982). To date, two tests have been performed within the Mccoy Canyon basalt flow top on the same internal (Leonhart and others 1982, 1984). Estimates for effective thickness ranged between $2x10^{-3}$ to $3x10^{-3}$ meter (.006 to .01 feet). Effective porosity of this flow top is between .01 and 1 percent.

Specific Capacity

Specific capacity of a well may sometimes be termed the productivity of a well or the rate of water pumped in gallons per minute divided by the drawdown, in feet. Generally, high specific capacity indicates a high transmissivity and low specific capacity means low transmissivity. Tanaka and others (1974) estimated transmissivities from the specific capacities. Most specific capacity data in the Hanford area are from wells east of the Columbia River (Gephart and others, 1979) or near the cities of Pasco and Kenewick, Washington. Specific capacity data used to estimate hydraulic conductivity gives ranges from .02 to forty feet per day for interflow zones. Hydraulic conductivities of between .08 and 40 feet per day were obtained when test zones penetrated are one or more interbeds. These ranges compare with other estimates of conductivity for the Wanapum and Grande Ronde.

Longitudinal Dispersivity

The above mentioned tracer tests in the McCoy Canyon gave a longitudinal dispensivity ranging between .6 and 1.7m.

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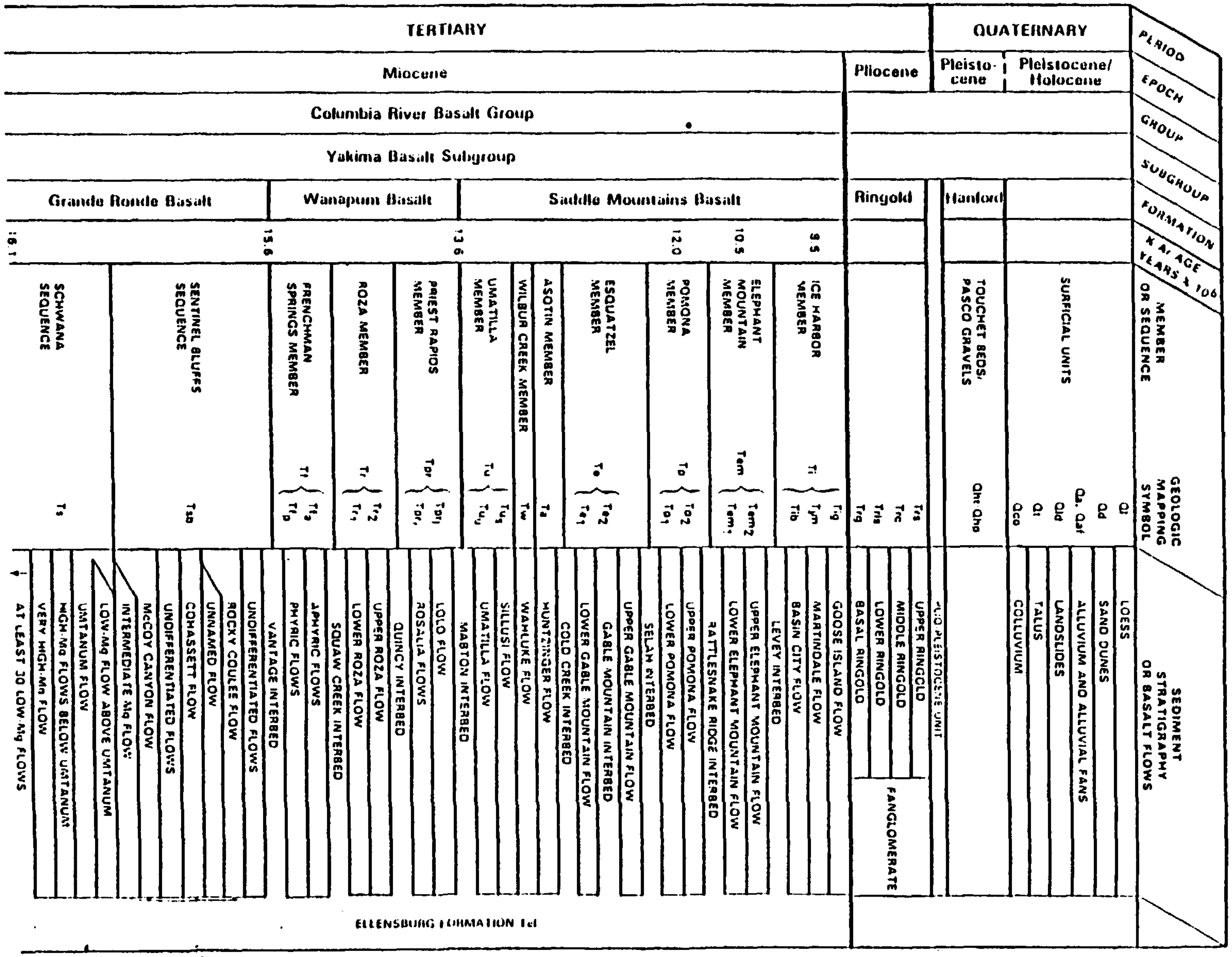

Stratigraphic units present in the Pasco Basin.

Fig. 1

Fig 2.

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HORIZONTAL HYDRAULIC CONDUCTIVITY FOR LAYERS IN LOCAL MODEL

LAYER NUMBER	UNIT	K_H (m/s)
25	HANFORD & UPPER RINGOLD FMS	10^{-6} – 10^{-2}
24	MIDDLE & LOWER RINGOLD FMS	10^{-7} – 10^{-5}
23	ELEPHANT MTN. BASALT	(FT 10^{-7} – 10^{-3}) (I 10^{-12} – 10^{-11})
22	RATTLESNAKE RIDGE INTERBED	10^{-7} – 10^{-5}
21	POMONA BASALT	(FT 10^{-7} – 10^{-4}) (I 10^{-12} – 10^{-11})
20	SELAH INTERBED	10^{-7} – 10^{-5}
19	ESQUATZEL BASALT	(FT 10^{-6}) (I 10^{-12} – 10^{-10})
18	COLD CREEK INTERBED	10^{-7} – 10^{-4}
17	UMATILLA BASALT	(FT 10^{-7} – 10^{-5}) (I 10^{-12} – 10^{-11})
16	MABTON INTERBED	10^{-9} – 10^{-4}
15	PRIEST RAPIDS FLOW TOP	10^{-8} – 10^{-2}
14	PRIEST RAPIDS INTERIOR AND ROZA BASALT	(FT 10^{-10} – 10^{-3}) (I 10^{-12} – 10^{-11})
13	FRENCHMAN SPRINGS BASALT	(FT 10^{-8} – 10^{-3}) (I 10^{-12} – 10^{-11})
12	VANTAGE INTERBED	10^{-8} – 10^{-6}
11	UPPER SENTINEL BLUFFS BASALTS	(FT 10^{-9} – 10^{-5}) (I 10^{-13} – 10^{-12})
10	COHASSETT FLOW TOP	10^{-8} – 10^{-5}
9	COHASSETT INTERIOR	10^{-13} – 10^{-12}
8	LOWER SENTINEL BLUFFS BASALTS	(FT 10^{-9} – 10^{-6}) (I 10^{-13} – 10^{-12})
7	UMTANUM FLOW TOP	10^{-7} – 10^{-5}
6	UMTANUM INTERIOR AND SCHWANA BASALTS	(I 10^{-14} – 10^{-13}) (FT 10^{-10} – 10^{-7})
1-5		

FT-FLOW TOP
I-INTERIOR

Z8000.59

Figure 3

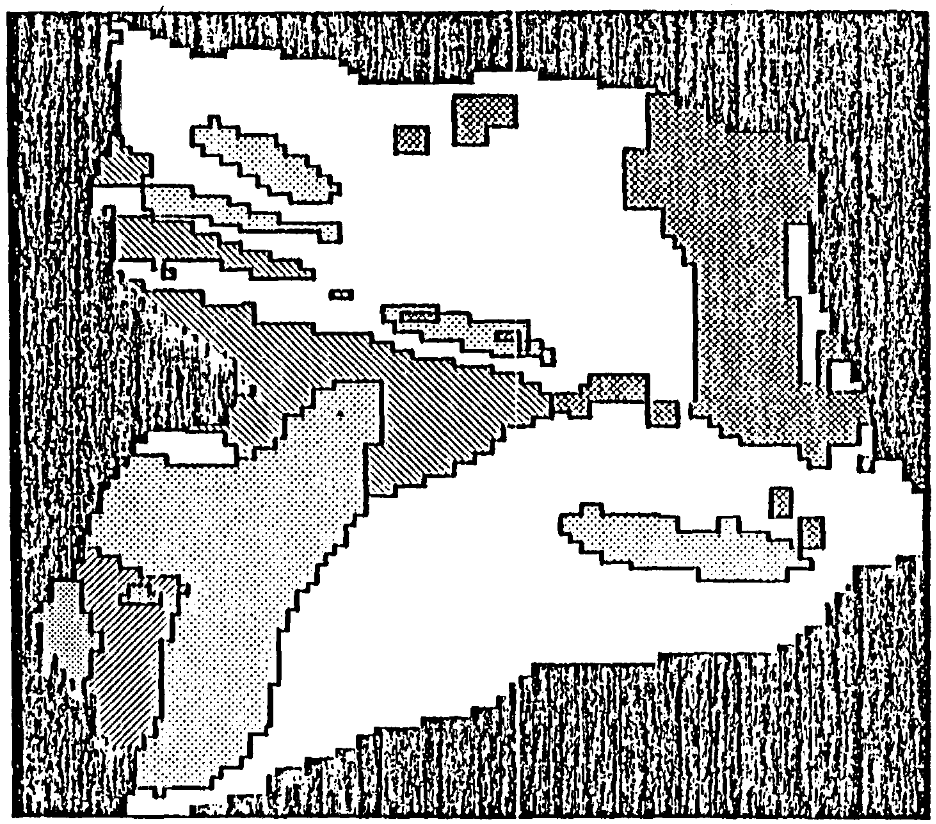
DISTRIBUTION OF RECHARGE

RAINFALL

- 20-25 INCHES
- 15-20 INCHES
- 10-15 INCHES
- <10 INCHES

IRRIGATION

- APPROXIMATE DISTRIBUTION OF IRRIGATION IN MODEL AREA THAT IS PART OF COLUMBIA BASIN PROJECT (FROM AEGIS TECHNOLOGY DEMONSTRATION)
- APPROXIMATE DISTRIBUTION OF IRRIGATION IN MODEL AREA THAT IS PART OF YAKIMA PROJECT (ESTIMATED FROM COLOR LANDSAT PHOTO, REPT. RHO-BWI-ST-5)



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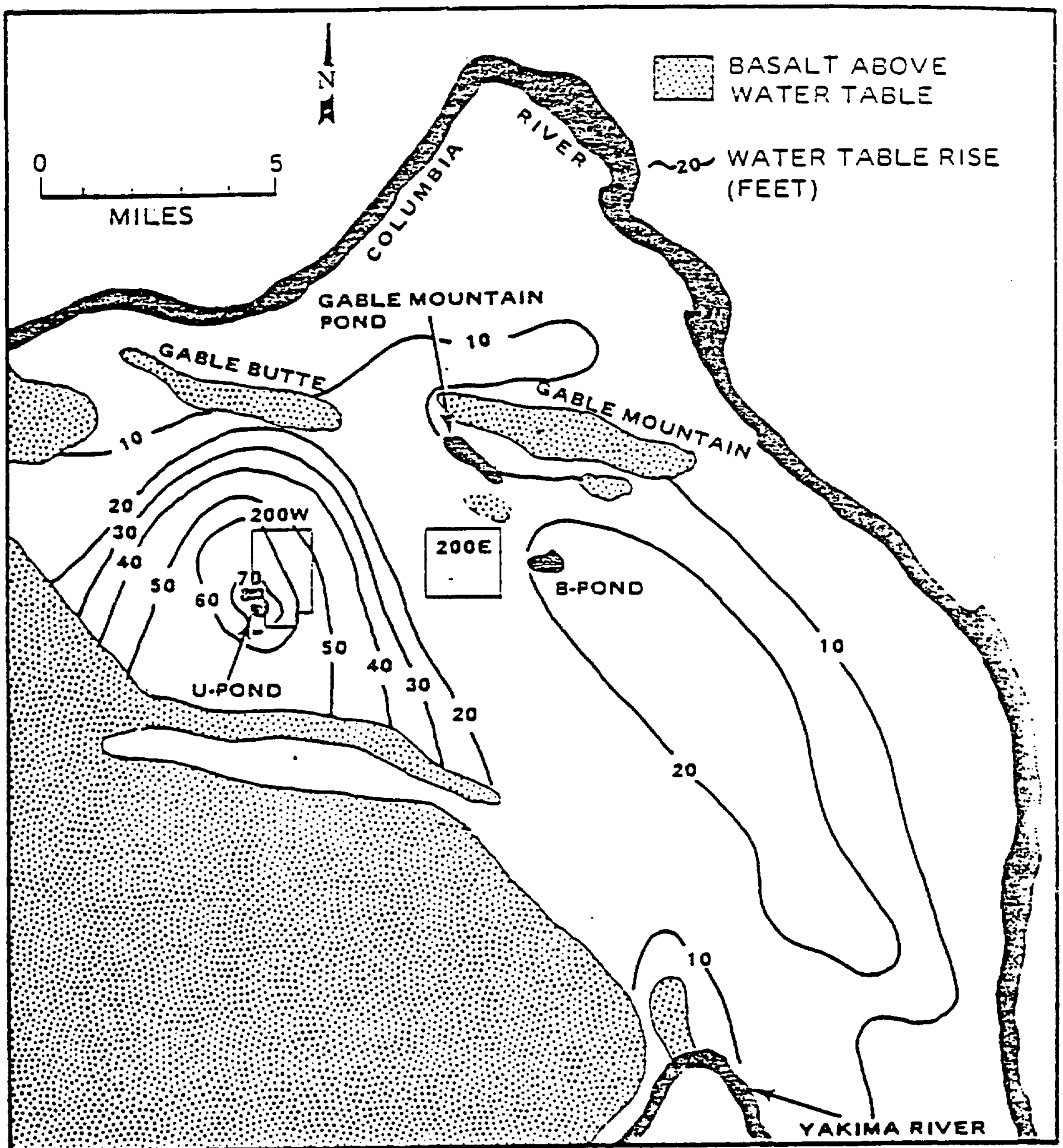


FIGURE 3. Water Table Rise beneath the Hanford Site, 1944-1978.

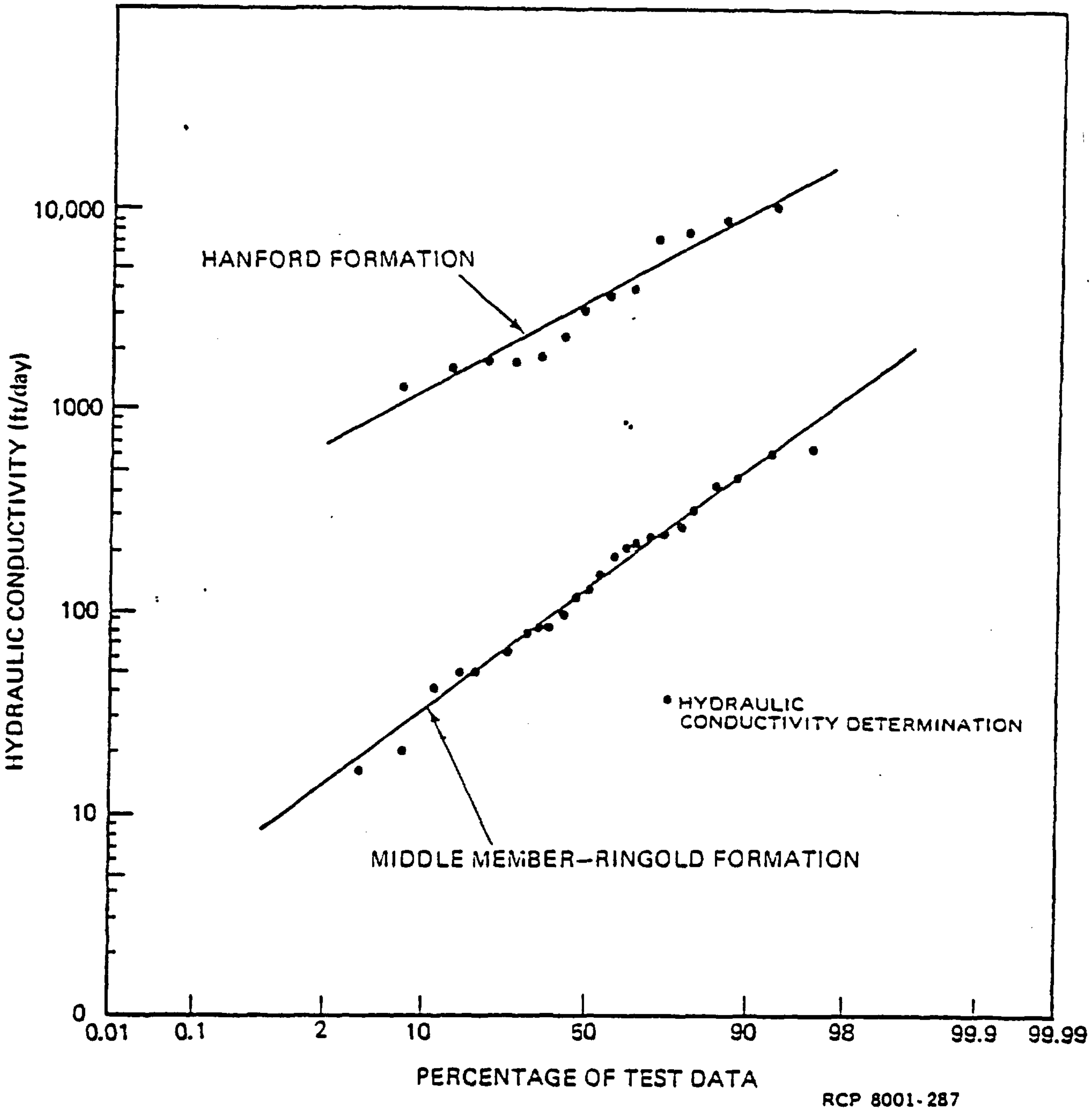
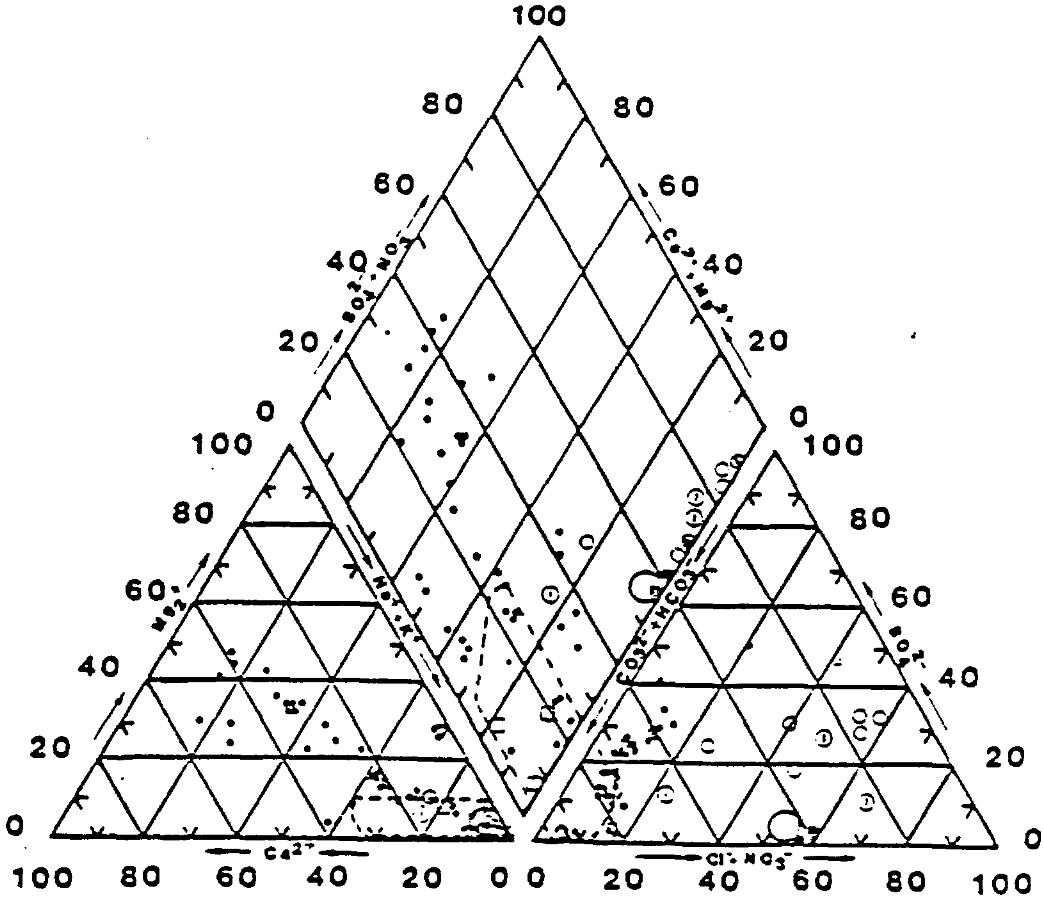


FIGURE III-~~T8~~5. Probability Relationship between Hydraulic Conductivity and Two Geologic Units.



(filled circle)	Samples from surface aquifers at Hanford Site; from USGS WSP 1199-N:	□	Mean composition of samples from the Mabton Interbed; from RHO-BWI-80-100-2Q:
①	Synthetic GR-1; see text:	■	Samples from Priest Rapids Interflow; from RHO-BWI-80-100-2Q:
②	Synthetic GR-2; see text:	----	Delineates chemical composition of ground water within the Saddle Mountains basalt boreholes DC-14 and DC-15; from RHO-BWI-80-100-3Q:
③	Synthetic RSGC; see text:	◯	Delineates chemical composition of ground waters within the Wanapum basalt at Boreholes DB-15 and DC-12; from RHO-BWI-80-100-3Q:
○	Samples from boreholes in Grande Ronde Formation; from RHO-BWI-80-100-2Q, RHO-BWI-80-100-3Q and RHO-BWI-78-100:		

Figure N-1. Piper (trilinear) Diagram of Major Ion Composition of Various Ground Waters Associated with the Hanford Site.

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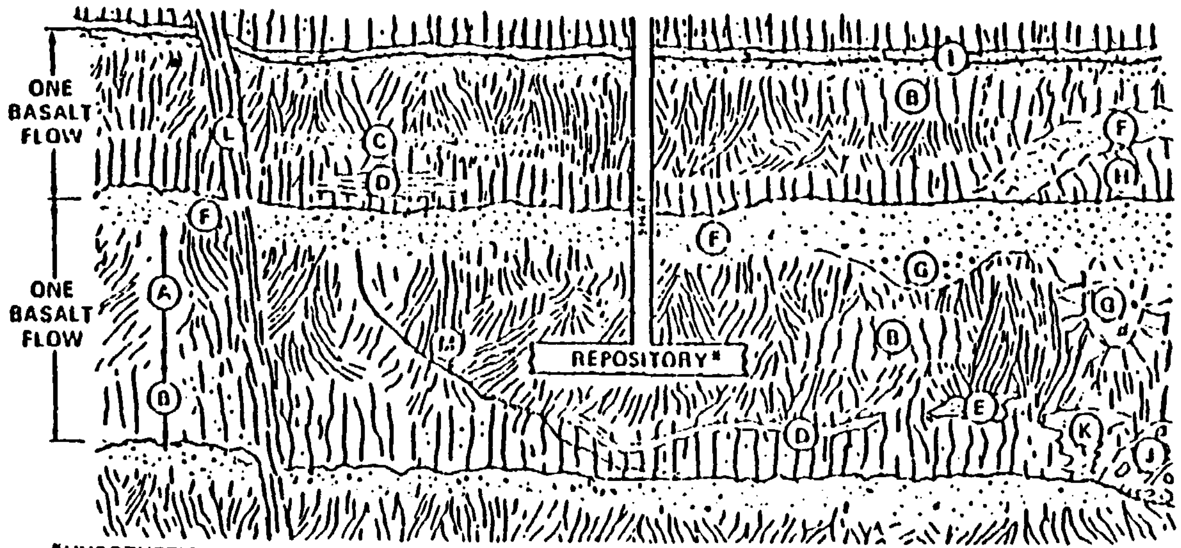

*HYPOTHETICAL LOCATION

NO HORIZONTAL OR VERTICAL SCALE INTENDED

FLOW INTERIOR DISCONTINUITIES

A ENTABLATURE JOINTS
B COLONNADE JOINTS
C VESICULAR ZONE
D PLATY ZONE
E LOCAL FRACTURED ZONE

FLOW CONTACT

F FLOW TOP
G LOCAL THICKENING OF FLOW TOP BRECCIA
H FLOW TERMINATION
I SEDIMENTARY INTERBED
J PILLOW BRECCIA
K SPIRACLE OR SPIRACLE-LIKE FEATURE

BEDROCK STRUCTURAL DISCONTINUITIES

L FAULT OR FRACTURE ZONE, HINGE OF FOLD, OR SHEAR ZONE
M LOCALIZED TECTONIC FRACTURE

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FIGURE 5. Composite Cross Section of Possible Geologic Features in a Layered Basalt Sequence.

From Gephart, et al

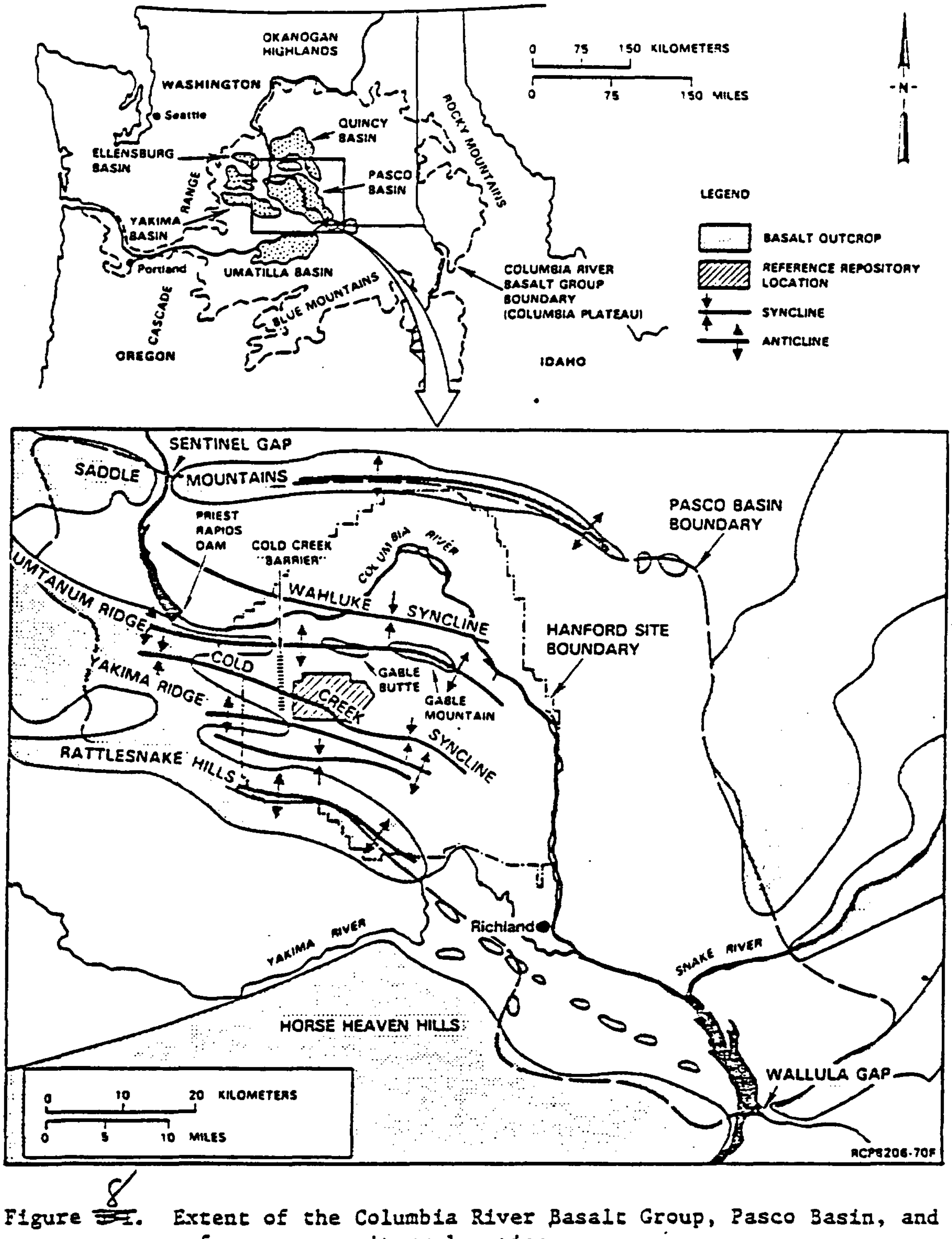

Figure ~~3-1~~ 8. Extent of the Columbia River Basalt Group, Pasco Basin, and reference repository location.

(From EA)

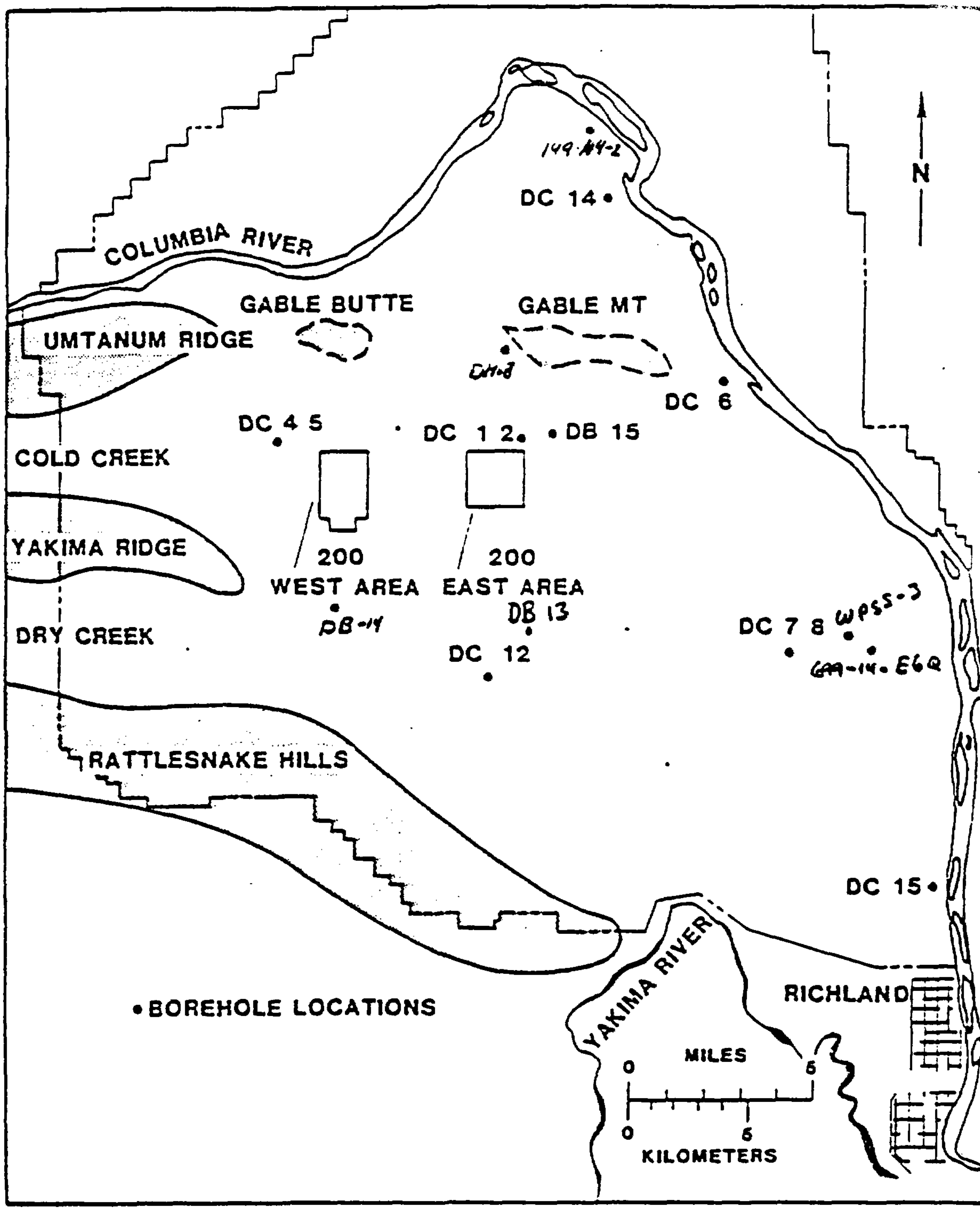

Figure ~~2?~~ 9. Location of Selected Drill Holes in Pasco Basin (Deju, 1980e).

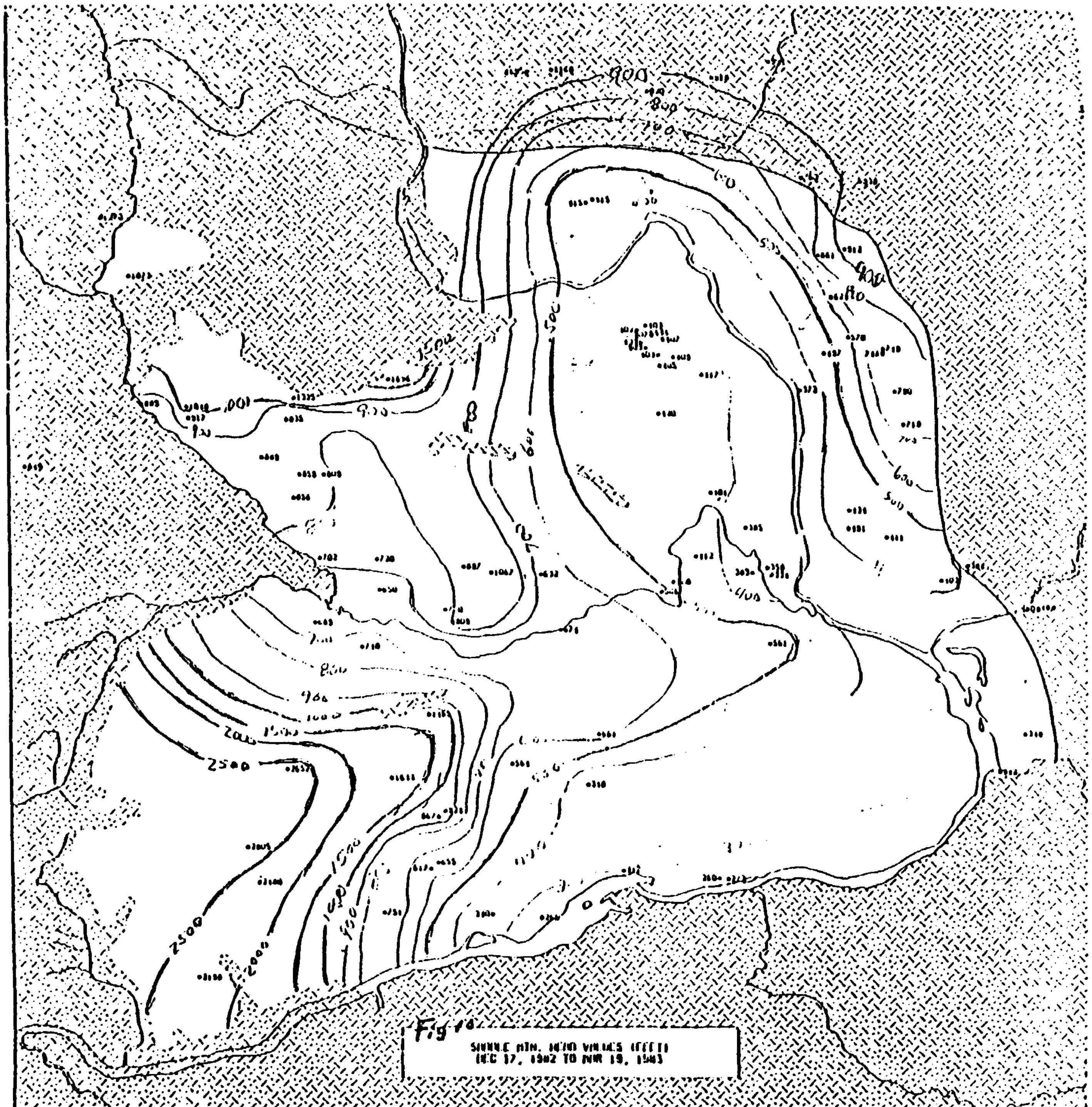

Fig 10

SADDLE MTN. HEAD VALUES (FEET)
DEC 17, 1982 TO MAR 19, 1983

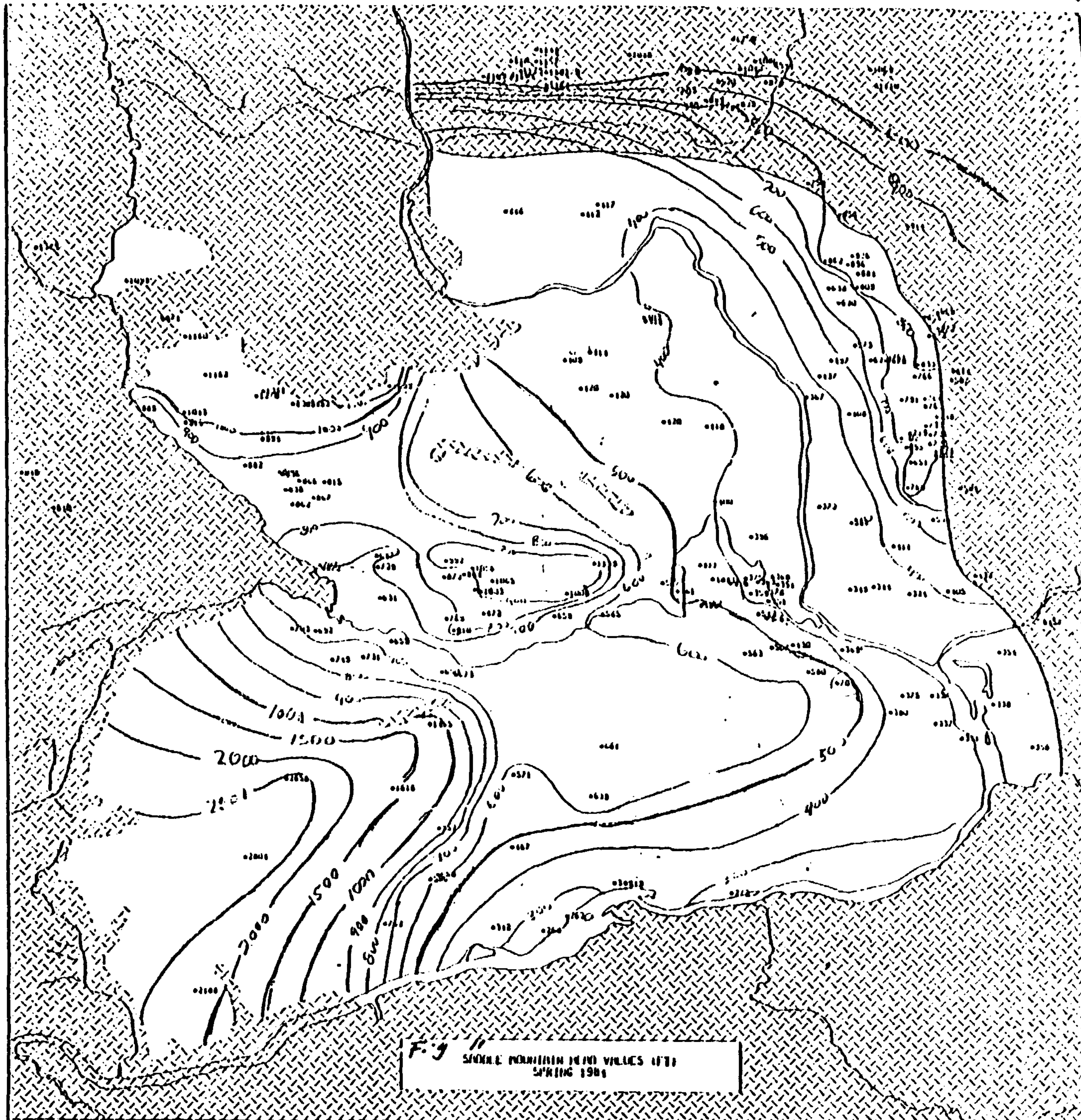

Fig 11
SADDLE MOUNTAIN HEAD VALUES (FT)
SPRING 1984

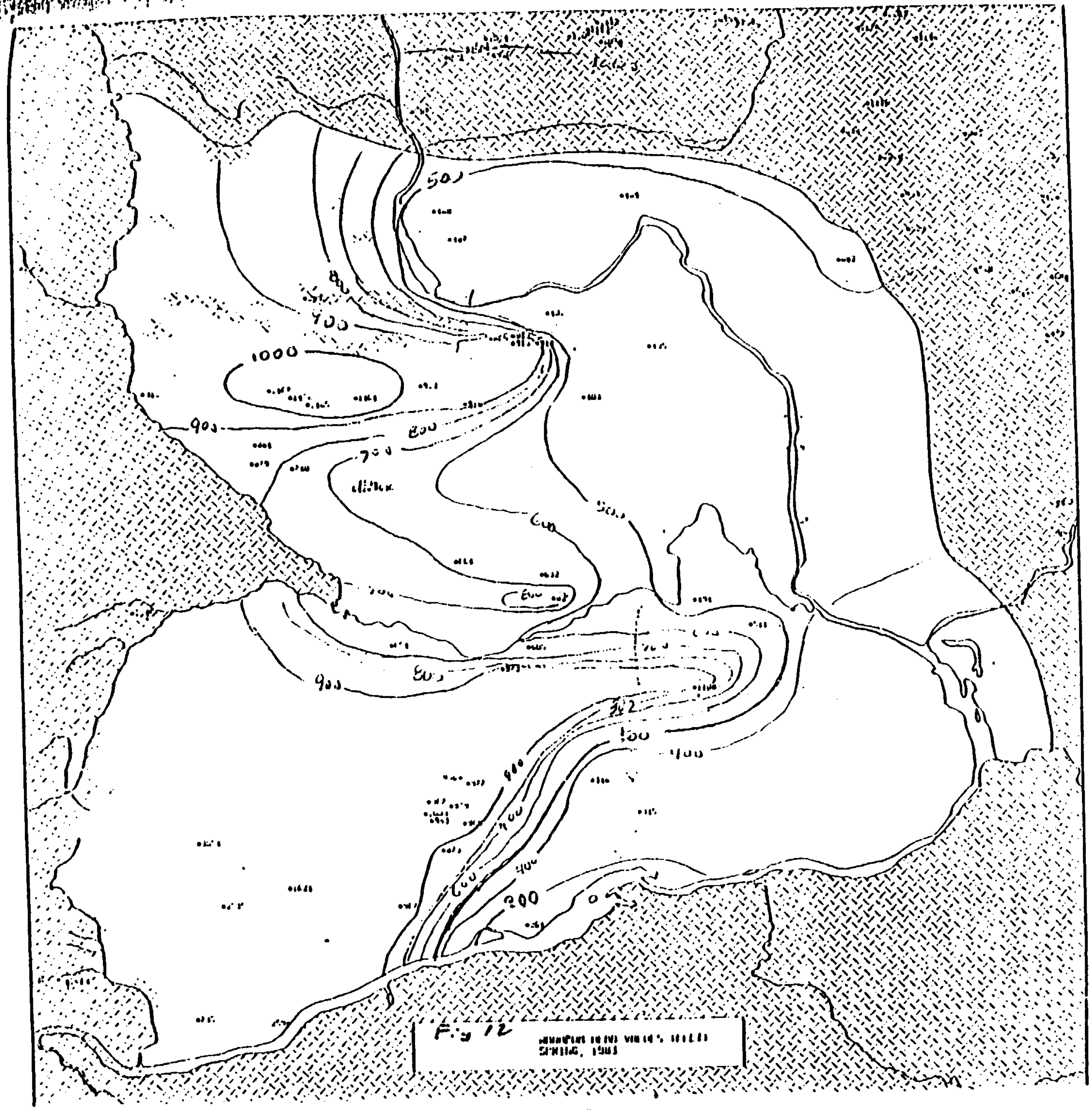

Fig 12

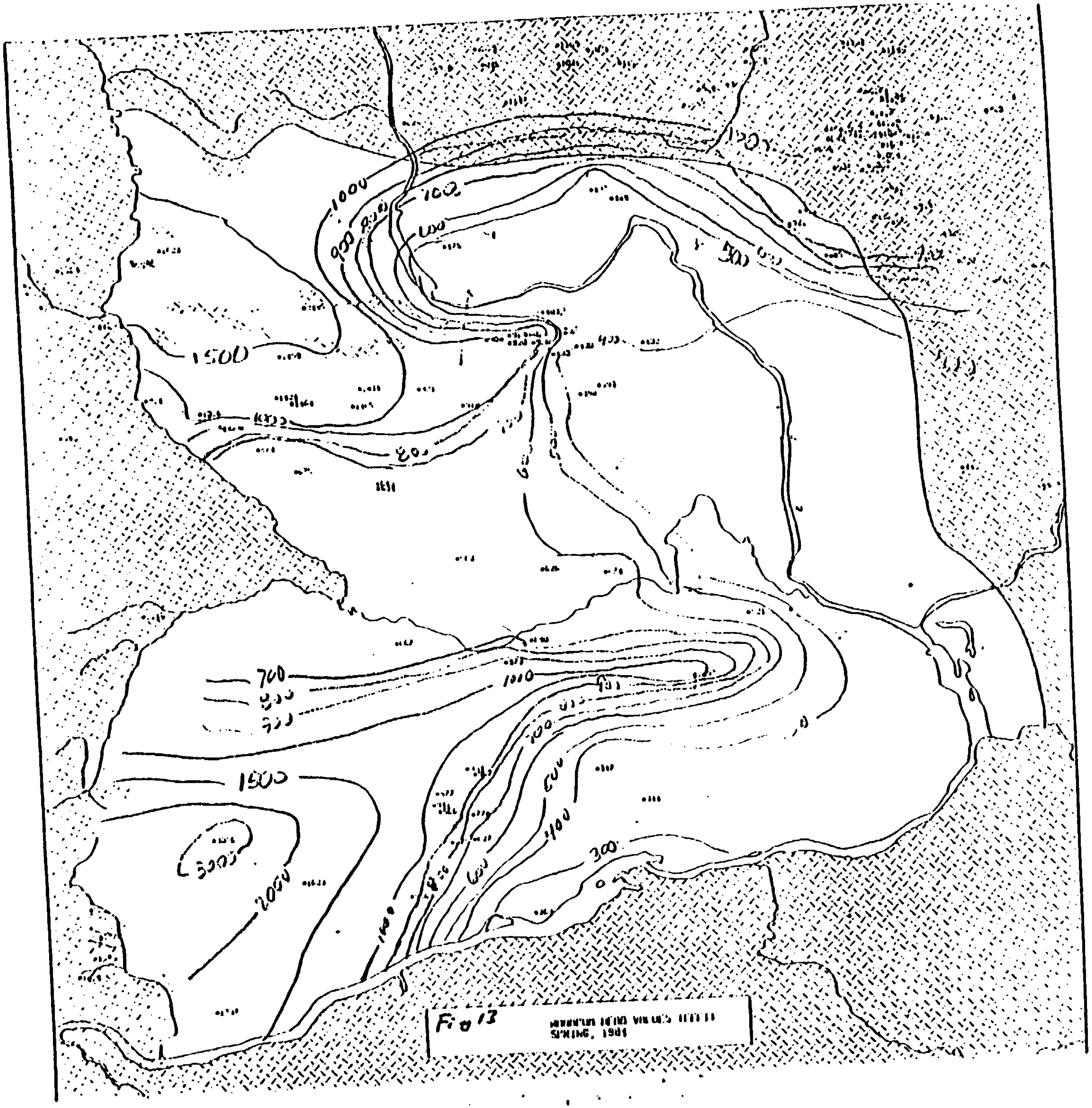

Fig 13

SPRING, 1981

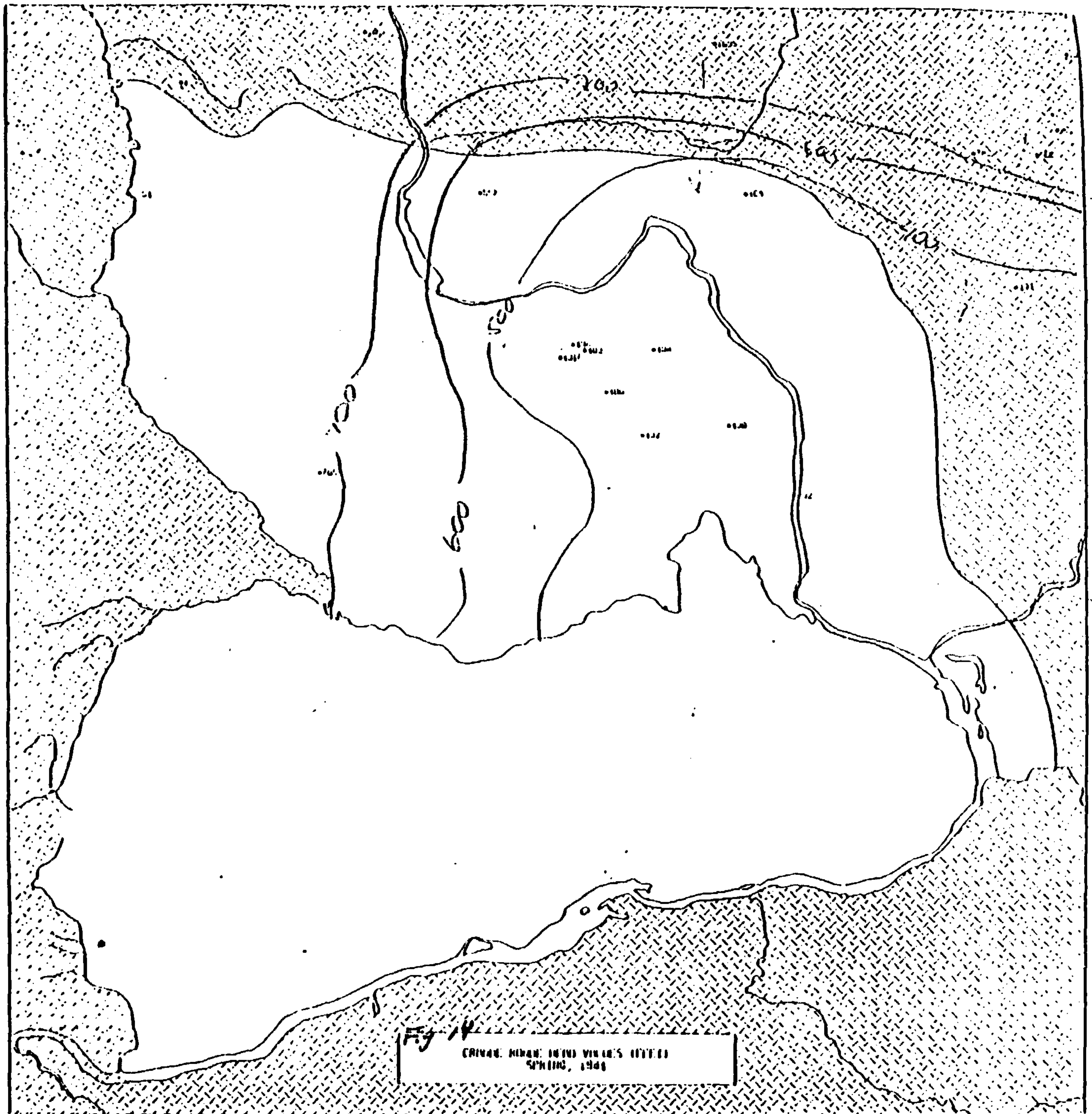

Fig 14

[illegible]
SPRING, 194[illegible]

~~Pasco Basin~~

Precipitation/Infiltration/Deep Percolation

Parameter	AF/yr
Precipitation (P)	756,000
Evapotranspiration (ET)	750,000
Runoff (RO)	0

PR = P - ET - RO

= 6,000 AF/yr (Probable groundwater recharge from precipitation)

Stream Reach Inventory

Parameter	AF/yr
Inflow (IF), Priest Rapids Dam	87,230,000
Tributaries (TR)	43,832,000
Return Flows (RF)	225,000
Outflow (OF), McNary Dam	134,200,000

PSL = IF + TR + RF - DW - OF

= -2,913,000 AF/yr (Probable groundwater discharge to the Columbia River)

Water Use Inventory

Parameter	AF/yr GW	AF/yr SW
Municipal (M)	8,961	20,372
Industrial (IN)	15,361	403,575
Irrigation (IR)	47,760	907,500

AR = $0.1\ IN_{sw} + 0.3\ IR_{sw}$ = 313,000 AF/yr

WG = $0.35\ M_{gw} + 0.3\ IN_{gw} + IR_{gw}$ = 63,000 AF/yr

RAM = AR - WG

= 250,000 AF/yr (Probable groundwater recharge from artificial mechanisms)

Net Exchange

Recharge Parameter	AF/yr
Precipitation (PR)	6,000
Stream loss (PSL)	-2,913,000
Artificial mechanisms (RAM)	250,000

NR = PR + PSL + RAM

= -2,657,000 AF/yr (Probable groundwater discharge from basin)

~~The balance shows a net discharge from the basin of about -2,657,000 acre-feet per year. This suggests probable groundwater inflow from adjacent basins.~~

Table 81 Water Budget of the Pasco Basin.

Table 2

Stratigraphic Interval	Hydraulic Conductivity (feet per day)
Hanford formation	500 - 20,000
Undifferentiated Hanford and Middle Ringold unit	100 - 7,000
Middle Ringold unit	20 - 600
Lower Ringold unit	0.11 - 10

Region	Transmissivity (square feet per day)
North of Gable Butte and Gable Mountain	4,000 - 25,000
On the flank of Gable Butte and Gable Mountain and along paleochannels	40,000 - 600,000
Other areas on the Hanford Site	2,000 - 40,000

	Storage Coefficients
Throughout the unconfined aquifer	0.01 - 0.1

TABLE 3-. Results of Pumping Tests Completed within the Unconfined Aquifer.
(From Gephart et al, 1979)

Sources of Data[a]	Hanford Test Site Coordinates[b]	Tested Interval[c]	Hydraulic Conductivity[d] (ft/day)	Transmissivity[d] (ft^2/day)	Coefficient of Storage[d]	Remarks
1	199-F7-1	MR-H	520	7,800		Data as reported
3	199-K-10	MR	53	4,500	0.04	48-hour test, observation wells
3	299-W21-1	MR	150	29,000		4-hour test
5	299-E28-15	MR-H	3,685	135,000		7-hour test, insufficient stress
1	699-1-18	MR	61	10,000		2-hour test, variable discharge
3	699-2-3	MR	420	25,000		6-hour test, variable discharge
2	699-8-17	MR	640	35,000		8-hour test
3	699-8-32	MR	20	1,000		6-hour test
1	699-17-5	MR	17	750		8-hour test
2	699-17-47	MR-LR	50	5,300		Multiple aquifers
3	699-20-20	MR	150	30,000		No drawdown data, 3-hour recovery
2	699-20-39	LR		8		Short duration, poor well construction
1	699-24-33	MR-H	8,600	373,000		Data as reported
2	699-26-15	MR	200	9,500		6-hour test

Table III-14 (continued)

Sources of Data[a]	Hanford Test Site Coordinates[b]	Tested Interval[c]	Hydraulic Conductivity[d] (ft/day)	Transmissivity[d] (ft^2/day)	Coefficient of Storage[d]	Remarks
2	699-28-40	LR		5		Poor construction
1	699-31-31	MR-H	7,000	246,000		Data as reported
3	699-31-53	MR	120	14,000	0.06	8-hour test
3	699-32-77	MR	260	57,000		6-hour test
3	699-33-56	MR	230	21,000		8-hour test
3	699-35-9	MR	220	11,000		4-hour test
2	699-36-61	MR	43	2,800	0.05	Variable discharge rate
1	699-40-33	LR?	1.3	210		Data as reported
3	699-41-23	MR	190	28,000		Variable discharge rate
3	699-42-12	MR-H	460	60,000		No drawdown data, 5-hour recovery
3	699-43-89	MR?	85	19,000	0.016	24-hour test
2	699-47-60	MR	80	3,300		7-hour test
2	699-55-50	H	9,100	594,000	0.07	48-hour test, observation wells
3	699-61-66	MR-H	600	51,000		Insufficient stress
3	699-62-43	H	1,700	50,000	0.06	13 observation wells
2	699-63-90	H	2,300	296,000		Insufficient stress

Table III-14 (continued)

Sources of Data[a]	Hanford Test Site Coordinates[b]	Tested Interval[c]	Hydraulic Conductivity[d] (ft/day)	Transmissivity[d] (ft^2/day)	Coefficient of Storage[d]	Remarks
1	699-65-50	H	1,800	64,000		8-hour test
3	699-71-77	MR	84	1,600		4-hour test, variable discharge rate
3	699-77-54	MR	175	13,000	0.03	24-hour test
2	699-84-35	LR	0.11	4		Very short duration
2	699-87-55	MR	130	4,500		24-hour test
3	699-S8-19	MR	57	9,100		Poor drawdown, 6-hour recovery
1	699-S12-3	MR-LR	7	280		8-hour test
4	10/28 14K	MR-H		144,000		Data as reported

[a]Sources of data:

1. Bierschenk (1959);
2. Deju (1974);
3. Kipp and Mudd (1973);
4. Newcomb and Others (1972).
5. Information on file at Rockwell Hanford Operations.

[b]Refer to McGhan and Damschen (1979) for explanation of Hanford Site Coordinate System.

[c]Tested interval:

H - Hanford formation;
MR - middle member of Ringold Formation;
LR - lower member of Ringold Formation.

[d]Blank spaces indicate information not reported.

Table N-5. Trace Element Concentrations in Ground Water at the Hanford Site

	Confined aquifers of Grande Ronde Formation: Apps and others 1979		Gephart and others 1979	Priest Rapids Member of Upper Wanapum basalt, Gephart and others 1979		Mabton Interbeds Gephart and others 1979	Unconfined Ground water at Hanford Site Gephart and others 1979
Ag	<0.010	--	--	--	--	--	<0.010 - 0.002
Al	--	--	0.11	<0.05	0.086	<0.020 - 2.170	<0.050 - 0.470
As	<0.002	0.001	--	--	--	--	0.001 - 0.014
B	--	--	1.39	0.10	0.013	<0.005 - 0.550	<0.009 - 0.150
Ba	0.150	<0.112	<0.005	0.027	0.053	<0.005 - 0.065	0.007 - 0.100
Br	0.201	0.285	--	--	--	--	
Cd	0.007	0.089	<0.005	<0.005	<0.005	<0.005 - 0.009	<0.003 - 0.140
Co	<0.017	0.047	<0.020	<0.005	<0.005	<0.005	<0.002 - 0.010
Cr	<0.0002	<0.0004	<0.005	<0.005	<0.005	<0.005	<0.050 - 0.100
Cu	0.050	0.060	<0.005	0.005	<0.005	<0.005	<0.010 - 0.047
Fe	0.017	0.015	0.054	0.228	0.181	<0.005 - 4.700	<0.005 - 3.9
Mm	0.004	<0.009	<0.010	<0.100	<0.10	<0.010	<0.001 - 0.480
Mo	0.270	0.31	0.310	<0.020	<0.020	<0.010	<0.001 - 0.030
Ni	0.070	--	<0.005	<0.005	<0.005	<0.005 - 0.030	--
Sr	0.012	0.003	<0.005	--	--	0.009 - 0.111	--
Zm	0.260	0.240	0.096	<0.005	<0.015	<0.005 - 0.093	<0.005 - 1.6

from Gurzowski (?) p. N.14

TABLE III-19. Principal Organizations Involved in Basalt Hydrologic Testing.

Date	Organization	Borehole***	Work Accomplished	Basalt Tested
1968	Raymond and Tillson (1968)	RHS-1	7 DST and 7 head measurements	Grande Ronde and pre-Grande Ronde
1969	LaSala and Doty (1971)	DC-1	4 pumping tests 11 fluid injection and withdrawal tests 22 head measurements Water samples	Saddle Mountains, Wanapum, and Grande Ronde
1977	Gephart and Others (1979)	RSH-1	7 withdrawal and injection tests Water samples	Grande Ronde
1978	Science Applications, Inc. (1978)	DC-2	6 injection tests 2 head measurements	Grande Ronde
1978	Apps and Others (1979)	DC-2	6 head measurements 1 water sample	Grande Ronde
		DC-6	15 head measurements 12 flow tests 1 water sample	Grande Ronde
		DC-8	4 head measurements	Wanapum
1978	W. K. Summers and Associates*	DC-6	5 injection tests 9 head measurements	Grande Ronde
1978	Rockwell Hanford Operations **	DB-1,2,4 5,7,9,10, 12,13,14 and DH-8	20 head measurements 12 pump tests	Saddle Mountains
		DB-11	Water samples and head measurements	Wanapum
1978-79	Rockwell Hanford Operations **	Several boreholes. Refer to text.	Pump tests, water samples, and head measurements	Saddle Mountains and Wanapum

*Data on file in the Basalt Waste Isolation Project Library.
**Results of data analyses presented in this report.
***McGhan and Damschen (1979).

TABLE 6(?). General Basalt Lithology Given as a Percentage of Formation Thickness Drilled in Borehole DC-1.

(After LaSala and Doty, 1971.)

Columbia River Basalt	Interval Thickness (ft)	Dense Basalt (%)	Interflows of Vesicular or Brecciated Basalt (%)	Sedimentary Interbeds (%)
Saddle Mountains	625	54	4	42
Wanapum	1,120	61	11	28*
Grande Ronde	2,055	62	32	6

*Percentage probably high because LaSala and Doty (1971) reported several weathered basalt zones as tuff.

From Gephart et al (1979) p. III-95

TABLE ~~III-21~~ 27 Hydraulic Heads within Selected Stratigraphic Intervals in the Saddle Mountains Basalt.

From Gephart

Borehole Identification*	Aquifer**	Year of Measurement	Hydraulic*** Head Elevation (feet)
DB-1	Mabton	1979	385
DB-2	Mabton	1979	385
DB-4	Mabton	1979	419
DB-5	Mabton	1979	407
DB-7	Mabton	1979	404
DB-9	Mabton	1979	403
DB-10	Mabton	1979	405
DB-12	Selah	1978	402
	Mabton	1979	402
DB-13	Elephant Mountain interflow	1978	417
	Rattlesnake Ridge	1978	418
	Cold Creek	1978	420
	Mabton	1979	421
DB-14	Rattlesnake Ridge	1978	449
	Selah	1978	424
	Cold Creek	1978	423
	Mabton	1979	422
DC-1	Selah	1969	407
	Cold Creek	1969	409
	Mabton	1969	400 (?)
DH-8	Mabton	1979	403
WPPSS-3	Rattlesnake Ridge	1979	380
699-14-E6Q	Rattlesnake Ridge	1969	389
199-H4-2	Rattlesnake Ridge	1968	414

*Refer to McGhan and Damschen (1979) for explanation of Hanford Coordinate System.
**Interbeds except where noted.
***Accuracy ± 0.1 foot, except DC-1 which is ± 20 feet.
Elevations in feet above mean sea level.

TABLE ~~III-2~~ 8. Hydraulic Heads within the Wanapum Basalt in Borehole DC-1.*

Test Interval (feet below ground level)**	Head*** (feet above mean sea level)	Comment
820 - 1,190	402	Straddles bottom of Saddle Mountains and top of Wanapum Basalt
1,130 - 1,190	409	
1,330 - 1,520	405	Value estimated
1,560 - 1,750	405	
1,760 - 1,950	407	
1,970 - 2,150	407	Straddles bottom of Wanapum and top of Grande Ronde Basalt

*Data from LaSala and Doty (1971).
**Ground level elevation 572 feet.
***Accuracy ± 20 feet.

TABLE 8 ~~III-1~~3. Hydraulic Heads within the Wanapum Basalt in Borehole DC-8.*

Test Interval (feet below ground level)**	Head*** (feet above mean sea level)
1,710 - 1,740	433
1,810 - 1,840	431
1,990 - 2,020	435
2,033 - 2,063	422

*Apps and Others (1979).
**Ground level elevation 545 feet.
***Reported accuracy ± 2.5 feet.

TABLE ~~III-~~10~~5~~. Hydraulic Heads within the Grande Ronde Basalt of Borehole DC-1.

Test Interval* (feet below ground level)	Head (feet above mean sea level)	Comment**
1,970 - 2,160	407	Straddles bottom of Wanapum Basalt and top of Grande Ronde Basalt
2,170 - 2,225	406	
2,430 - 2,610	403	
2,600 - 2,780	402	
2,730 - 2,910	411	
3,146 - 3,236	411	
3,166 - 3,196	409	
3,206 - 3,246	403	
3,320 - 3,451	408	
3,774 - 3,934	379	
3,910 - 4,070	366	
4,080 - 4,283	368	

*Data from LaSala and Doty, (1971). Ground level elevation 572 feet.
**Head measurement accuracy ± 20 feet.

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TABLE ~~III-3~~7. Hydraulic Heads Reported for the Grande Ronde Basalt in Borehole DC-2.

Test Interval (feet below ground level)[c]	Rock Density[d]	Head[e] (feet above mean sea level)
[a]2,269 - 2,299	High	470
2,340 - 2,370	Low	443
2,625 - 2,655	Low	438
2,795 - 2,825	Low	421
2,960 - 2,990	Low	395
3,160 - 3,190	Low	377
3,243 - 3,273	Low	362
[b]2,344 - 2,376	Low	444
2,376 - 2,409	High	423
2,955 - 3,007	Low	419
3,019 - 3,071	High	421
3,069 - 3,122	High	446
3,116 - 3,170	High	423

[a]Apps and Others (1979).
[b]Data from Science Applications Inc. (1978).
[c]Ground level elevation 572 feet.
[d]Low density--Test straddled at least one zone of low-density (≈2.4-2.6 grams/cubic centimeter) basalt. High Density--Test straddled only high-density (≈2.7-2.8 grams/cubic centimeter) basalt. Densities were determined by geophysical log interpretation.
[e]Head accuracy of ± 2.5 feet reported by Apps and Others (1979).

TABLE 12. Hydraulic Heads Reported for the Grande Ronde Basalt in Borehole DC-6.[a]

Test Interval (feet below ground level)[b]	Rock Density[c]	Head[d] (feet above mean sea level)
*2,240 - 2,270	Low	450
2,400 - 2,430	Low	447
2,454 - 2,484	Low	456
2,708 - 2,738	Low	423
2,896 - 2,936	Low	454
3,025 - 3,055	Low	460
3,343 - 3,373	Low	443
3,620 - 3,650	Low	421
3,650 - 3,680	Low	432
3,683 - 3,713	Low	429
3,692 - 3,722	Low	432
3,341 - 4,336	Several high and low	426
3,477 - 4,336	Several high and low	437
3,601 - 4,336	Several high and low	434
3,802 - 4,336	Several high and low	466

[a]Apps and Others (1979).
[b]Ground level elevation 402 feet.
[c]Low density--Test interval includes at least one zone of low-density basalt which normally corresponds to an interflow zone. High density--Test interval in high-density basalt which normally corresponds to a section of columnar basalt.
[d]Head accuracy ± 2.5 feet as reported by Apps and Others (1979).
*Head elevations are above ground level. Artesian flow is ~10 gpm.

Figure E-3. Histogram of Effective Porosity/Total Porosity Ratio for Basalt.

Table 13. Porosity of Basalt - Columbia Plateau

SOURCE	LOCATION OR BASALT UNIT	TOTAL Ø(%)	Effective Ø (%)
Colorado School of Mines (1978)	Pomona flow	0.96->37.8	-
Deere and Miller (1966)	Columbia River basalt	-	0.75-1.92
Duvall and others (1978)	Pomona flow	-	1.60-2.39
Erikson and Krupka (1980)	Pomona flow	-	0.50-0.60
Foundation Sciences Inc. (1980a)	Pomona flow	2.71-8.14[c]	0.5 -1.4
Foundation Sciences Inc. (1980b)	Pomona flow	1.0 -7.7[c]	0.1 -0.6
Foundation Sciences Inc. (1980c)	Pomona Umtanum flows	0.71-9.68[c]	0.19-1.85
Foundation Sciences Inc. (1981)	Umtanum flow	0.71-9.68[c]	0.19-2.06
Nace and others (1959)	Columbia River basalt	3.8 -24.8	-
Podnieks and others (1972)	Columbia River basalt	-	2.0
Robertson (1970)	Columbia River basalt	18.5[c]	-
Schmidt and others (1980)	Summary, Hanford basalts	-	1.5 -2.8[a]
Stephenson and Triandafilidis (1974)	Columbia River basalt	2.2	-
White and Sarcia (1978)	Columbia River basalt	0.55-3.84	0.18-1.34

4.0 Review of Ground-water Flow Models of the Hanford Site

This contains reviews of available groundwater flow models of the Hanford site. The reviews are designed to provide a brief description of each model, its limitations and assumptions, and its relevance to NRC licensing rules. Following the reviews is a summary of all the modeling efforts at the Hanford site.

REFERENCE:

Arnett, R. C., 1980; "Far-Field Modeling: Simulation of the Natural Groundwater System in the Pasco Basin," in Basalt Waste Isolation Project Annual Report - Fiscal Year 1980; RHO-BWI-80-100

PURPOSE OF THE STUDY:

Understanding the groundwater flow systems in the Pasco Basin and identifying data and conceptual model limitations and calculating preliminary travel times.

SOURCES OF DATA:

Spane, F. A. Jr., 1980, RHO, BWI-80-100

DISCRETIZATION: (see Figure 4)

Layer discretization is given in "hydrostratigraphic units."

IMPLEMENTATION OF BOUNDARY CONDITIONS: Not described.

IMPLEMENTATION OF INITIAL CONDITIONS:

Not important for steady-state simulation.

MODEL CALIBRATION:

Data Set Used for Comparison

See Spane 1980, RHO-BWI-80-100 and figure 5. Note: only Mabton heads used for comparison.

Type of Calibration Procedure: Trial and error

Type of Statistics Relating Model to Measured Heads: None

Accuracy of Calibrated Model:

All calculated heads are substantially above the measured heads

SENSITIVITY ANALYSIS: None

MODEL RESULTS: The authors state the following results:

Hydraulic Heads: (Note: only the heads for the top of the Wanopum Basalt are reported)

1) A composite hydraulic conductivity ratio of 10^{-4} to 10^{-5} provides a better match of the "relative pattern" of the hydraulic head surface than a ratio of 10^{-2}.

2) With a composite hydraulic conductivity of 10^{-4} to 10^{-5}, the vertical pathway from a potential candidate site is a significant portion of the total path in terms of overall travel time to the biosphere.

3) The problem of the model-calculated heads being "significantly" higher than the measured heads is attributed to absence of the "Cold Creek Syncline Barrier" in the model.

Fluxes:

No information on model-calculated fluxes was provided.

Travel Times

No travel times were reported. However, Figures 6 and 7 reveal significantly different flow directions from the location of a hypothetical repository. For anisotropy ratios of 10^{-2} to 10^{-3} (Figure 6), the inferred direction of flow is to the north/northeast toward the Columbia River. As revealed in Figure 7, anisotropy ratios of 10^{-4} to 10^{-5} produce flow toward the north, then vertically upward. This letter path would probably result in longer travel times to the accessible environment (that is, a given distance from the repository) because of the additional time spent in law permeability dense flow interiors.

Significance to Licensing

If the assumption was made that these model results represent the "true" hydrologic conditions of the Pasco Basin, then the indicated longer travel time would aid the DOE in meeting the 1000 years ground-water travel time of 10CRF60.

EVALUATION:

• Conceptual Model

The most important aspects of a steady-state model are the boundary conditions and the choice of layering. Unfortunately, very little information was provided about the boundary conditions and the discussion of layering is internally inconsistent. Below is a discussion of each of these important aspects of the conceptual model.

- Boundary Conditions

• Bottom

There is no explicit description of the of the bottom boundary. I assume, however, that it has been treated as a no-flow boundary. The exact nature of this boundary has not been determined as there is an extreme paucity in any unit below the Wanapum Basalts. There is a possibility that the Pasco Basin is a discharge area for regional flow in the flood

GEOHYDROLOGIC FRAMEWORK: (Conceptual Flow Model)

Hydrostratigraphic Units - See figure 1

Selection based on "groundwater head and chemistry measurements." That is, reversal of hydraulic head gradient with depth and abrupt changes in chemical composition with depth (see figure 2). Note, however, that the layers shown in figure 1 do not correspond with the model reported in this study which includes only the Grande Ronde Wanapum, and Saddle Mountains basalt along with possibly the alluvium as an upper boundary condition.

Hydraulic Parameters

Listed in Table 1 are the parameters used as a starting point. However, presented results are not for these valves but correspond to ratios of Kv/Kh shown in Table 2.

BOUNDARY CONDITIONS:

The location of the model boundaries is shown in Figure 3. These boundaries correspond to the surface-water drainage boundaries of the Pasco Basin. The type of boundary condition imposed at these locations is not discussed but the report indicates that they are fixed potential or constant-head boundaries. I could not ascertain whether the top boundary was a recharge boundary or fixed potentials representing the elevation of the rivers and the water table in the sediments.

NUMERICAL IMPLEMENTATION:

- CODE DESCRIPTION

Name: RHAFE - Rockwell Hanford Finite - Element Model

Reference: Gupta, S. K., Tanji, K. K., and Jon Luthin; 1975; A Three-dimensional Finite Element Groundwater Model; Contribution Number 152, California Water Resource Center, University of California. (version of FE3D6W?)

Dimensions: 3

Equations Solved: Steady-state and transient isothermal ground-water flow equations

Method of Solution: Finite element

basalts. If this is the case, then treating this boundary as impermeable could produce unrealistically vertical gradients, and exaggerated travel times.

- Top and Lateral Boundaries

The treatment of these boundaries is not described by the authors. My guess is that they were treated as a constant hydraulic head boundaries with heads being equal to the water-table elevation for the top boundary and equal to heads measured from wells near completed in the appropriate units for the lateral boundaries. This would be consistent with other modeling studies of the Pasco Basin. However, the document seems to make contradictory statements with regards to the lateral boundaries. On page III-51, the authors state that the boundary conditions may need adjustment but appear to be in the proper range. This statement suggests that the boundaries were treated as constant heads. However, on Figures 6 and 7 (this report) the model-calculated heads are different at the boundary for the two cases. This would not be possible if the boundaries were constant heads. In a steady-state simulation, these held potentials will dominate the model results. The adequacy of employing these conditions depends on the data needed to support them in terms of their input value and measures of the resulting output. That is, a head valve is needed at every computational point along the boundary. If hydraulic head data are scarce, as they are for most basalts within the Pasco Basin, then a large uncertainty is introduced by interpolating or extrapolating valves to the boundary. In addition, these input head valves along with the input hydraulic conductivities result in a model-calculated flux across the boundaries. Unfortunately, no information on the real flux exists thereby eliminating the possibility of cross-checking the accuracy of the boundary conditions.

In summary, the lack of a description of the type and possible valves of flux or head assigned to the model makes the evaluation of the boundary conditions impossible. Also, because the boundary conditions dominate steady state simulations, the ability to evaluate the overall modeling effort is severly limited.

-Hydrostratigraphic Units

Several questions arise in evaluating the hydrostratigraphic units simulated in this study: 1) Which units were simulated?, 2) How were the units chosen?, and 3) How are model results affected by this choice?

Shown in Figure 1 are the five layers the authors state have been simulated. However, in their "SUMMARY OF RESULT," they indicate that four layers were simulated. One possible resolution of this descrepancy is that the top layer was held as a constant-head boundary.If this were true, then the model would have five layers of which only the lower four were being simulated. However only three layers are mentioned. This could mean that the three basalts were simulated and the top layer was held as constant heads.

Due to the complexity of the flood basalts, no unique set of hydrostratigraphic units exists. In addition, even if every zone of different hydraulic properties could be identified and characterized sufficient computer recources do not exist to simulate all of them. The units that were chosen were on the basis of changes in the geochemistry and hydraulic heads with depth. These may or may not be indicators of distinct hydrostratigraphic units. However because some lumping of smaller units will always be necessary, a more important question is what affect the choice of units has on model results. Of course the obvious effect is to lose detail of the hydraulic-head distribution. Perhaps less notable is the incorrect travel path that would be predicted by a grid which is less detailed than reality. In addition, any comparison of model results to measured values requires some interpolation or lumping procedure for the measured parameters. This introduces additional uncertainty into model calibration.

Numerical Implementation

Except for the finite-element grid, no details of numerical implementation are provided in the document.

Model Calibration

The only calibration that was performed involved adjusting the ratio of vertical to horizontal hydraulic conductivity for the three basalt layers. the resulting hydraulic-head surface for the top of the Wanapum was then subjectively compared in the same measured surface. All simulations resulted in heads that are significantly higher than the measured values in some places at least 100ft. However the authors believe the simulations with lower ratios of vertical to horizontal conductivities produced a "relative pattern" of hydraulic heads that more closely resembles the measured heads.

Following is a summary of my evaluation of the model calibration:

1) Insufficient data, in terms of input parameters, boundary conditions, and data used for model comparison is provided to allow for a complete evaluation of the model calibration.

2) The fact that all model calculations produce heads that are too high is indicative of a systematic plan flow in either the model set up or the model parameters. If the top and lateral boundaries of the model are being held at a constant hydraulic heads which were interpolated from measured valves, then the most liekly cause of the high heads is that the model hydraulic conductivities are too low. If the top boundary is a recharge condition, then the amount of assumped recharge could be too large.

3) Assuming that: a) the shape of the potentiametric surface presented in figure 5 is accurate; b) the model boundary conditions are held potentials with valves being close to the "real" valves; and c) the shape of the model-predicted potentiometric surface

would not change as a more accurate calibration is achieved; then the fact that lower conductivity ratios produce a more realistic pattern of hydraulic heads indicates that the lower units are controlled more by the shape of the basin and perhaps a more regional flow system than by the Columbia River.

4) The authors believe that if the Cold Creek barrier were included in the model the overall calibration would improve. This is unlikely as heads in all regions, even far to the south, are too high.

5) Even though the lower conductivity ratios appear to produce more realistic patterns of hydraulic heads, the absolute valves of heads for the higher ratios are closer to the measured valves.

Sensitivity Analysis: None performed

Model Results.

The fact that this model has not been calibrated combined with the lack of information on boundary conditions makes any results from this model highly suspect. At best, the significance of this study was to parameterize the vertical to horizontal hydraulic conductivity ratios. However, even these results are not reliable given the inability of the model to produce accurate hydraulic heads in any region.

TABLE 1. Baseline Material Hydraulic Conductivities Used in Calculating Basalt Composite Conductivities

Basalt	Material	Percent of Total Basalt Thickness	K (feet per day)	Layer Values* (m/d) Kv	Kh	Kv/Kh
Saddle Mountains	Basalt	60	10^{-6}			
	Interflow	20	10	1.7E-6	4	4E-7
	Interbed	20	10			
Wanapum	Basalt	60	10^{-6}			
	Interflow	35	10	1.7E-6	4	4E-7
	Interbed	5	10			
Grande Ronde	Basalt	60	10^{-6}			
	Interflow	39	10^{-2}	1.7E-6	.1	1.7E-5
	Interbed	1	10			

*Data from RHO-BWI-80-100

TABLE 2. Ratios of Kv to Kh used to Produce Model-Calculated Heads in RHO-BWI-80-100

Basalt	Simulation 1 (see figure)	Simulation 2 (see figure)
Saddle Mountains	2×10^{-3}	2×10^{-5}
Wanapum	8×10^{-3}	8×10^{-5}
Grande Ronde	3×10^{-2}	3×10^{-4}

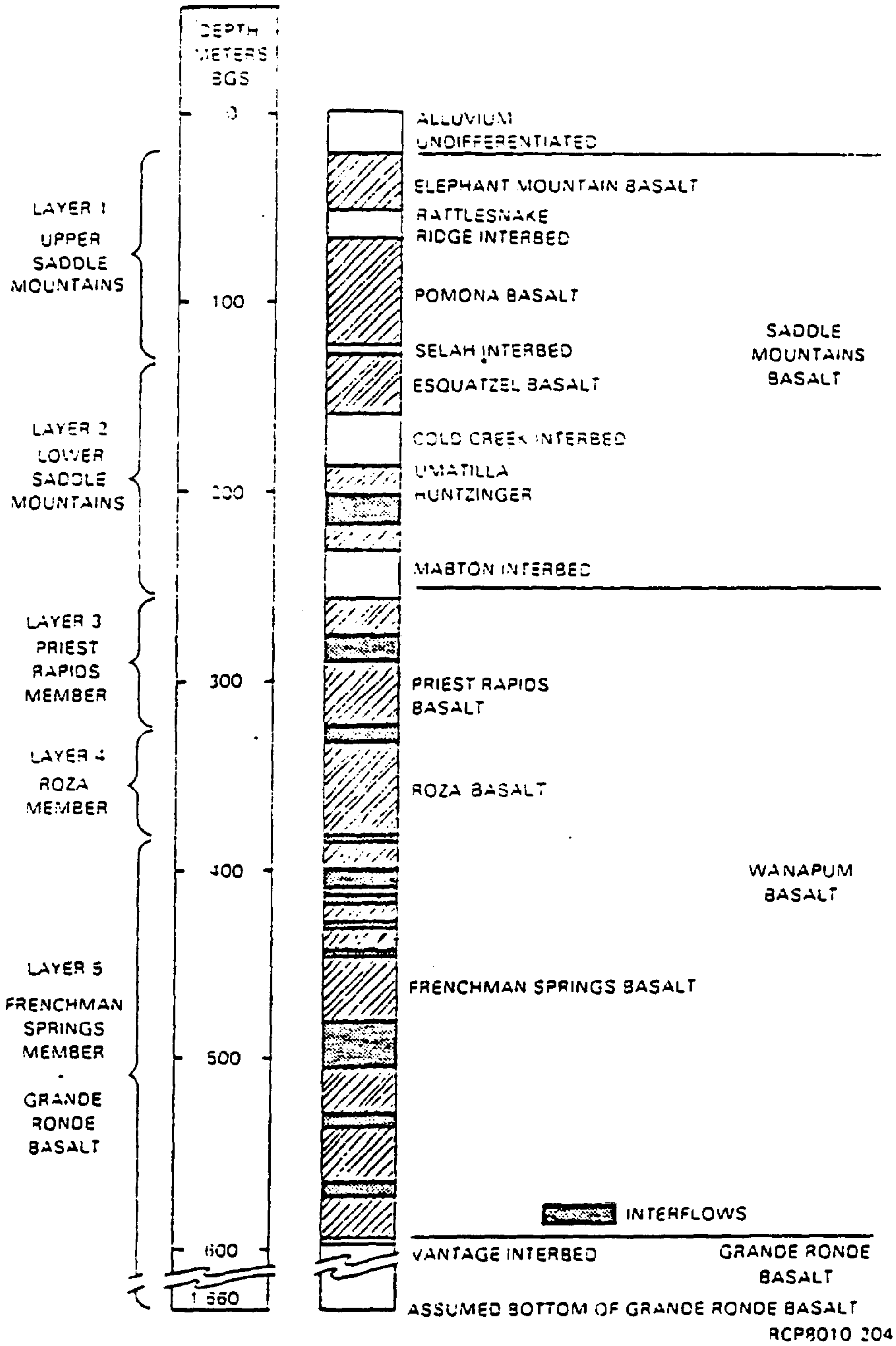

FIGURE 1. Vertical Layering for Pasco Basin Three-Dimensional Model at Well DC-15.

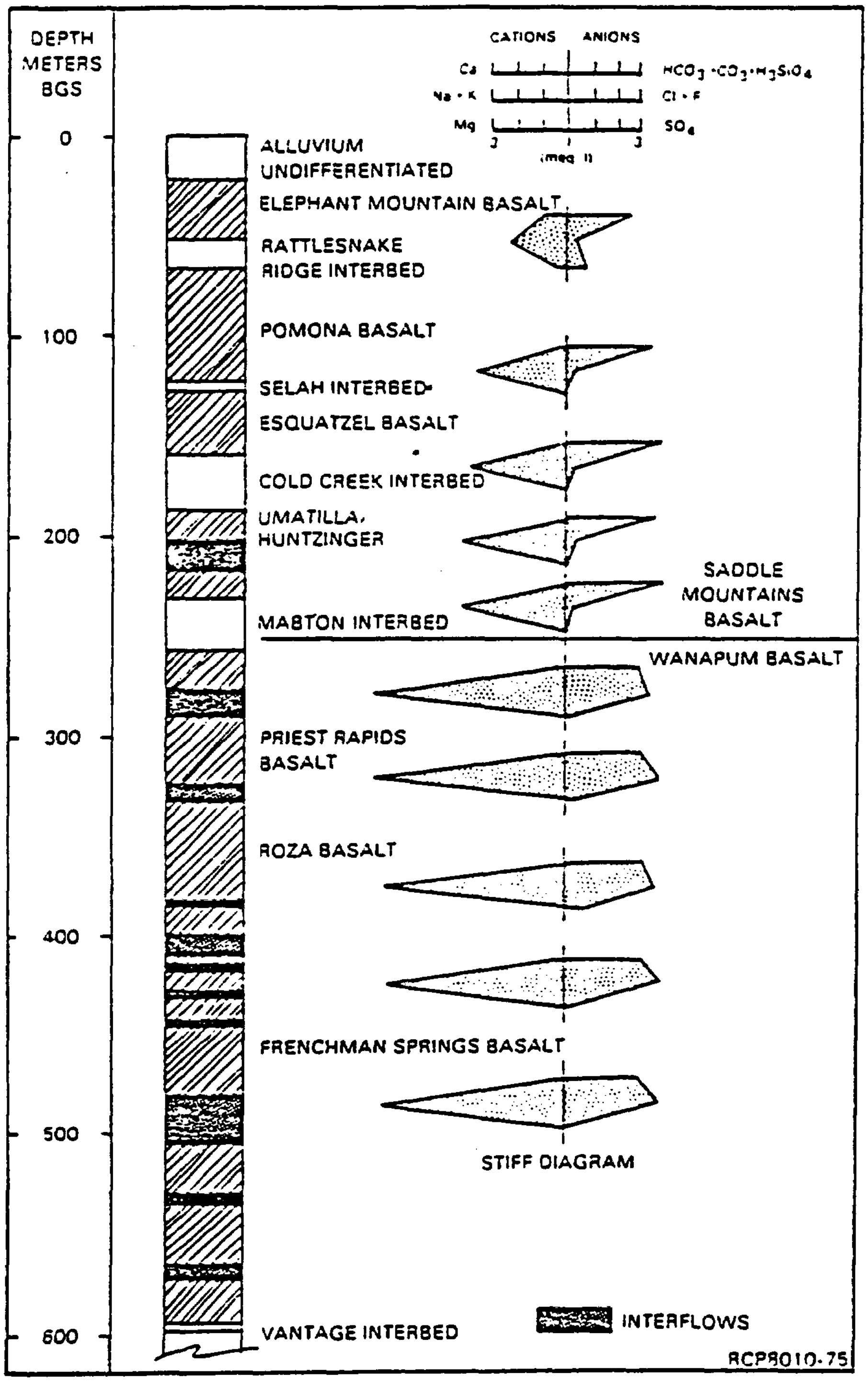

FIGURE 2 Preliminary Hydrogeologic and Hydrochemical Data within the Saddle Mountains and Wanapum Basalts at Borehole DB-15.

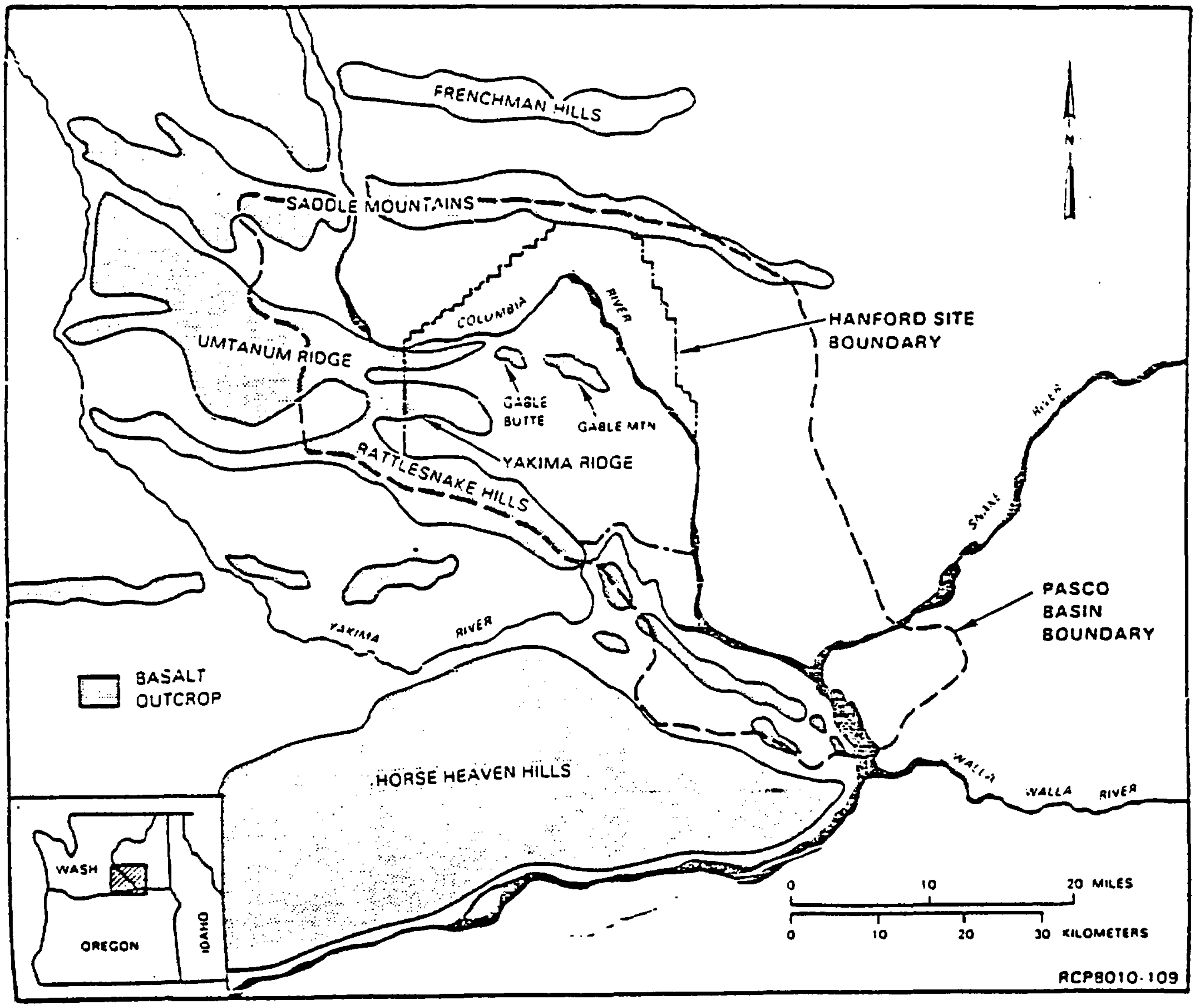

FIGURE 2. Pasco Basin and Hanford Site.

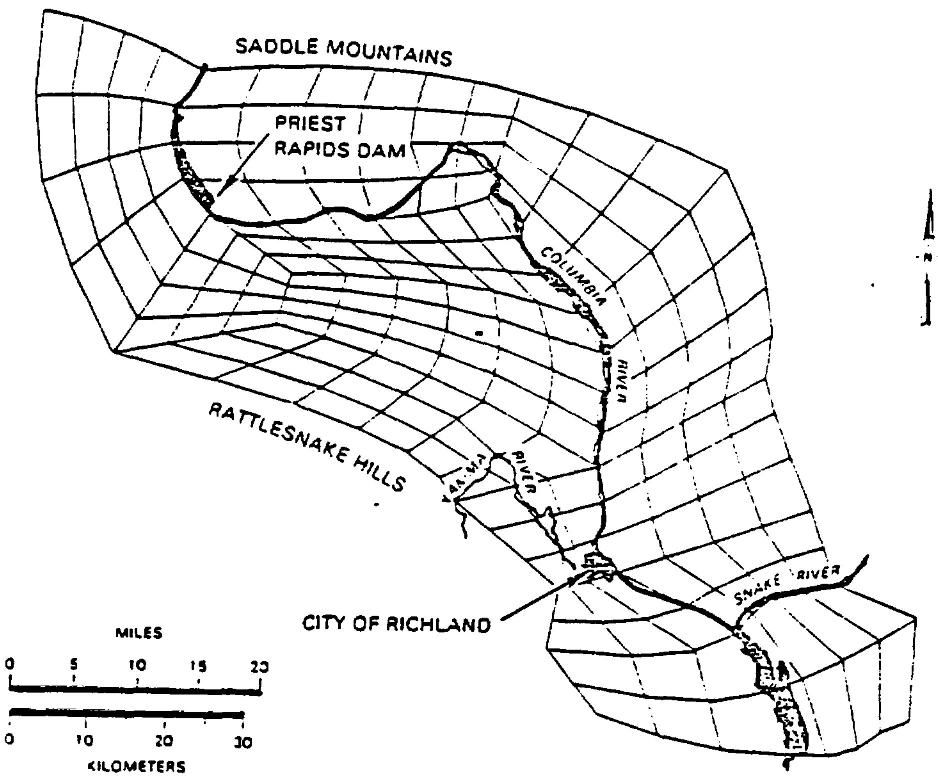

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FIGURE 4. Plan View of Three-Dimensional Finite Element Network for Pasco Basin.

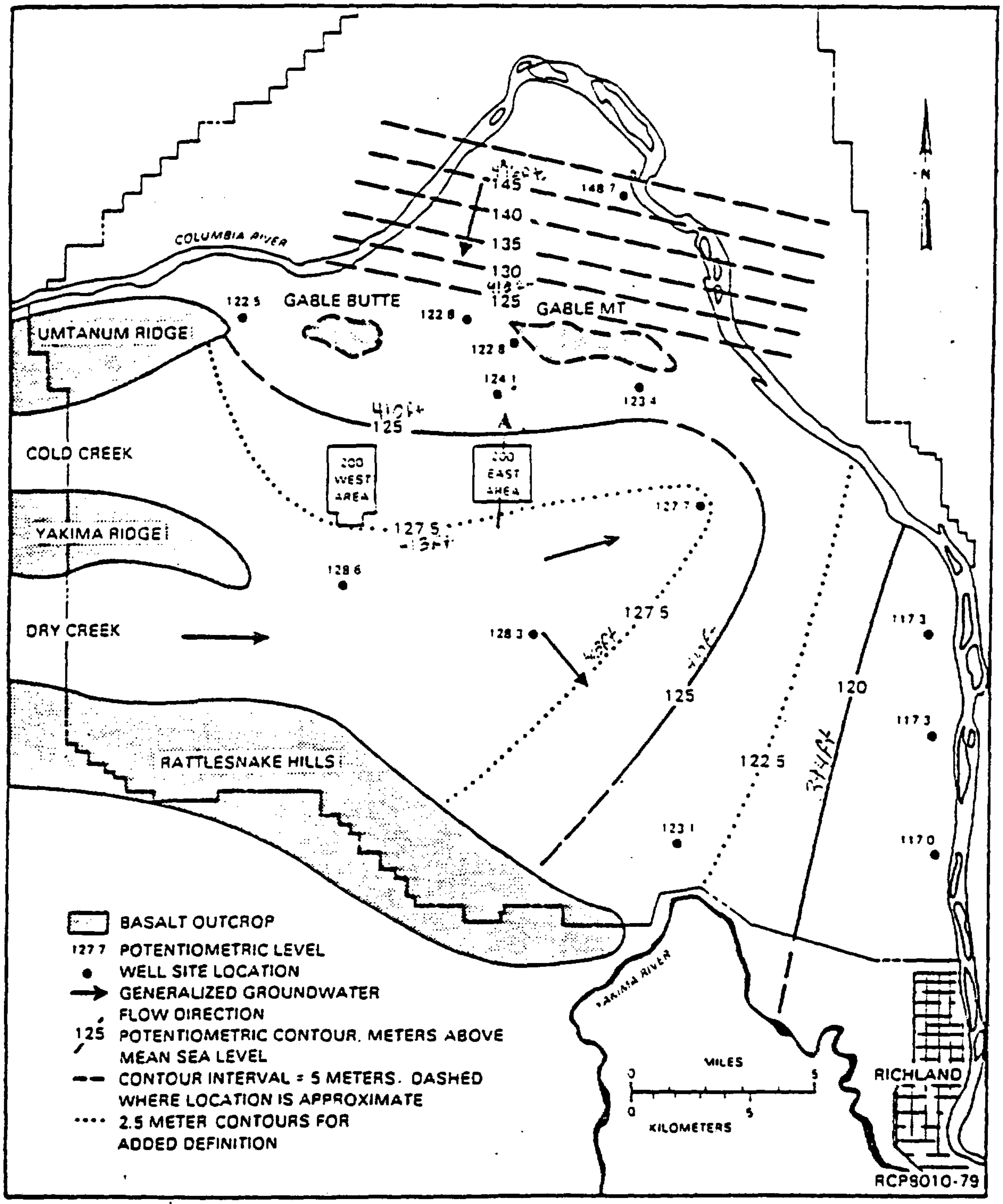

FIGURE 7 Potentiometric Map for and Inferred Flow Directions of Groundwater within the Mabton Interbed beneath the Hanford Site.

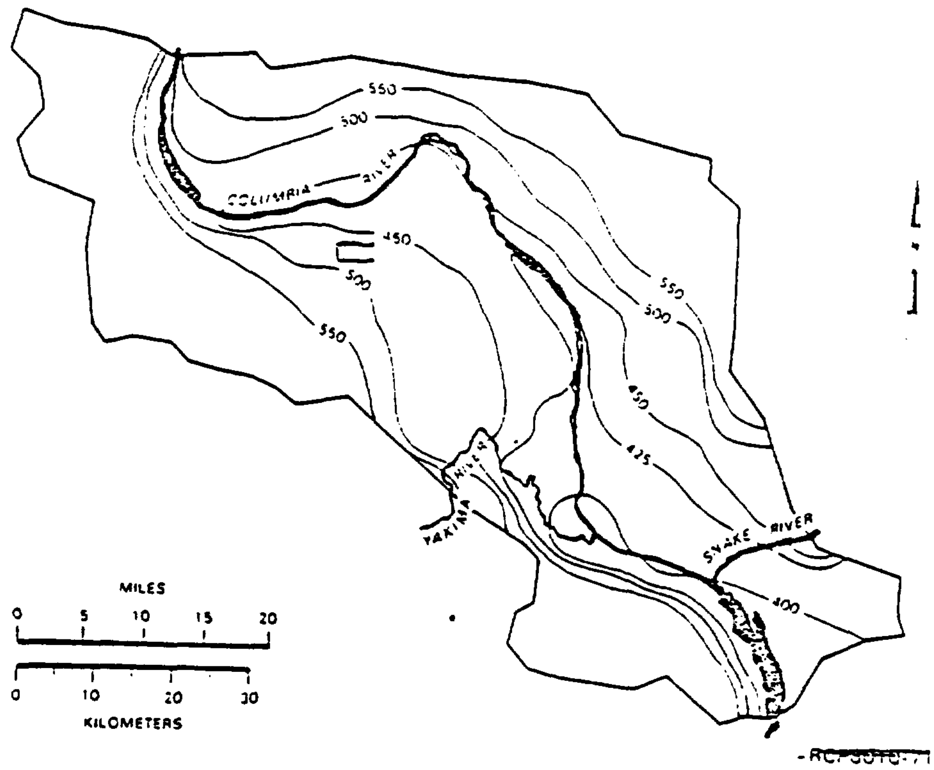

FIGURE . Model-Calculated Heads, Top of Wanapum Basalt K_Z/K_X from 10^{-2} to 10^{-3}.

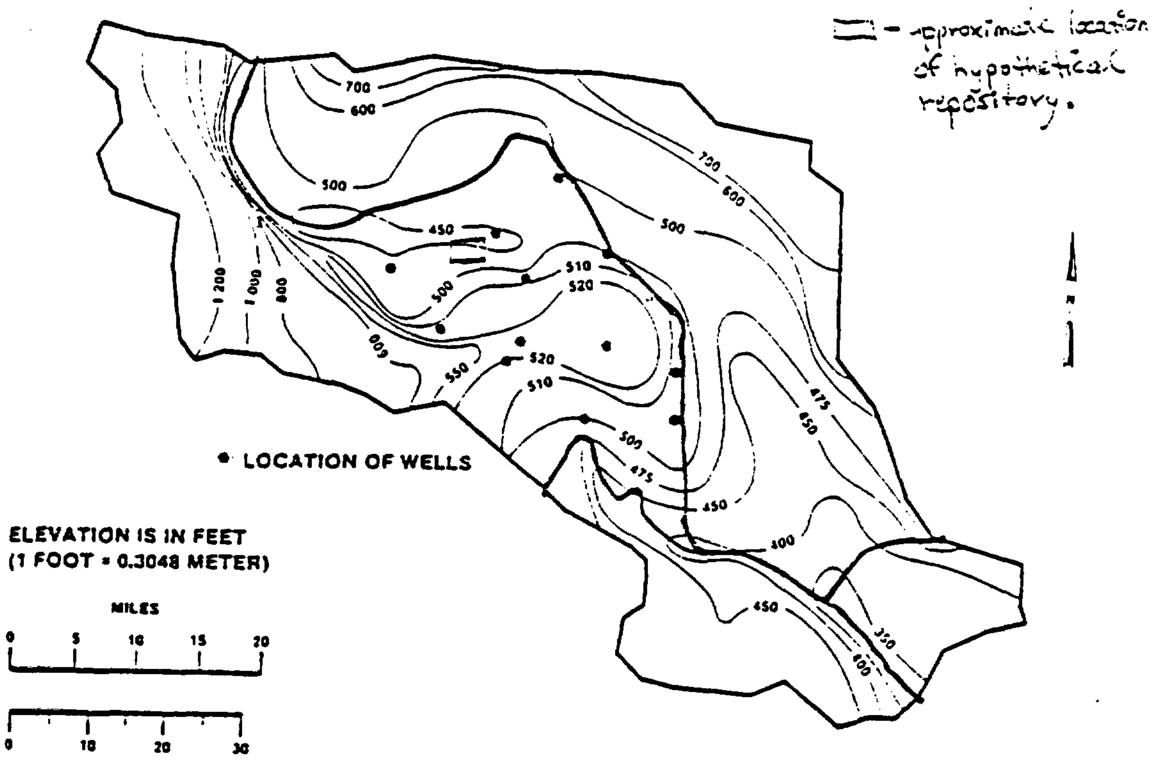

FIGURE . Model-Calculated Heads, Top of Wanapum Basalt K_Z/K_X from 10^{-4} to 10^{-5}.

from August 1985 monthly A1756

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FYI

Attachment-3

WK

GEOCHEMICAL SENSITIVITY ANALYSIS FOR PERFORMANCE ASSESSMENT OF HLW REPOSITORIES: EFFECTS OF SPECIATION AND MATRIX DIFFUSION*

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ABSTRACT

Performance assessment requires calculating radionuclide discharge for many sets of conditions and scenarios. In general, such calculations use empirical retardation factors that describe the average effect of all radionuclide/fluid/rock interactions. This method, however, may underestimate radionuclide discharges and disguise potential violations of regulatory standards. An alternative approach, coupled reaction-transport models, can be used to obtain a detailed understanding of physicochemical phenomena but the general application of such rigorous models may be impractical in repository performance assessment.

The objective of this geochemical sensitivity analysis is to use simple, approximate models to calculate upper bounds for radionuclide discharges and to identify physicochemical conditions where more rigorous theoretical transport calculations must be done. An approximate model is given for bounding discharges of radionuclides in porous rock in scenarios where radioactive production is negligible but decay is appreciable, and several nuclides of an element migrate and undergo a speciation reaction. The model is incorporated into a methodology to determine critical combinations of hydrological and chemical parameter values that result in discharges that violate the HLW standard proposed by the U.S. Environmental Protection Agency (40CFR 191). As an example, the methodology is applied to the discharges of ^{243}Am and ^{237}Np from a reference repository. It also is shown how results from the sensitivity analyses can be used to develop criteria for designing laboratory experiments so that effects of significant speciation reactions will be detected. Approximate methods for calculating radionuclide discharge are given for extending these analyses to transport in fractured rock where diffusion of radionuclides into the matrix may occur.

INTRODUCTION

Geochemical interactions between radionuclides and rocks are but one of several barriers to the transport of radioactive waste from proposed HLW repositories. Performance assessment calculations consider the roles of the waste package, engineered facility and hydrogeochemistry of the repository site in limiting potential releases of radioactivity. The overall objective of geochemical sensitivity analysis is to assess the relative contribution of

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the uncertainty in geochemical data and models to the overall uncertainty in the predicted performance of candidate HLW repositories.

In the past, performance assessment calculations[1-3] have used simple models to represent complex geochemical processes. In particular, solute-water-rock interactions have been represented with retardation factors calculated from empirical sorption ratios (Kd, Rd, or Rs)[4,5] obtained under conditions which simulate the range of environments predicted to prevail at specific repository sites. Figure 1 illustrates the general structure of calculations carried out at Sandia National Laboratories to assess compliance of hypothetical HLW sites with the proposed EPA Standard 40CFR Part 191.[6] More detailed discussions of these calculations can be found in References 1-3. In these calculations the discharge of radionuclides at the accessible environment is calculated over a ten thousand year period. The use of simple algorithms to represent geochemical processes has been justified in part by the complexity of the calculation of integrated discharge for solutes which are affected by radioactive decay and production. In addition, statistical sampling of model input parameters[7] and a large number of calculations are required to represent the uncertainties in possible hydrogeologic and geochemical conditions at the candidate HLW sites.[8,9]

The adequacy of the use of simple retardation factors and sorption ratios in calculations of radionuclide discharge and the utility of the large amount of sorption data that have been collected by the Department of Energy and its contractors have been questioned by a number of researchers.[10-12] In general, the speciation of the radioelements in the sorption experiments is not known and sorption behavior cannot be confidently predicted for conditions that differ from those of the experiments. Radionuclides are not introduced into the experimental solutions in the forms that would be released from the nuclear waste, and the relatively short duration of the experiments may preclude detection of any slow speciation reactions that could change sorption behavior and lead to increased radionuclide discharge.[13]

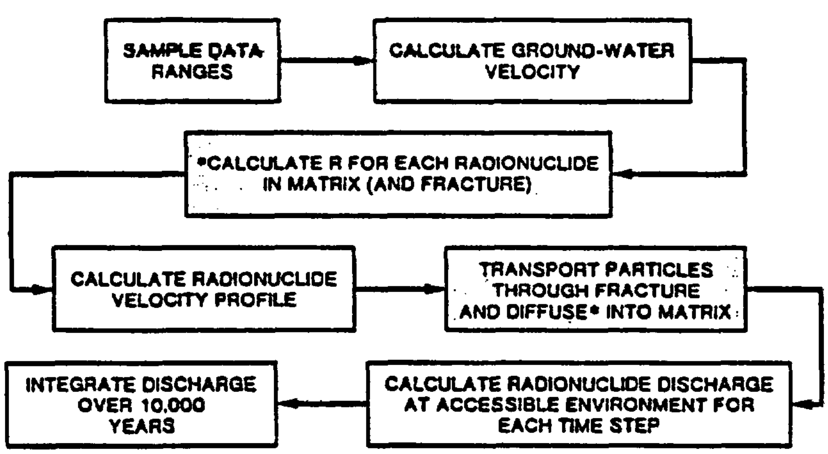


Figure 1. Simplified Outline of Performance Assessment Calculations. Shaded areas indicate steps in which geochemical processes are considered.

Coupled reaction-transport models which explicitly model geochemical reactions have been proposed as an alternative to currently available performance assessment models.[11,14] The use of such models has been hampered in part by the lack of fundamental thermochemical data describing surface complexation reactions and by difficulties in extrapolating theoretical models of the sorption of trace metals by simple oxides and aluminosilicates to the behavior of natural materials.[15,16] In addition, the high computing costs associated with realistic calculations of radionuclide discharge over a 10 km distance and 10,000 year period, at present, preclude the use of such models in repository performance assessment. For example, it has been estimated that a single calculation using the code TRANQL[17] for a relatively geochemically simple system would cost more than $20,000.[16] The calculation examined involved 14 aqueous species of a single element, one-dimensional transport in a monomineralic column, and did not consider radioactive decay or production. For comparison, a calculation using the computer code NWFT/DVM[9] which considers transport of 10 elements of a radioactive decay chain through a column consisting of several layers of minerals with contrasting sorptive capacities costs less than $50.[18] This code, however, represents geochemical interactions with a simple retardation factor as illustrated in Figure 1 and is subject to the criticisms described above.

Coupled reaction-flow models such as TRANQL are clearly useful in providing basic mechanistic insights and identifying key chemical parameters in radionuclide transport. However, as illustrated above, the routine use of such codes in performance assessment is impractical. The objective of the geochemical sensitivity analysis described below is to identify physicochemical conditions under which the use of such complex codes is truly required in order to assess compliance of candidate HLW repositories with the EPA Standard 40CFR 191. In this analysis, a general model is given for bounding radionuclide discharge in scenarios where radioactive production is negligible, but decay is appreciable; several nuclides of a radioelement are present, and a speciation reaction occurs during transport. The model is incorporated into a methodology for determining critical combinations of hydrologic and geochemical parameter values that result in discharges that violate the EPA Standard. As an example, the methodology is applied to releases of ^{237}Np and ^{243}Am from a reference repository. It is shown that the results of the analysis can be used to develop criteria for designing laboratory experiments so that significant speciation reactions will be detected. The analysis is developed initially for porous media. Hydrological and chemical criteria are also derived for application of the methodology to fractured media.

THEORY

General Transport Model

In general, transport of radionuclides involved in any number of homogeneous and heterogeneous chemical reactions is described by equations of the form:

$$\left\{\begin{matrix}\text{rate}\\ \text{of}\\ \text{accumulation}\end{matrix}\right\} = \left\{\begin{matrix}\text{net rate of}\\ \text{influx by}\\ \text{convection}\end{matrix}\right\} + \left\{\begin{matrix}\text{net rate of}\\ \text{influx by}\\ \text{dispersion}\end{matrix}\right\}$$

$$- \left\{\begin{matrix}\text{rate of}\\ \text{radioactive}\\ \text{decay}\end{matrix}\right\} + \left\{\begin{matrix}\text{rate of}\\ \text{radioactive}\\ \text{production}\end{matrix}\right\} \quad (1)$$

$$+ \left\{\begin{matrix}\text{net rate of}\\ \text{production}\\ \text{by heterogeneous}\\ \text{reactions}\end{matrix}\right\} + \left\{\begin{matrix}\text{net rate of}\\ \text{production}\\ \text{by homogeneous}\\ \text{reactions}\end{matrix}\right\} ,$$

where a separate equation is written for each species of each radionuclide.

The objective of this analysis is to derive simple analytical expressions from the comprehensive transport Equation (1) which will yield conservative estimates of integrated radionuclide discharge. These expressions can be used for parametric sensitivity analyses or can be used to formulate more accurate retardation factors for use in performance assessment calculations.

The first five terms on the right hand side of the above expression are normally included in solute transport models. The fifth term is generally used to represent reversible first-order sorption reactions (adsorption and ion exchange). Similar terms also could be used to calculate upper bounds on radionuclide discharge when colloid retention and irreversible sorption must be considered.

The last term in the above expression represents reactions between dissolved constituents. These may include changes in radionuclide speciation, precipitation by homogeneous nucleation, and colloid formation. As discussed later for the purpose of calculating upper bounds to radionuclide discharge, these reactions can be represented by expressions of the form:

$$\left\{\begin{matrix}\text{net rate of}\\ \text{production by}\\ \text{homogeneous}\\ \text{reactions}\end{matrix}\right\} = \sum_n k_n C_i \quad (2)$$

where k_n is the rate constant for the n^{th} reaction involving the i^{th} species of the radionuclide and C_i is the species concentration.

The proposed EPA Standard 40CFR 191[6] regulates the integrated discharge of radionuclides from a HLW repository to the accessible environment. Critical combinations of values of geochemical and hydrologic parameters which violate the EPA Standard can be identified in the following manner:

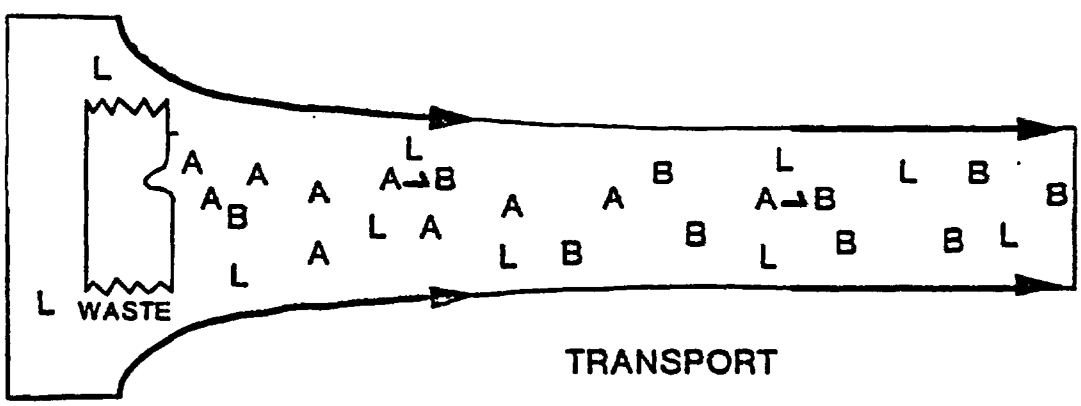
1. Terms for both homogeneous and heterogeneous reactions are incorporated into the radionuclide transport equation for each species;

2. The equations are simplified, using conservative assumptions which calculate an upper bound to radionuclide discharge, and are solved.

3. The integrated discharge is calculated for the 10,000-year regulatory period; the discharges of all chemical species of a radionuclide are summed and the resultant expression is set equal to the EPA radionuclide release limit W;

4. The resulting equation is solved numerically to determine combinations of the parameters which cause violations of the EPA Standard.

This method of sensitivity analysis can best be illustrated by its application to a specific scenario. For this paper, a scenario is chosen in which radionuclide discharges are greater than those predicted by calculations which do not include the effects of speciation reactions. Figure 2 depicts the release of a radionuclide as an unstable sorbing species A which transforms to a mobile species B during transport. Such a transformation could occur due to kinetic constraints (i.e., the metastable species A is released easily from the waste form due to steric factors but is unstable in the solutions in the repository near-field) or due to changes in the geochemical conditions. Clearly, the total integrated discharge of the radionuclide as species A and B will be greater than that predicted by calculations of the discharge which assume that all the nuclide is released as species A. The magnitude of the error will depend upon the relative mobilities of species A and B as well as the rate of the transformation A→B.



DEFINITIONS

A : SORBING AQUEOUS SPECIES [eg - UO_2^{2+}, $(UO_2)_3(OH)_5^+$]

B : NON-SORBING AQUEOUS SPECIES [eg. $UO_2(CO_3)_3^{4-}$]

L : GROUND-WATER LIGAND [eg HCO_3^-]

k : RATE CONSTANT FOR REACTION A + L → B

Figure 2. A Scenario for Geochemical Sensitivity Analysis. Species A is a hypothetical sorbing species which has been studied in sorption experiments. The sensitivity of radionuclide discharge to the production of another species B is examined in this study.

Step 1: Formulate General Transport Equation

The reaction rate expressions for this scenario are:

$$-\frac{dC_A}{dt} = k_1 C_A^x C_L^z - k_2 C_B^y = \frac{1}{b}\frac{dC_B}{dt} \tag{3}$$

where C denotes concentration; k_1 and k_2 denote forward and reverse reaction rate constants, respectively; t denotes time, and the exponents x, y, and z are usually positive integers.

Simultaneously, species A and B can be involved in heterogeneous reactions with the rock matrix. In this analysis, such reactions are restricted to sorption phenomena, and local sorption equilibrium between matrix and pore water is assumed. Under these conditions, the material balance for species A can be written:

$$\begin{aligned}\frac{\partial C_A}{\partial t} &= -v\cdot\nabla C_A + \nabla\cdot D\nabla C_A - \lambda\cdot\left(C_A+(\rho^*/\phi)F_A(C_A,pH,T\ \ldots)\right)\\ &- (\partial C_A/\partial t)\cdot(\rho^*/\phi)\ \partial F_A(C_A,pH,T\ \ldots)/\partial C_A\\ &- k_1 C_A^x C_L^z - k_2 C_B^y + P_A\end{aligned} \tag{4a}$$

and the material balance for species B can be written:

$$\begin{aligned}\frac{\partial C_B}{\partial t} &= -v\cdot\nabla C_B + \nabla\cdot D\nabla C_B - \lambda\cdot\left(C_B+(p^*/\phi)\ F_B(C_B,pH,T\ \ldots)\right)\\ &- (\partial C_B/\partial t)\ (\rho^*/\phi)\ \partial F_B(C_B,T,pH\ \ldots)/\partial C_B\\ &+ b\left(k_1 C_A^x C_L^z - k_2 C_B^y\right) + P_B\ .\end{aligned} \tag{4b}$$

Here, $\vec{v}$ is the interstitial velocity; D the dispersion coefficient; λ the radionuclide decay constant; P the rate of radioactive production; ϕ the matrix porosity; and ρ^* the bulk density of the rock. $F_A(C_A,pH,T\ \ldots)$ is the concentration of species A associated with the matrix as described by the sorption equilibrium isotherm. It is generally a function of C_A, temperature (T), and solution composition.

Step 2: Formulate and Solve Simplified Expressions for Bounding Radionuclide Discharge

Equations 4a and 4b can be approximated by simpler expressions that will give upper bounds to integrated radionuclide discharge. A detailed discussion of the approximation is given in Reference 20. The terms for chemical reaction rate and sorption are simplified as follows.

- Reaction Rate

If the exponents x, y, and z in Equation 4 are unity or greater and if C_A is less than 1 molar, then the rate expression

$$-dC_A/dt = k^*C_A = (1/b)dC_B/dt \quad (5)$$

will give reaction rates and radionuclide discharges equal to or greater than those obtained from Equation 3. Here, $k^* = k_1 C_{Lmax}^z$, where C_{Lmax} is the maximum possible value of C_L.

- Sorption Equilibria

Sorption ratios (Rd, Kd, or Rs) can be defined as

$$Rd_A \equiv \frac{F_A(C_A, T, pH \ldots)}{C_A} \quad \text{and} \quad Rd_B \equiv \frac{F_B(C_B, T, pH \ldots)}{C_B}$$

Often, solution-phase concentrations will be sufficiently dilute, and the temperature, solution-phase pH, and ionic strength sufficiently constant so that the sorption isotherms for species A and B are at least approximately linear. This means that $Rd_A \approx$ a constant $\approx \partial F_A/\partial C_A$ and $Rd_B \approx$ a constant $\approx \partial F_B/\partial C_B$. If the sorption ratios are not constants, minimum values can be determined which will yield predicted cumulative radionuclide discharges that are greater than those obtained using the more exact expressions for sorption equilibria.

- Radioactive Production

Many of the isotopes important to high-level waste disposal are not produced by radioactive processes in significant quantities during the 10,000-year period regulated by the EPA standard.[20]

Consideration of initial inventories and half-lives of radionuclides can lead to a number of simplifying assumptions in speciation and transport calculations for different radioelements in different scenarios. In a previous report,[13] radioactive production and decay of neptunium-237 could be ignored in an analysis of discharge of this radionuclide after a 1000-year isolation period. In this report radioactive decay is considered; however, consideration of radioactive production will be deferred until a later work.

• 1-D Equation

For purposes of bounding cumulative radionuclide discharges under most conditions, Equations 4a and 4b can be reduced to one spatial dimension with no dispersion when the mean radionuclide residence time is much less than the regulatory period. (See Reference 20). The material balances, Equations 4a and 4b, then can be reduced to

$$\frac{\partial C_A}{\partial t} + \frac{v}{R_A}\frac{\partial C_A}{\partial x} + \lambda C_A + \frac{k^*}{R_A} C_A = 0 \qquad (6a)$$

and

$$\frac{\partial C_B}{\partial t} + \frac{v}{R_B}\frac{\partial C_B}{\partial x} + \lambda C_B - \frac{bk^*}{R_B} C_A = 0 \qquad (6b)$$

where $R_A = 1 + (\rho^*/\phi)Rd_A^*$, and $R_B = 1 + (\rho^*/\phi)Rd_B^*$,

and Rd_A^* and Rd_B^* are the sorption ratios corresponding to linear isotherms or appropriate values for bounding cumulative radionuclide discharges. For the case in which radionuclide release from the repository is solubility limited, initial and boundary conditions for Equation 6a are

$$C_A(x,0) = 0 \text{ and } C_A(0,t) = C_A^o$$

and for Equation 6b

$$C_B(x,0) = 0 \text{ and } C_B(0,t) = C_B^o \ .$$

For purposes of illustration let b = 1. Equations 6a and 6b with the above initial and boundary conditions can be solved using the method of Laplace transforms,

$$C_A = C_A^o \exp\left[-(\lambda R_A + k^*)x/v\right] H(t - R_A x/v) \quad (7a)$$

and

$$\begin{aligned} C_B = {} & C_B^o \exp(-\lambda R_B x/v) H(t - R_B x/v) \\ & + \Gamma_B \left\{1 - \exp\left[-\alpha(t - R_B x/v)\right]\right\} H(t - R_B x/v) \\ & - \Gamma_A \left\{1 - \exp\left[-\alpha(t - R_A x/v)\right]\right\} H(t - R_A x/v) \end{aligned} \quad (7b)$$

where $H(t) = \begin{cases} 0 & t < 0 \\ 1 & t > 0 \end{cases}$

$$\alpha = \frac{(R_A - R_B)\lambda + k^*}{R_A - R_B}$$

$$\Gamma_A = \frac{k^* C_A^o}{(R_A - R_B)\lambda + k^*} \exp\left[-(\lambda R_A + k^*)x/v\right]$$

$$\Gamma_B = \frac{k^* C_A^o}{(R_A - R_B)\lambda + k^*} \exp(-\lambda R_B x/v) \quad .$$

- Systems of Multiple Radionuclides

Equations 7a and 7b rigorously apply to a system in which a single radionuclide exists for the element of interest, and only two chemical species are present. If several radionuclides of the element were present, sorption equilibria and chemical reaction rates would be functions of the total concentration of the element. The transport equations for the radionuclides would be coupled and require simultaneous solution. However, to bound cumulative radionuclide discharges the transport equations can be uncoupled, as shown in Reference 20 and solved independently, provided that reaction rates and sorption equilibria do not differ appreciably between nuclides. The uncoupled equations would be of the same form as Equations 7a and 7b.

- Transport in Fractured Media

Equations 7a and 7b rigorously apply only to transport in a porous medium in which sorption equilibrium between the fluid and bulk rock exists. Several of the potential HLW repository sites are in fractured media where fluid flow is primarily in the fractures. In these rocks, the time required for radionuclide diffusion into the rock matrix must be considered in transport calculations.

Approximate methods for calculating radionuclide discharges in fractured, porous rock can be derived from a set of rigorous general transport equations.[22,23] When the relaxation times for concentration perturbations in the porous matrix are small relative to the radionuclide residence time, then the fracture fluid and the porous matrix are locally near equilibrium (or more generally, a quasi-steady-state is approached with respect to radionuclide diffusion). Under these conditions, transport in the fractured medium can be represented by a porous medium approximation.

In order to identify these conditions, three approximate methods for calculating radionuclide discharges in fractured, porous rock have been evaluated: (1) the porous medium approximation where radionuclide diffusion rates into the matrix are proportional to depletion rates in the fracture fluids; (2) a linear-driving-force approximation where radionuclide diffusion rates into the matrix are proportional to the difference between bulk concentrations in the matrix and the fracture fluids, and (3) a semi-infinite-medium approximation where radionuclide diffusion rates into the matrix are calculated assuming a semi-infinite matrix. The above three methods are described, criteria for application of each given, and the respective uncertainties in calculated cumulative radionuclide discharges are assessed in References 23 and 24. The criteria for application of each method were derived from a general consideration of fluid residence times in the fractures and relaxation times for radionuclide concentration gradients in the matrix. The same criteria were then obtained from the solution to the transport equations for specific cases involving radionuclide decay, chemical reaction, and varying matrix properties. For example, if fluid flow in saturated rock is one-dimensional and primarily occurs in parallel fractures having relatively uniform aperture 2b and spacing 2B, and if matrix porosity ϕ_m, grain density ρ_s, fracture porosity ϕ_f, and sorption isotherms F(C) in the matrix are relatively uniform, then the porous medium approximation applies when

$$x/v > 50\ B^2\alpha^2\phi_f/\phi_m D(1-\phi_f) \quad . \tag{8}$$

The linear-driving-force applies when

$$x/v > 0.2\ B^2\alpha^2\phi_f/\phi_m D(1-\phi_f) \tag{9}$$

and the semi-infinite medium applies when

$$x/v < B^2\alpha^2\phi_f/\phi_m D(1-\phi_f) \quad . \tag{10}$$

Here, D is the radionuclide diffusion coefficient in the pore water; v is the average fluid velocity in the fractures; x is the radionuclide transport path length, and α is a tortuosity/constructivity factor for the matrix.

Site-specific data for tuff and granite[2,23-27] were used with the above criteria. Results are shown in Figure 3. For tuff, the porous medium approximation will be applicable even for relatively thin beds (x = 30m). The linear-driving-force or semi-infinite-medium approaches would be necessary for extreme cases involving relatively unrealistic porosities and fluid velocities. For granite, the semi-infinite medium or linear-driving-force approaches may be required, while the porous medium approximation may be applicable only to relatively large granitic bodies.

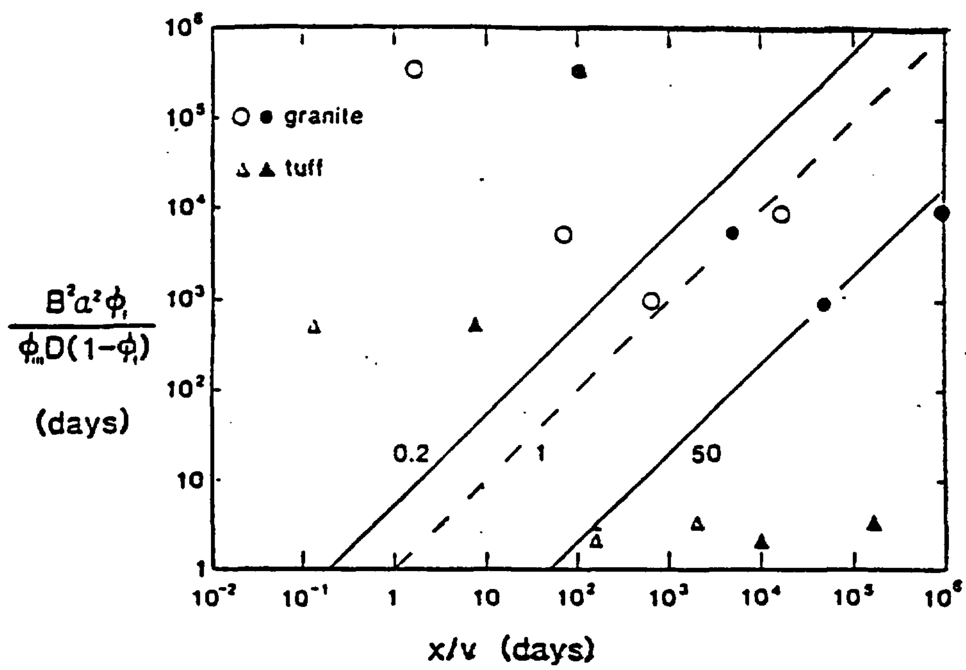


Figure 3. Application of Criteria to Representative Site-Specific Data for Granite and Tuff. Numbers on lines are ratios of $B^2\alpha^2\phi_f/\phi_m D(1-\phi_f)$ to x/v. Areas below lines marked '0.2' and '50' correspond to conditions under which linear-driving-force and porous medium approximations, respectively, apply. The semi-infinite-medium approach applies in the area above the line marked '1'. Solid and open symbols refer to transport distances of x = 2000 meters and x = 30 meters respectively.

Step 3: Integrate Equations for Integrated Discharge and Sum over Species

The sum of the integrated discharges of species A and B is now set to a specified release limit for the radionuclide of interest.

$$Q\int_{t_o}^{t=10,000\text{ yr}} (C_A+C_B)dt = f(x/v, R_A, R_B, k^*, \lambda, t_o, C_A^o, C_B^o, t^*) \leq W \qquad (11)$$

where t_o is the initial containment period; Q is the annual volumetric flux of ground water through the engineered facility; W is the release limit; $t^* = 10{,}000 - t_o$; λ is the radioactive decay constant; C_A^o and C_B^o are concentrations of species A and B in the repository, and the other terms have been defined previously.

For $R_A x/v > R_B x/v > t^*$, C_A and C_B at the accessible environment should be negligible, and Equation 12 is satisfied.

For $R_B x/v < t^* < R_A x/v$, $C_A = 0$ at the accessible environment, and Equations 7 and 11 give

$$W \geq \left(QC_B^o + \frac{kQC_A^o}{(R_A-R_B)\lambda + k^*}\right)(t^*-R_B x/v) \cdot \exp(-\lambda R_B x/v)$$

$$+ \frac{kQC_A^o(R_A-R_B)}{\left[(R_A-R_B)\lambda + k\right]^2}\left[\exp \frac{\left(-\lambda t^*-k(t^*-R_B x/v)\right)}{R_A - R_B} - \exp(-\lambda R_B x/v)\right] . \qquad (12)$$

If $t^* > R_A x/v > R_B x/v$, then both C_A and C_B at the accessible environment are nonzero and Equations 7 and 11 give

$$\frac{W}{Q} \geq Q\left(C_B^o + \Gamma\right)(t^*-R_B x/v)\exp(-\lambda R_B x/v)$$

$$+ \frac{Q\Gamma}{\alpha}\left\{\exp -\left[\frac{(R_A\lambda+k^*)x}{v}\right] - \exp(-\lambda R_B x/v)\right\}$$

$$+ Q\left(C_A^o - \Gamma\right)(t^*-R_A x/v)\exp\left[-\frac{(R_A\lambda+k^*)x}{v}\right] \qquad (13)$$

where $$\Gamma = \frac{k^* C_A^o}{(R_A-R_B)\lambda + k^*}$$

$$\alpha = \frac{(R_A-R_B)\lambda + k^*}{R_A - R_B} .$$

The detailed derivations of Equations 12 and 13 are given in Reference 20.

Step 4: Determination of Critical Parameter Combinations

Equations 12 and 13 were solved numerically for release limits and decay constants for ^{237}Np and ^{243}Am. Solutions are plotted as bivariate curves of $1/k^*$ and $1/R_B$ values with various combinations of values of the other parameters in Figures 4 to 7. The chemical-reaction parameter $1/k^*$ is analogous to the mean lifetime $1/\lambda$ of a radionuclide with respect to radioactive decay. It describes the stability of the relatively immobile species A to conversion to a more mobile species B.

Figure 4 shows solutions of Equations 12 and 13 for ^{237}Np for several values of x/v. Neptunium is assumed to be contained in the waste package for 1,000 years after waste emplacement and then is released from the engineered facility at a rate determined by a solubility-limited concentration C_A^o of 10^{-7} moles/liter and a flux of water Q through the facility of 10^7 liters/yr. These parameters result in a neptunium source term QC_A^o of 1.0 mole/yr.

Solutions to Equations 12 and 13 for ^{243}Am are shown in Figures 5-7. In these figures, the release limit for Am-243 was assumed to be 100 Ci/1000 MTHM. Release was assumed to start immediately after emplacement and the ground-water travel time to the accessible environment was 1000 years. The fractional release rate listed in the figure captions refers to the inventory at emplacement, 6.6×10^5 Ci (1.41×10^4 moles) for an assumed repository inventory of 46,800 MTHM of BWR and PWR spent fuel assemblies (cf. Reference 1).

Figures 5 and 6 demonstrate the effect of changes in R_A and C_o (total concentration in the engineered facility), respectively, on the shapes of the curves when the initial concentration of a nonsorbing species B, C_B^o, is very small but non-zero.

The sensitivity of the results to the near-field speciation of ^{243}Am is illustrated in Figure 7. In the three curves of this figure a small variation in the concentration of C_B^o leads to profound changes in the shapes of the curves.

RESULTS

Application to EPA Standard and NRC Regulation

Retardation factors and reaction rates for the interconversion of the species of interest in HLW management generally are currently not available. The methodology developed in the previous sections, however, can be applied to available data as follows. If R_B equals 1.0, then species B is unretarded and migrates at the velocity of the ground water. For a given combination of release rate, ground-water travel time, and R_A, the value of k^* which corresponds to R_B equal to 1.0 can be obtained from Equation 13 and Figures 4-7 and is denoted k_m. This is the lower limit of the reaction rate constant that needs to be considered for performance assessment studies. In other words, if the reaction rate is lower than k_m, the conversion of A to B cannot cause a discharge of the radionuclide greater than its EPA release limit. This means that if a regulatory agency wished to use available sorption data to assure compliance of a site with the EPA standard, then it

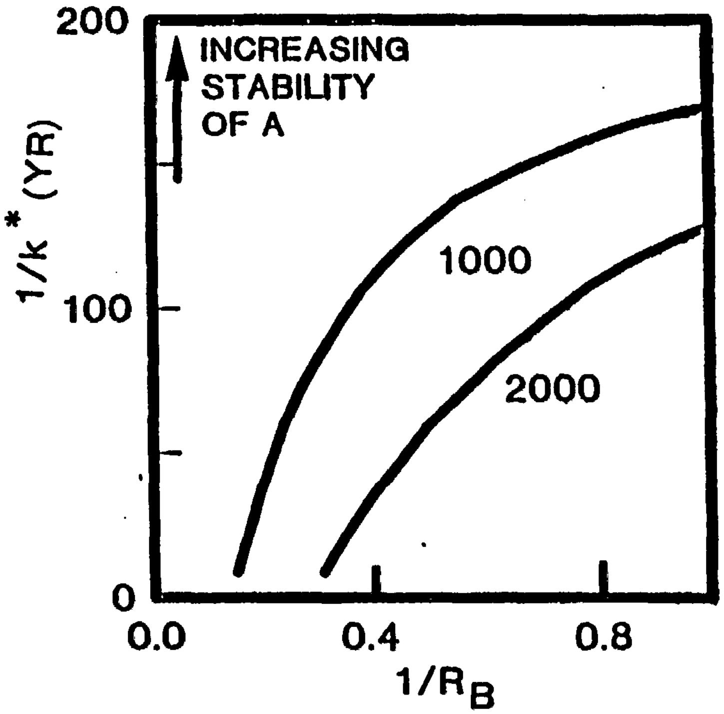


Figure 4. Combinations of Values of Reaction Rate Constant k* and Retardation Factor R_B of Mobile Species B Which Lead to Discharge of ^{237}Np Equal to a Specified Release Limit. Curves for two values of ground-water travel time x/v are shown. Retardation factor R_A = 200; source term QC_A^0 = 1.0 mole/yr; containment period = 1,000 yr; Release limit = 20 curies (120 moles Np-237) per kiloton of heavy metal.

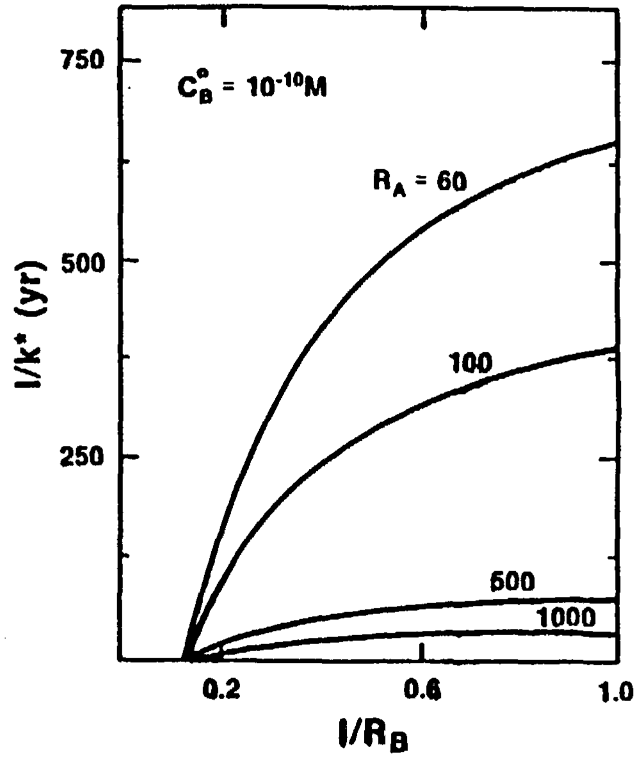


Figure 5. Effect of Retardation of Species A on EPA Compliance Curves (Annual Fractional Release Rate = 10^{-5}; Q = 1.4 x 10^6 liter/yr; $C_A^0 = 10^{-7}$ M; t* = 10,000 yr; t_0 = 0 yr; x/v = 1000 yr; $C_B^0 = 10^{-10}$ M; W_{Am-243} = 100 Ci/1000 Metric Tons Heavy Metal, MTHM). Areas below curves correspond to violations of EPA standard. Each curve corresponds to a different value of the retardation factor for species A, R_A.

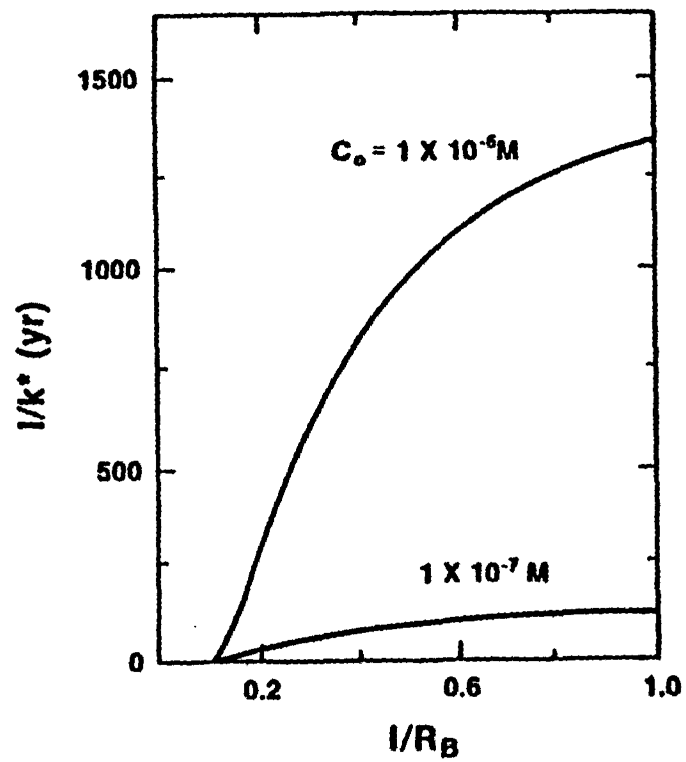


Figure 6. Effect of Near-Field Concentration of Am-243 (C_0) on EPA Compliance Curves (R_A = 100; x/v = 1000 yr; t* = 10,000 yr; W_{Am-243} = 100 Ci/1000 MTHM; t_0 = 0 yr; C_B^0 = 10^{-12} M; Q = 1.4 x 10^6 liter/yr). Areas below curves correspond to violations of EPA standard. Note that $C_A^0 \approx C_0$ = total concentration.

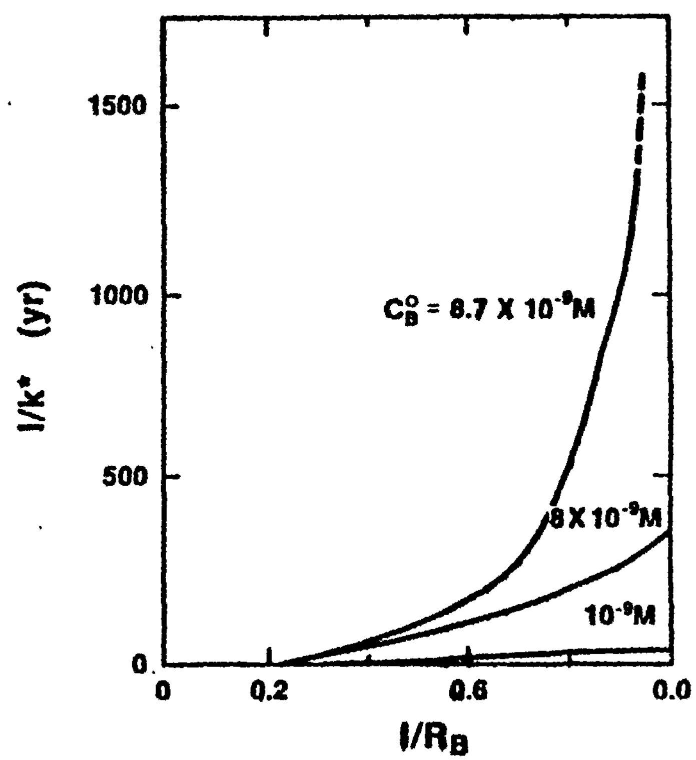


Figure 7. Effect of Near-Field Concentration of Species B on EPA Compliance Curves (W_{Am-243} = 100 Ci/1000 MTHM; t* = 10,000 Yr; C_0 = C_A^0 + C_B^0 = 3 x 10^{-8} M; Q = 1.4 x 10^6 liter/yr; R_A = 300; x/v = 1000 yr). Areas below curve correspond to violations of EPA standard for Am-243. Note that small changes in C_B^0 cause large changes in shapes of curves. For C_B^0 = 8.7 x 10^{-9} M, violation occurs due to initial inventory of species B alone for low values of R_B.

must be shown that the reaction rate constant is less than k_m. A conservative analysis (i.e., one that will overestimate radionuclide discharge) can be made by assuming that measured sorption ratios can be used to calculate values of R_A. The actual integrated discharge of a multi-species system of americium-243, for example, will be less than that of a two-species system in which Rd_B is zero and Rd_A is taken from the measured sorption ratios Rd_{avg} for americium.

Table 1 lists R_A values for ^{237}Np and ^{243}Am for several geologic media calculated from available sorption and hydrogeologic data.[1-3]

Table 1

Retardation Factors Assumed for Species A of ^{237}Np and ^{243}Am

	^{237}Np		^{243}Am	
Medium	Minimum	Mean	Minimum	Mean
Basalt	35	1,500	60	1,600
Salt	10	500	110	2,400
Zeolitized Tuff	10	110	1,020	7,600
Vitric/ Devitrified Tuff	20	250	300	1,200

$R_A = 1 + \beta Rd$ where $\beta = \rho(1-\phi)/\phi$ for tuff and salt; $\beta = 2.3$ for basalt. Sources of data for density (ρ), porosity (ϕ) and sorption ratio R_d are References 1-3.

Extreme and mean values of density ρ and porosity ϕ were used to calculate the minimum and mean β values listed in the table. The ranges of R_A values presented in Table 1 represent conservative estimates of the actual ranges and uncertainty in available information on the sorptive properties of rocks from each of the geomedia listed. For each R_A value in the table, a minimum mean lifetime $1/k_m$ for species A, which would ensure compliance with an EPA release limit (20 or 100 Ci), was calculated. In this way, the uncertainty represented by ranges in R_A values was converted to ranges in values of $1/k_m$ for each rock type. The results of these calculations are presented in Figures 8 and 9 for ^{237}Np and ^{243}Am respectively. An annual fractional release limit of 10^{-5} per year, $R_B = 1$, and travel time of 1000 years were assumed; other parameter values are given in the figure captions.

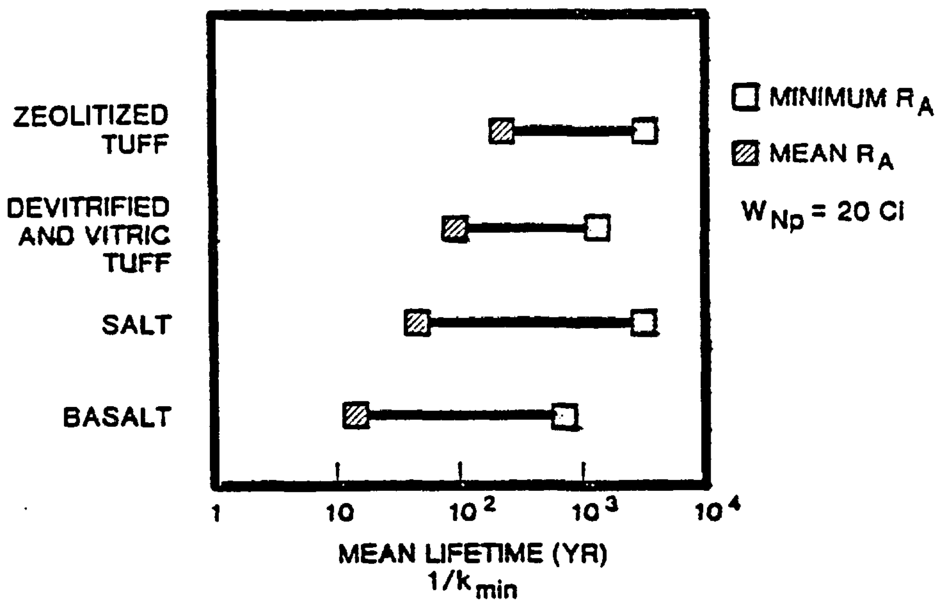


Figure 8. Media-Specific Chemical Stability of ^{237}Np Required to Comply With Release Limit of 20 Ci/1000 MTHM. (t_o = 1000 yr, QC^o_A = 2.6 moles/yr).

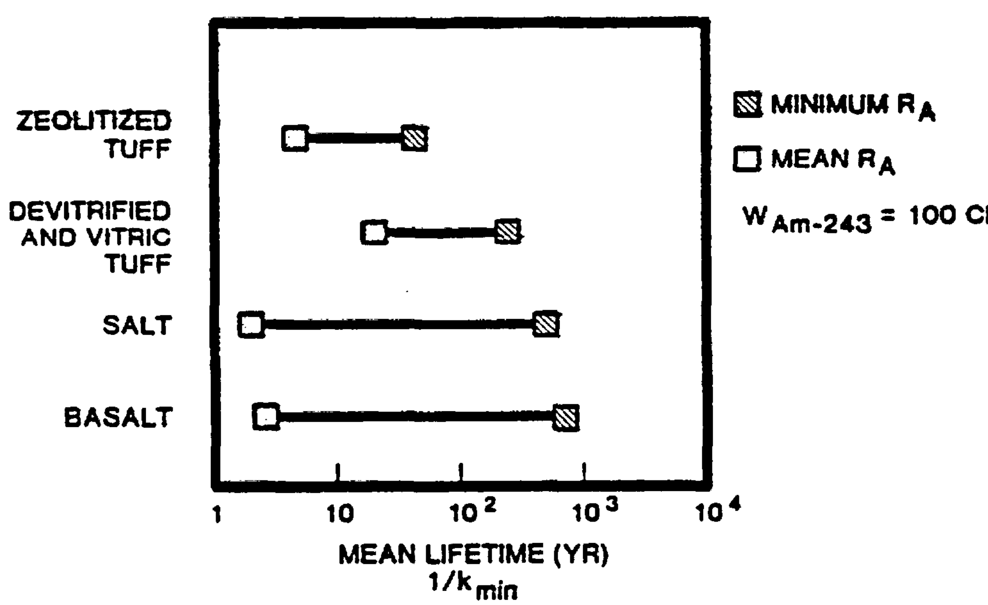


Figure 9. Media-Specific Chemical Stability of ^{243}Am Required to Comply With Release Limit of 1000 Ci/1000 MTHM. (t_o = 0 yr, C^o_B = 1×10^{-10} M, $Q(C^o_A + C^o_B)$ = 0.14 moles/yr).

Application to Experimental Design

In this section, the application of the calculated values of minimum chemical stability for neptunium-237 to the design of batch laboratory sorption experiments will be illustrated. It will be shown that it is possible to determine the required duration of kinetic and sorption experiments for quantitative observation of the effects of potential speciation reactions that could disguise violations of the EPA standard.

In a carefully designed batch experiment, it would be desirable to introduce the radioactive tracer in the same chemical form that is released by the waste (glass or spent fuel). The sorption ratio obtained from such an experiment may provide information about the sorption behavior of the species in the near-field environment. However, as discussed previously, it cannot be assumed that the chemical species released into the near field will remain stable indefinitely. Figures 2 and 10 depict hypothetical batch experiment and field scenarios in which species A, the initially dominant, more strongly sorbing species, converts irreversibly to species B, a more mobile species. Such a transformation could occur at a rate that is too low to detect in a batch sorption experiment yet still be significant on the time scale relevant to HLW disposal.

In a sorption experiment similar to that depicted in Figure 10, the material balances for species A can be represented as

$$dC_A/dt = -(m/v)dq_A/dt - kC_A \tag{15}$$

$$dq_A/dt = \rho ha(Rd_A C_A - q_A) \tag{16}$$

where m = mass of solid substrate

v = solution volume

q_A = concentration of A on solid

C_A = concentration of A in liquid

ρ = grain density

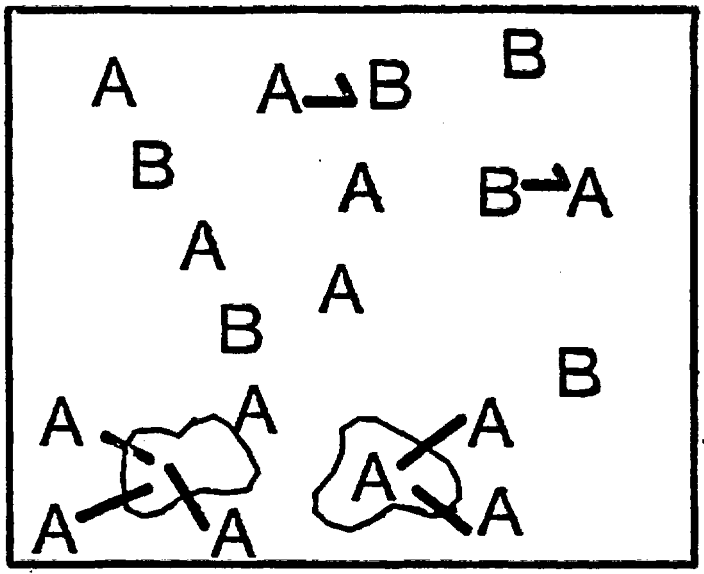
h = mass transfer coefficient for sorption

a = interfacial surface area per gram of solid

k = reaction rate constant.

The initial conditions are

$$C_A(t=0) = C_o = \text{constant and } q_A(t=0) = 0 \quad .$$



BATCH EXPERIMENT

Figure 10. Scenario for Geochemical Sensitivity Analysis. Conversion of hypothetical sorbing species A to a nonsorbing species B during a batch sorption experiment.

The term ρha is the rate constant for the sorption reaction. If it is assumed that $Rd_B = 0$, then the material balances for species B can be written

$$dC_B/dt = kC_A \tag{17}$$

$$q_B(t) = 0 \tag{18}$$

with the initial condition of $C_B(t=0) = 0$ and all of the terms for species B are defined analogously to those for species A. Equations 15 to 17 were solved using Laplace transforms[20] to obtain

$$\frac{C_A + C_B}{C_o} = 1 + \frac{1}{\left(b^2 - 4C\right)^{1/2}}\left[(\rho ha-b_1)(1-k/b_1)e^{-b_1t}\right.$$

$$\left. - (\rho ha-b_2)(1-k/b_2)e^{-b_2t}\right] . \tag{19}$$

where $$b_1 = \frac{-b + \left(b^2 - 4C\right)^{1/2}}{2}$$

$$b_2 = \frac{-b - \left(b^2 - 4C\right)^{1/2}}{2}$$

$$b = \rho ha\left(1 + \frac{mRd_A}{v}\right) + k$$

$$C = \rho hak \quad .$$

Values of $(C_A+C_B)/C_o$ are shown in Figure 11 for values of k and Rd_A relevant to neptunium-237 and for values of the other parameters that may be typical for batch sorption experiments.[20,21] The curve shows that if species A converts irreversibly to species B, then the concentration of neptunium in solution will initially decrease rapidly as species A is sorbed by the solid, reach an apparent steady state for several days, but then increase as significant amounts of species A convert to the poorly sorbed species B. Figure 12 shows that the time needed for the solution concentration to rise detectably above the "steady state" concentration depends on the experimental precision of the analytical techniques used to monitor the solution concentration, as well as the values of 1/k and R_A. If the precision were equal to ϵ_1, then after t_1 days it would be clear that the solution concentration had not reached steady state and that speciation reactions unaccounted for by a simple sorption model were occurring.

Discussion

Use of the methodology for geochemical sensitivity analysis as developed in this paper can be illustrated as follows. A range of retardation factors for a radionuclide (eg. ^{237}Np) can be obtained from data from laboratory and/or field studies for a potential HLW repository site. Equations 12 and 13 can be used to calculate a corresponding range of chemical stabilities which ensure that discharges of the radionuclide will not exceed a given limit (see for example Figure 7). Pairs of values of R_A and k_m obtained in this way could be used in Equation 19 to produce graphs such as Figure 11. From these graphs and from knowledge of the analytical precision of the method used to monitor solution concentration in the batch test, it is possible to determine the duration of the experiment required to quantitatively observe speciation effects that could lead to unforeseen violations of the EPA standard (or any other specified release limit). Thus, from Equations 12 and 13, if it is assumed that the retardation factor calculated for neptunium from batch sorption experiments is not lower than 1000; the groundwater travel time at the site is at least 1000 years; the waste isolation period is at least 1000 years; the annual fractional release rate of neptunium is 10^{-5} or less, and only one aqueous Np species is present in the near field, then $1/k_m$ must be at least 1.5 years. Figure 11 shows that batch experiments for neptunium should run at least t_2 days before it can be concluded that no potential speciation effects can cause unforeseen violations of the EPA standard if the analytical precision is ϵ_2. In other words, if the above assumptions

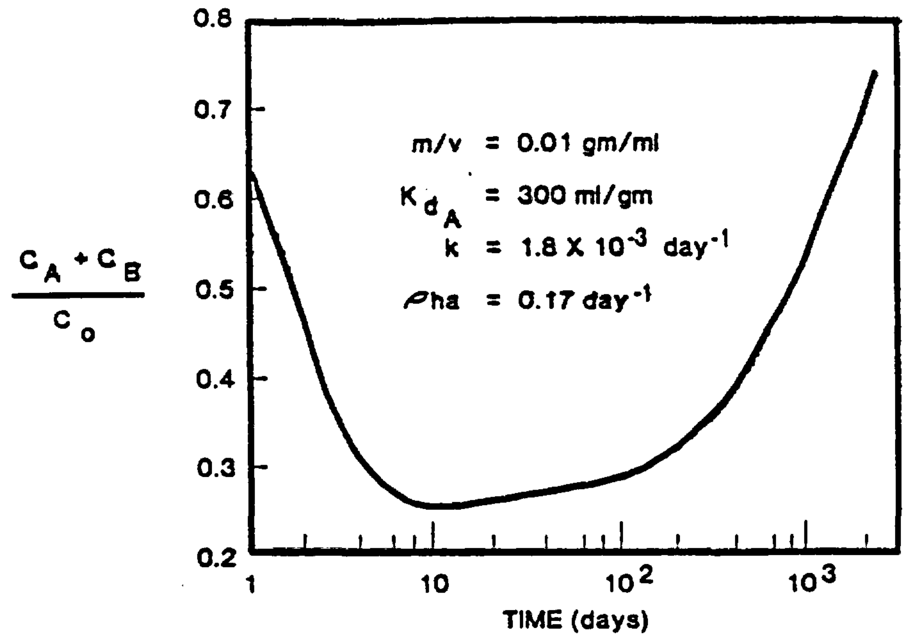


Figure 11. Relative Concentration in Batch Experiment Solution Calculated From Equation 19 for Scenario in Which Sorbing Species Converts Irreversibly to Nonsorbing Species. See text for definition of variables.

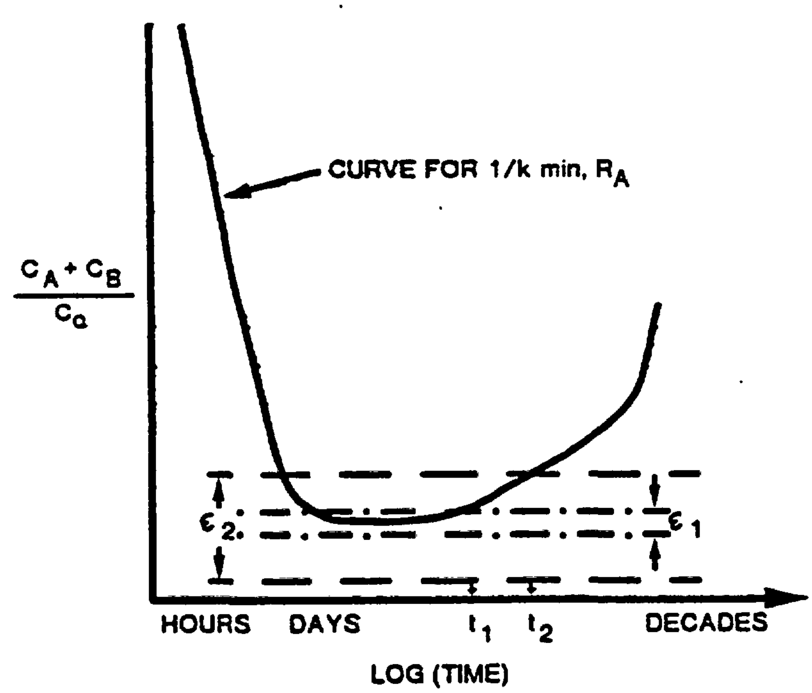


Figure 12. Relationship Between Analytical Precision ϵ_i and Experimental Run Time t_i Required to Observe Disequilibrium Due to Irreversible Conversion of A B.

about the site and waste package are valid, then even if the detailed speciation of neptunium along far-field migration paths is not known, sorption data from a batch experiment can be used to obtain bounding estimates of potential radionuclide discharges with confidence. Even if the actual discharge is not known (or knowable) it would be possible to know whether or not the discharge will exceed the EPA release limit.

Figures 7, 8, and 10 are based on an assumed R_B value of unity. This is the most conservative value of R_B that is possible and this value leads to conservative estimates of 1/k and design criteria for batch sorption experiments. In some cases the minimum required chemical stability consistent with $R_B = 1.0$ may not be demonstrable with available technology. The use of R_B values estimated from geological and thermochemical data for radionuclide species would produce a more realistic estimate of 1/k and more achievable experimental design specifications. Estimates of 1/k combined with estimates of R_B would enable the NRC and DOE to identify radionuclides for which the available sorption data are sufficient to carry out performance assessment calculations. The results of such an analysis could also be used to determine when complex phenomenological models (coupled reaction-flow models) are truly required for repository performance assessment.

Conclusion

Potential aqueous speciation reactions introduce uncertainty into performance assessment calculations designed to assess the compliance of nuclear waste repositories with the proposed EPA Standard (40CFR Part 191). In this report, a method was illustrated for determining hydrologic and geochemical conditions where such reactions could significantly affect the integrated radionuclide discharge. A minimum chemical stability can be described for radionuclide species examined in laboratory studies in order to assure compliance with the EPA Standard. The above method can be used by regulatory agencies to prioritize research needs and to evaluate published or ongoing radionuclide transport studies. The calculations may be used to determine the criteria for experiments designed to quantitatively observe the effect of important chemical speciation reactions.

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Attachment-4

B0827 SHORT-TERM TECHNICAL ASSISTANCE (FY 85)*

Request	Task	Date	Assignment	Est. Level of Effort	Report No.
1	2-4	Oct 84	Attend meeting/report on Sandia-ORNL Coordination of Technical Assistance	1 Week	MR-5.2
2	2-4	Oct 84	Attend meeting/report on Conference (Penrose), "Geochemistry of the Environment Near a High-Level Nuclear Waste Repository	1 Week	MR-5.3
3	2-2	Nov 84	Hold Workshop of "Application of Geochemical Models to High-Level Nuclear Waste Repository Assessment"	3 Months (12 Weeks)	N.A.
4	2-1	Nov 84	Document review "An Application of the Population Balance to the Assessment of the Importance of Radioactive Colloids In High-Level Waste Management	2 Days	LR-4.1-19
5	2-1	Nov 84	Letter Report on the Chemistry of Americium	1.5 Months (6 Weeks)	------------
6**	2-1	Nov 84	Letter Report on the Chemistry of Plutonium	1.5 Months (6 Weeks)	TBD

* (see page 3)
** (work not started)

B0827 SHORT-TERM TECHNICAL ASSISTANCE (FY 85)*

Request	Task	Date	Assignment	Est. Level of Effort	Report No.
7	2-4	Dec 84	Attend meeting/report - Materials Research Society Symposium	1 Week	MR-290-1
8	2-4	Dec 84	Attend meeting/report - Geological Society of America	2 Weeks	MR-287-1
9	2-5	Jan 85	Meeting to review NRC EA comments	1 Week	Mark-up of NRC comments
10	2-2	Feb 85	Evaluation of Natural Analogs for Problems of Radioactive Waste	5 Months (20 Weeks)	-------------
11	2-2	Apr 85	Publish modeling conference proceedings	1.5 Months (6 Weeks)	NUREG/CR-0062
12	2-1	Apr 85	Document review - Geochemical Sensitivity Analysis	2 Days	LR-287-2
13	2-3	May 85	Meeting to review draft NRC technical position on sorption	3 Days	Mark-up of T.P.

* (see page 3)

B0827 SHORT-TERM TECHNICAL ASSISTANCE (FY 85)*

Request	Task	Date	Assignment	Est. Level of Effort	Report No.
14	2-3	Jun 85	Review of Hydrazine Site Technical Position	2 Days	Mark-up of STP
15	2-1	Jun 85	Document review - "The Potential of Natural Analogues in Accessing Systems for Deep Disposal of High-Level Radioactive Waste"	2 Days	LR-287-3
16	2-1	Jun 85	Document review - "The Dissolution of Rainier Mesa Volcanic Tuffs, and its Application to the Analysis of the Groundwater Environment"	2 Days	LR-287-4
17	2-4	Jul 85	Attend/report on workshop on hydrogeochemistry/organics	1 Week	-------------

TOTAL: APPROXIMATELY 53 Work Weeks*
13 Work Months*

* NOTE: Funding for short term T.A. = 140K (Level of Effort approx. 1.2 man years, 14 work months, or 61 work weeks.

Attachment - 5

GENERAL CATEGORY

-- Igneous intrusions
  --major plutons; contact effects
  --minor intrusions (mainly dikes); contact effects (intruded media include basalt, tuff, bedded salt, shales, sandstones)
-- Active and semi-dormant geothermal systems
-- Areas of hydrothermal alteration
  --accompanying ore deposition
  --minor veins of mineralization (focus on elemental distribution, mobilization, mechanisms for retardation-retention)
-- Behavior of clay minerals in geomedia
  --alteration studies in bedded salts, tuffs, basalt
  --other media (granitic rocks; post-epigenetic effects in shales; argillaceous sandstones)--application to problems of engineered backfill

REFERENCE: Complete listing of the source of information; author(s), title, journal, pagination, year

BACKGROUND ON STUDY
-- Purpose of investigation
-- Methods used (e.g. petrography, chemical, other)
-- Summary of results

APPLICATION TO PROBLEMS OF RADIOACTIVE WASTE DISPOSAL IN GEOMEDIA
-- Explanation of how particular study can be used as analog for any (or multi-) part of the buried radwaste
-- Constraints on application (i.e. parametric evaluation of analog)
-- Mechanisms for elemental behavior
-- Role of aqueous phases in study
-- Summary, with conclusions if warranted, or suggestions as to how future studies may be oriented for more useful information.

Attachment-6

federal register

Thursday
September 19, 1985

Part II

Environmental Protection Agency

40 CFR Part 191

Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 191

[AH-FRL 2870-3]

Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes

AGENCY: Environmental Protection Agency.

ACTION: Final rule.

SUMMARY: The Environmental Protection Agency (EPA) is promulgating generally applicable environmental standards for the management and disposal of spent nuclear fuel and high-level and transuranic radioactive wastes. The standards apply to management and disposal of such materials generated by activities regulated by the Nuclear Regulatory Commission (NRC) and to disposal of similar materials generated by atomic energy defense activities under the jurisdiction of the Department of Energy (DOE). These standards have been developed pursuant to the Agency's authorities and responsibilities under the Atomic Energy Act of 1954, as amended; Reorganization Plan No. 3 of 1970; and the Nuclear Waste Policy Act of 1982.

Subpart A of these standards limits the radiation exposure of members of the public from the management and storage of spent fuel or high-level or transuranic wastes prior to disposal at waste management and disposal facilities regulated by the NRC. Subpart A also limits the radiation exposures to members of the public from waste emplacement and storage operations at DOE disposal facilities that are not regulated by the NRC.

Subpart B establishes several different types of requirements for disposal of these materials. The primary standards for disposal are long-term containment requirements that limit projected releases of radioactivity to the accessible environment for 10,000 years after disposal. These release limits should insure that risks to future generations from disposal of these wastes will be no greater than the risks that would have existed if the uranium ore used to create the wastes had not been mined to begin with. A set of six qualitative assurance requirements is an equally important element of Subpart B designed to provide adequate confidence that the containment requirements will be met. The third set of requirements are limitations on exposures to individual members of the public for 1,000 years after disposal. Finally, a set of ground water protection requirements limits radionuclide concentrations for 1,000 years after disposal in water withdrawn from most Class I ground waters to the concentrations allowed by the Agency's interim drinking water standards (unless concentrations in the Class I ground waters already exceed the limits in 40 CFR Part 141, in which case this set of requirements would limit the increases in the radionuclide concentrations to those specified in 40 CFR Part 141). Subpart B also contains informational guidance for implementation of the disposal standards to clarify the Agency's intended application of these standards, which address a time frame without precedent in environmental regulations. Although disposal of these materials in mined geologic repositories has received the most attention, the disposal standards apply to disposal by any method, except disposal directly into the oceans or ocean sediments.

This notice describes the final rule that the Agency developed after considering the public comments received on the proposed rule published on December 29, 1982, and the recommendations of a technical review conducted by the Agency's Science Advisory Board (SAB). The major comments received on the proposed standards are summarized together with the Agency's responses to them. Detailed responses to all the comments received are discussed in the Response to Comments Document prepared for this final rule.

DATE: These standards shall be promulgated for purposes of judicial review at 1:00 p.m. eastern time on October 3, 1985. These standards shall become effective on November 18, 1985.

ADDRESSES: *Background Information*—The technical information considered in developing this rule, including risk assessments of disposal of these wastes in mined geologic repositories, is summarized in the Background Information Document (BID) for 40 CFR Part 191, EPA 520/1-85-023. Single copies of both the BID and the Response to Comments Document, as available, may be obtained from the Program Management Office (ANR-458), Office of Radiation Programs, Environmental Protection Agency, Washington, DC 20460; telephone number (703) 557-9351.

Docket—Docket Number R-82-3 contains the rulemaking record for 40 CFR Part 191. The docket is available for inspection between 8 a.m. and 4 p.m. on weekdays in the West Tower Lobby, Gallery 1, Central Docket Section, 401 M Street, SW., Washington, DC. A reasonable fee may be charged for copying.

FOR FURTHER INFORMATION CONTACT: Dan Egan or Ray Clark, Criteria and Standards Division (ANR-460), Office of Radiation Programs, Environmental Protection Agency, Washington, DC 20460; telephone number (703) 557-8610.

SUPPLEMENTARY INFORMATION: Fissioning of nuclear fuel in nuclear reactors creates a small quantity of highly radioactive materials. Virtually all of these materials are retained in the "spent" fuel elements when they are removed from the reactor. If the fuel is then reprocessed to recover unfissioned uranium and plutonium, most of the radioactivity goes into acidic liquid wastes that will later be converted into various types of solid materials. These highly radioactive liquid or solid wastes from reprocessing spent nuclear fuel have traditionally been called "high-level wastes." If it is not to be reprocessed, the spent fuel itself becomes a waste. The nuclear reactors operated by the nation's electrical utilities currently generate about 2,000 metric tons of spent fuel per year. The relatively small physical quantity of these wastes is apparent when compared to the chemically hazardous wastes regulated under the Resource Conservation and Recovery Act, which are produced at a rate of about 150,000,000 metric tons per year.

Although they are produced in small quantities, proper management and disposal of high-level wastes and spent nuclear fuel are essential because of the inherent hazard of the large amounts of radioactivity they contain. Spent fuel from commercial nuclear power reactors contains about 1.6 billion curies of radionuclides with half-lives greater than 20 years. Over the next decade, this inventory is projected to grow at a rate of about 300 million curies per year from reactors currently licensed to operate. Most of this spent fuel is currently stored at reactor sites. Reprocessing reactor fuel used for national defense activities has produced about 700 million curies of radionuclides with half-lives greater than 20 years. Most of these wastes are stored in various liquid and solid forms on three Federal reservations in Idaho, Washington, and South Carolina.

In addition, a wide variety of wastes contaminated with man-made radionuclides heavier than uranium have been created by various processes, mostly from the atomic energy defense activities conducted by the DOE and its predecessor agencies (the Atomic Energy Commission and the Energy

Research and Development Administration). These wastes are usually called "transuranic" wastes. Most of them are stored at Federal reservations in Idaho, Washington, New Mexico, and South Carolina.

National Programs for Disposal of These Wastes

Since the inception of the nuclear age in the 1940's, the Federal government has assumed ultimate responsibility for the care and disposal of these wastes regardless of whether they are produced by commercial or national defense activities. In October 1976, President Ford ordered a major expansion of the Federal program to demonstrate a permanent disposal method for high-level wastes. The Agency was directed to develop generally applicable environmental standards to govern the management and disposal of these wastes as part of this initiative. Among EPA's first activities in response to this directive were a series of public workshops conducted in 1977 and 1978 to better understand the various public concerns and technical issues associated with radioactive waste disposal.

In 1981, the DOE, after completing a comprehensive programmatic environmental impact statement, decided to focus the national program on disposal in mined geologic repositories (46 FR 26677). In 1982, Congress passed the Nuclear Waste Policy Act (henceforth designated "NWPA"), which President Reagan signed into law on January 7, 1983. The NWPA contains several provisions that are relevant to this rulemaking. First, it affirmed the DOE's 1981 decision that mined repositories should receive primary emphasis in the national program, although research on some other technologies would be continued. Second, it established formal procedures regarding the evaluation and selection of sites for geologic repositories, including steps for the interaction of affected States and Indian tribes with the Federal Government regarding site selection decisions. Third, the NWPA levied a fee on utilities that generate electrical power with nuclear reactors in order to pay for Federal management and disposal of their spent fuel or high-level wastes. Fourth, the NWPA reiterated the existing responsibilities of the Federal agencies involved in the national program to develop mined geologic repositories, and it assigned some additional tasks regarding site evaluation. Finally, the Act provided a timetable for several key milestones that the Federal agencies were to meet in carrying out the program.

Section 121 of the NWPA reiterated the Agency's responsibility for developing the overall framework of requirements needed to assure protection of public health and the environment, in accordance with the Agency's authorities under the Atomic Energy Act of 1954 and Reorganization Plan Number 3 of 1970. Section 121 also called for the Agency to promulgate these standards by January 7, 1984. The Agency did not meet this deadline. On February 8, 1985, the Natural Resources Defense Council and four other environmental interest groups filed suit to bring about compliance with the NWPA mandate. This litigation was settled by the Agency and the plantiffs agreeing to a consent order requiring promulgation not later than August 15, 1985. The generally applicable environmental standards promulgated by this notice satisfy the terms of this consent order. However, they also represent the culmination of an effort that began almost nine years ago and that has included frequent interactions with the public to help formulate standards responsive to the concerns about disposal of these dangerous materials.

Objective and Implementation of the Standards

In developing the standards for disposal of spent nuclear fuel and high-level and transuranic radioactive wastes, the Agency has carefully evaluated the capabilities of mined geologic repositories to isolate the wastes from the environment. Because such repositories are capable of performing so well, it has been possible to choose containment requirements that will provide exceptionally good protection to current and future populations for at least 10,000 years after disposal. In fact, EPA's analyses indicate that the small residual risks allowed by the disposal standards would be comparable to the risks that future populations would have been exposed to if the uranium ore used to produce the high-level wastes had not been mined to begin with.[1] The Agency believes that achieving this protection should not significantly increase the cost or difficulty of carrying out the national program for disposing of the wastes from commercial nuclear power plants. In addition, the containment requirements in the final rule are complemented by six qualitative assurance requirements designed to provide confidence that the containment requirements will be met, given the substantial uncertainties inherent in predictions of systems performance over 10,000 years. Because of this comprehensive framework, the Agency is confident that the national program to dispose of these wastes will be carried out with exceptional protection of public health and the environment.

The Nuclear Regulatory Commission (NRC) and the DOE are responsible for implementing these standards. The NRC has already promulgated procedural and technical requirements in 10 CFR Part 60 for disposal of high-level wastes in mined geologic repositories (46 FR 13971, 48 FR 28194). The NRC will obtain compliance with 40 CFR Part 191 for disposal of all high-level wastes by issuing licenses to the DOE, in accordance with 10 CFR Part 60, at various steps in the construction and operation of a repository. The NWPA directs the DOE to select a number of potential sites for geologic repositories, successively reducing this set of alternatives from five to three to one, in consultation with affected States and Indian Tribes and with participation by the public in key steps in the selection process. The DOE will accomplish this through use of site selection guidelines (10 CFR Part 960) that it has developed in accordance with section 112 of the NWPA. Both NRC's 10 CFR Part 60 and DOE's 10 CFR Part 960 incorporate the standards the Agency is promulgating today as the overall performance requirements for a geologic repository. Both of these other rules were designed in concert with EPA"s ongoing development of 40 CFR Part 191. However, both the NRC and DOE must now review these regulations to determine what specific changes will be needed to properly implement the final version of 40 CFR Part 191.

Review of the Proposed Standards

On December 29, 1982, shortly before the NWPA was enacted, the Agency published 40 CFR Part 191 for public review (47 FR 58196) and asked that comments be received by May 2, 1983. Eighty-three substantive replies were received from a broad spectrum of private citizens, public interest groups, members of the scientific community,

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[1] Specifically, the Agency estimates that compliance with the disposal standards would allow no more than 1,000 premature deaths from cancer in the first 10,000 years after disposal of the high-level wastes from 100,000 metric tons of reactor fuel, an average of no more than one premature death every ten years. As this residual risk level is referred to in the following discussion, it should be remembered that it is a speculative calculation that is primarily intended as a tool for comparing risk levels; it should not be considered a reliable projection of the "real" number of health effects resulting from compliance with the disposal standards.

representatives of industry, and State and Federal agencies. These responses contained information and recommendations regarding seven issues on which the Agency sought further public comment (48 FR 21666). Questions concerning these issues were directed to all of the witnesses at two public hearings held during May 1983 in Washington, D.C. and in Denver (48 FR 13444). Copies of these questions were also sent to all those who responded to the initial request for comment, and the availability of these questions was announced in the Federal Register (48 FR 21666). The comment period was then held open until June 20, 1983, to receive responses to these additional questions. Responses to major comments—including all those specifically highlighted for public review—are summarized below. Detailed responses to the full range of comments received is described in the Response to Comments Document prepared for the final rule.

Review of the Technical Basis of the Standards

In parallel with this public review and comment, the Agency conducted an independent scientific review of the technical basis for the proposed 40 CFR Part 191 through a special Subcommittee of the Agency's Science Advisory Board (SAB) (48 FR 509). This Subcommittee held nine public meetings from January 18, 1983, through September 21, 1983, and prepared a final report that was transmitted on February 17, 1984. While finding that the Agency had generally prepared comprehensive and scientifically competent technical analyses to support the proposed standards, the SAB review developed 46 findings and recommendations regarding specific improvements in the technical analyses and in the standards themselves. Since many of the SAB recommendations were to be considered in developing the final rule, the Agency sought public comment on the information and recommendations presented in the final SAB report (49 FR 19604).

Most of the SAB recommendations involve specific details of the technical assessments and judgments the Agency made in developing these standards. After evaluating the public comments received on the SAB report, the Agency agrees with almost all of the SAB's technical recommendations and has made corresponding changes in the technical basis of the final rule. A few of the Subcommittee's recommendations have implications that involve broader policy judgments. These recommendations have been treated as part of the public comment record and are described below as the major comments on the proposed 40 CFR Part 191 are discussed. A complete itemization of the Agency's responses to each of the findings and recommendations of the SAB is contained in the Response to Comments Document, together with a synopsis of the public comments on the SAB report.

Summary of the Final Rule

The rule being promulgated today establishes generally applicable environmental standards for the management and disposal of spent nuclear fuel, high-level radioactive wastes, and transuranic radioactive wastes. The final rule differs in a number of ways from the proposed rule because of changes the Agency has made in response to public comments and in response to the recommendations of the technical review by the Agency's Science Advisory Board. This section provides an overview of the major provisions of the final rule, and changes from the proposed rule are noted. More detail on many of these provisions is provided later as part of the discussion of the comments considered in development of 40 CFR Part 191. The final rule:

(1) Applies to management and disposal of spent nuclear fuel, high-level radioactive wastes as defined by the NWPA, and transuranic wastes containing more than 100 nanocuries per gram of alpha-emitting transuranic isotopes, except for wastes that either the NRC or the Administrator determines do not need the degree of isolation required by this rule. (The proposed rule applied to spent nuclear fuel, high-level wastes exceeding a specific set of concentration limits, and to transuranic wastes containing more than 100 nanocuries per gram.)

(2) Through Subpart A, "Standards for Management and Storage," establishes limits on annual doses to members of the public of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ from exposures associated with management, storage, and preparation for disposal of any of these materials at facilities regulated by the NRC. These limits apply to the combined exposures from all NRC-licensed facilities covered by this Part or 40 CFR Part 190, the Agency's standards for the commercial uranium fuel cycle. Subpart A also limits annual doses to members of the public from management and storage operations at DOE disposal facilities that are not regulated by the NRC to 25 millirems to the whole body and 75 millirems to any other organ. (The proposed rule applied to the combined exposures from operations regulated by 40 CFR Part 190, waste management and storage operations regulated by the NRC or Agreement States, *and* waste management and storage operations conducted at all DOE facilities.) Subpart A also contains a provision that allows the Administrator to issue alternative standards for waste management and storage operations at DOE disposal facilities that are not regulated by the NRC. (The proposed rule contained a provision to allow the implementing agency, either the NRC or the DOE, to grant variances for unusual operating conditions.)

(3) Establishes several sets of requirements for disposal of these wastes through Subpart B, "Standards for Disposal." The primary standards are *containment requirements* that limit projected releases of radioactivity to the accessible environment for 10,000 years after disposal. Equally important is a set of six *assurance requirements* chosen to provide adequate confidence that the containment requirements will be met. In addition, Subpart B of the final rule includes *individual protection requirements* that limit annual exposures from the disposal facility to members of the public in the accessible environment to 25 millirems to the whole body and 75 millirems to any organ for 1,000 years after disposal. The Subpart also contains *ground water protection requirements* that limit radioactivity concentrations in water withdrawn from most Class I ground waters near a disposal system (as defined in conjunction with the Agency's Ground Water Protection Strategy published in August 1984) for 1,000 years after disposal. Finally, Subpart B provides *guidance for implementation* that indicates how the Agency intends the various numerical standards to be applied. (The proposed rule contained only containment requirements, assurance requirements, and procedural requirements; this last category provided some of the basis for the "guidance for implementation" in the final rule.) Major provisions of each of these sets of requirements include the following:

(a) The containment requirements (Section 191.13) limit the total projected release of specific radionuclides over the entire 10,000-year period after disposal. Releases from all expected and accidental causes are included, except for releases from conceivable events that are judged to have an incredibly small likelihood of occurrence. Quantitative terms are used to identify the probabilities of the releases to which the containment requirements apply; however, the final rule acknowledges that determination of compliance will have to tolerate much larger uncertainties than would be appropriate for short-term estimates and that judgments may have to be substituted for quantitative predictions in certain situations. Disposal in compliance with the containment requirements is projected to cause no more than 1,000 premature cancer deaths over the entire 10,000-year period from disposal of all existing high-level wastes and most of the wastes yet to be produced by currently operating reactors—an average of 0.1 fatality per year. This level of residual risk to future generations would be comparable to the risks that those generations would have faced from the uranium ore used to create the wastes if the ore had never been mined. Actual risks will probably be significantly less because of the conservative approach called for by the other parts of Subpart B. (The quantitative probabilities in the proposed rule were an order of magnitude smaller than those incorporated into the final rule. The release limits in the final rule are different than those in the proposed rule due to changes in EPA's technical analyses that were recommended by the SAB Subcommittee; however, the level of residual risk is the same as for the proposed rule.)

(b) The assurance requirements (Section 191.14) call for cautious steps to be taken in disposing of these wastes because of the inherent uncertainties in selecting and designing disposal systems that must be very effective for more than 10,000 years. The assurance requirements incorporate the following principles:

(i) Although active institutional controls, such as guarding and maintaining a disposal site, should be encouraged, they cannot be relied upon to isolate these wastes from the environment for more than 100 years after disposal. (The proposed rule limited reliance to "a few hundred years" after disposal.)

(ii) Disposal systems must be monitored to detect substantial changes from their expected performance until the implementing agency determines that there are no significant concerns to be addressed by further monitoring. (This requirement was not included in the proposed rule.)

(iii) The sites where disposal systems are located must be identified by permanent markers, widespread records, and other passive institutional controls to warn future generations of the dangers and location of the wastes.

(iv) Disposal systems must use several different types of barriers, including both engineered and natural ones, to isolate the wastes from the environment to help guard against unexpectedly poor performance from one type of barrier.

(v) Sites for disposal systems should be selected to avoid places where resources have previously been mined, where there is a reasonable expectation of exploration for scarce or easily accessible resources, or where there is a significant concentration of any material which is not otherwise available. (The wording in the proposed rule would have ruled out sites with a significant possibility of being considered for resource exploration in the future. The final rule revises this requirement to allow use of sites with some resource potential if they have other significant advantages compared to potential alternative sites.)

(vi) Recovery of most of the wastes must not be precluded for a reasonable period after disposal if unforeseen events require this in the future.

(c) The individual protection requirements (Section 191.15) limit annual exposures to members of the public in the accessible environment from the disposal system to 25 millirems to the whole body and 75 millirems to any organ. These requirements apply to undisturbed performance of the disposal system for 1,000 years after disposal. All potential pathways of radiation exposure from the disposal system to people must be considered, including the assumption that individuals consume all of their drinking water (2 liters per day) from any "significant source of ground water" located outside the "controlled area" established around a disposal system. A "significant source" is identified by several parameters intended to describe an aquifer sufficient to meet the needs of a "community water system" as defined in the Agency's National Interim Primary Drinking Water Regulations (40 CFR Part 141). (No explicit individual protection requirements were included in the proposed rule.)

(d) The ground water protection requirements (Section 191.16) limit the concentrations of radioactivity (or the *increases* in concentrations, if preexisting concentrations already exceed these limits) in waters withdrawn from most Class I sources of ground water near a disposal system to no more than 15 picocuries per liter of alpha-emitting radionuclides (including no more than 5 picocuries per liter of radium-226 and radium-228 but excluding radon) and to no more than the combined concentrations of radionuclides that emit either beta or gamma radiation that would produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems if individuals consumed all of their drinking water from that source of ground water. These concentration limits are similar to those set in 40 CFR Part 141 for community water systems. Like the individual protection requirements, the ground water protection requirements apply to undisturbed behavior of the disposal system for a period of 1,000 years after disposal. (No explicit ground water protection requirements were included in the *proposed rule*.)

(e) Section 191.17 of the final rule establishes minimum procedural requirements that the Administrator must follow if additional information considered in the future indicates that it would be appropriate to modify any portion of the disposal standards through further rulemaking. (No similar provision was included in the proposed rule.)

(f) The "guidance for implementation" included as Appendix B to the final rule describes certain analytical approaches and assumptions through which the Agency intends the various long-term numerical standards of Subpart B to be applied. This guidance is particularly important because there are no precedents for the implementation of such long-term environmental standards, which will require consideration of extensive analytical projections of disposal system performance. (The proposed rule contained a corresponding, but less extensive, section entitled "procedural requirements.")

Overall Approach of the Final Rule

In general, the Agency developed the various elements of this rule by balancing several perspectives. One set of considerations was the expected capabilities of the waste management and disposal technologies to reduce both short- and long-term risks to public health and the environment. These capabilities were examined through a number of performance assessments of the waste management, storage, and disposal facilities planned for the wastes generated by commercial nuclear power plants. Since detailed plans have not yet been determined for disposition of the wastes generated by atomic energy defense activities, similar assessments were generally not performed for these materials. A second consideration, where applicable, was consistency with related environmental standards for radiation exposure. A third factor was evaluation of various benchmarks to assess the acceptability of the residual risks that might be allowed by the rule. This was particularly important for the disposal standards, where there were few precedents to guide the Agency's judgments. Finally, the Agency placed considerable emphasis on the public concerns expressed during the various phases of this rulemaking, particularly where these concerns involved addressing the substantial uncertainties inherent in the unprecedented time periods of interest.

The final rule reflects a combination of all these perspectives—no single factor predominated. For instance, no portion of this rule is based solely on projections of the "best" protection that technology might provide. If this had been the case, the rule would have been significantly different. On the other hand, the rule cannot be interpreted as setting precedents for "acceptable risk" levels to future generations that should not be exceeded regardless of the circumstances. Instead, because of a number of unique circumstances, the Agency has been able to develop standards for the management and disposal of these wastes that are both reasonably achievable—with little, if any, effort beyond that already planned for commercial wastes—and that limit risks to levels that the Agency believes are clearly acceptably small. The following paragraphs describe how these various perspectives were used in developing the final rule.

Standards for Management and Storage (Subpart A)

Upon surveying the expected performance of the technologies planned for the management, storage, and preparation of these wastes for disposal, the Agency found that the likely exposures to members of the public would generally be very small. Therefore, compatibility with related radiation protection standards became a more important perspective for Subpart A.

For waste management and storage operations to be regulated by the NRC, the most relevant existing standards are those provisions of 40 CFR Part 190 that limit annual exposures of members of the public to 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ from uranium fuel cycle facilities. Accordingly, the Agency has decided to extend this coverage to include such waste management and storage operations so that the *combined* exposure from all of the NRC-licensed facilities covered under Part 190 and Subpart A of Part 191 shall not exceed these limits. This will include all operations prior to final closure at high-level waste disposal facilities, since these are to be regulated by the NRC.

For waste management and storage operations conducted at atomic energy defense facilities operated for the Department of Energy (which are not regulated by the NRC), the most relevant existing standards are the 40 CFR Part 61 limitations on air emissions of radionuclides that were recently promulgated under the Agency's Clean Air Act authorities (50 FR 5190). These standards limit annual exposures to members of the public to 25 millirems to the whole body and 75 millirems to any organ, with less stringent alternative standards available if it can be shown that no member of the public will receive a continuous exposure of more than 100 millirems per year or an infreqent exposure of more than 500 millirems per year from all sources (excluding natural background and medical exposures.) These Clean Air Act standards are applicable to those facilities *not* covered by 40 CFR Parts 190, 191 or 192. For DOE waste disposal facilities covered by this rule but not regulated by NRC (i.e., those for defense transuranic wastes), the Agency has included standards in Subpart A similar to those included in the Clean Air Act rule.

For other DOE waste management and storage operations, which are usually conducted on large facilities with many other potential sources of radionuclide emissions, the Agency believes that continued regulation under the broader scope of 40 CFR Part 61 is the most effective and practical approach. Otherwise, similar types of emissions from adjoining operations would have to be assessed and regulated through separate rules developed under different authorities; this would cause complex implementation practices without providing any additional protection.

Standards for Disposal (Subpart B)

Developing the standards for disposal of spent fuel and high-level and transuranic wastes involved much more unusual circumstances than those for waste management and storage. Because these materials are dangerous for so long, very long time frames are of interest. Standards must be implemented in the design phase for these disposal systems because active surveillance cannot be relied upon over such periods. At the same time, the standards must accommodate large uncertainties, including uncertainties in our current knowledge about disposal system behavior and the inherent uncertainties regarding the distant future. Subpart B addresses these issues by combining several different types of standards. The primary objective of these standards is to isolate most of the wastes from man's environment by limiting long-term releases and the associated risks to populations. In addition, Subpart B limits risks to individuals in ways compatible with this primary objective.

Although developed primarily through consideration of mined geologic repositories, these disposal standards apply to disposal of spent fuel and high-level and transuranic radioactive wastes by any method—with one exception. The standards do not apply to ocean disposal or disposal in ocean sediments because such disposal of high-level waste is prohibited by the Marine Protection, Research, and Sanctuaries Act of 1972. If this law is ever changed to allow such disposal (DOE continues to study the feasibility of this technology, consistent with the NWPA), the Agency will develop appropriate regulations in accordance with the different authorities that would apply.

Also, these disposal standards do not apply to wastes that have already been disposed of. The various provisions of Subpart B are intended to be met through a combination of steps involving disposal system site selection, design, and operational techniques (i.e., engineered barriers). Therefore, the Agency believes it appropriate that these disposal standards only apply to disposal occuring after the standards have been promulgated—so that they can be taken into consideration in devising the proper selection of controls. Some transuranic wastes produced in support of national defense programs were disposed of before the current DOE procedures for transuranic waste management were adopted in 1970. The exclusion of wastes already disposed of applies to these transuranic wastes, for which selection of disposal system sites, designs, and operational techniques are no longer options.

Containment Requirements (Section 191.13)

To develop the containment requirements, the Agency assumed that some aspects of the future can be predicted well enough to guide the selection and development of disposal systems for these wastes. A period of 10,000 years was considered because that appears to be long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. On the other hand, this period is short enough so that major geologic changes are unlikely and repository performance might be reasonably projected.

The Agency assessed the performance of a number of model geologic repositories similar to those systems now being considered by DOE. Potential radionuclide releases over 10,000 years were evaluated, and very general models of environmental transport and a linear, non-threshold dose-effect relationship were used to relate these releases to the incidence of premature cancer deaths they might cause. For the various repository types, these assessments indicate that disposal of the wastes from 100,000 metric tons of reactor fuel would cause a population risk ranging from no more than about ten to a little more than one hundred premature deaths over the entire 10,000-year period, assuming that the existing provisions of 10 CFR Part 60 regarding engineered barriers are met.

The Agency also evaluated the health risks that future generations would be exposed to from the amount of uranium ore needed to produce 100,000 metric tons of reactor fuel, if this ore had not been mined to begin with. Population risks ranging between 10 and 100,000 premature cancer deaths over 10,000 years were associated with this much unmined uranium ore, depending upon the analytical assumptions made.

These analyses, which have been updated from those prepared for the proposed standards, reinforce the Agency's conclusion that limiting radionuclide releases to levels associated with no more than 1,000 premature cancer deaths over 10,000 years from disposal of the wastes from 100,000 metric tons of reactor fuel satisfies two important objectives. First, it provides a level of protection that appears reasonably achievable by the various options being considered within the national program for commercial wastes. Second, the Agency believes that such a limitation would clearly keep risks to future populations at acceptably small levels, particularly because it appears to limit risks to no more than the midpoint of the range of estimated risks that future generations would have been exposed to if the uranium ore used to create the wastes had never been mined. Thus, because mined geologic repositories appear capable of providing such good protection, the Agency has decided to establish containment requirements that meet these two objectives.

The specific release limits for different radionuclides in Table 1 of the final rule were developed by estimating how many curies of each radionuclide would cause 1,000 premature deaths over 10,000 years if released to the environment. The limits were then stated in terms of the allowable release from 1,000 metric tons of reactor fuel (so that the actual curie values in Table 1 correspond to a risk level of 10 premature deaths over 10,000 years). All of these limits have been rounded to the nearest order of magnitude because of the approximate nature of these calculations. For particular disposal systems, release limits based upon the amount of waste in the system will be developed and will be used in a formula that insures that the desired risk level will not be exceeded if releases of more than one type of radionuclide are predicted. For some of the wastes covered by this rule, 1,000 metric tons of reactor fuel is not an appropriate unit of waste. In these situations, the various Notes to Table 1 provide instructions on how to calculate the proper release limits. In particular, the final rule includes provisions for high-level wastes from reactor fuels that have received substantially different uses in national defense applications (and contain much different amounts of radioactivity) than is typical of most reactor fuel used to generate electricity. The proposed rule would have allowed releases for these different types of fuels to occur in much different proportions to their total radioactivity than the Agency intended.

The release limits apply to radionuclides that are projected to move into the "accessible environment" during the first 10,000 years after disposal. The accessible environment includes all of the atmosphere, land surface, surface waters, and oceans. However, it does not include the lithosphere (and the ground water within it) that is below the "controlled area" surrounding a disposal system. The standards are formulated this way because the properties of the geologic media around a mined repository are expected to provide much of the disposal system's capability to isolate these wastes over these long time periods. Thus, a certain area of the natural environment is envisioned to be dedicated to keeping these dangerous materials away from future generations and may not be suitable for certain other uses. In the final rule, this "controlled area" is not to exceed 100 square kilometers and is not to extend more than five kilometers in any direction from the original emplacement of the wastes in the disposal system. The implementing agencies may choose a smaller area whenever appropriate.

The containment requirements apply to accidental disruptions of a disposal system as well as to any expected releases. Accordingly, they are stated in terms of the probability of releases occurring. This is done in two steps.

First, the release limits calculated in accordance with Notes 1 through 5 to Table 1 apply to those release levels that are projected to occur with a cumulative probability greater than 0.1 for the entire 10,000-year period over which these disposal standards apply. This includes the total releases from those processes that are expected to occur as well as relatively likely disruptions (which the Agency assumes will primarily include predictions of inadvertent human intrusion).

Second, these release limits multiplied by ten apply to all of the releases projected to occur with a cumulative probability greater than 0.001 over the 10,000-year period. The Agency expects that this will include releases that might occur from the more likely natural disruptive events, such as fault movement and breccia pipe formation (near soluble media such as salt formations). This range of probabilities was selected to include the anticipated uncertainties in predicting the likelihood of these natural phenomena. Greater releases are allowed for these circumstances because they are so unlikely to occur.

Finally, the containment requirements place no limits on releases projected to occur with a cumulative probability of less than 0.001 over 10,000 years. Probabilities this small would tend to be limited to phenomena such as the appearance of new volcanos outside of known areas of volcanic activity, and the Agency believes there is no benefit to public health or the environment from trying to regulate the consequences of such very unlikely events.

The containment requirements call for a "reasonable expectation" that their various quantitative tests be met. This phrase reflects the fact that unequivocal numerical proof of compliance is neither necessary nor likely to be obtained. A similar qualitative test, that of "reasonable assurance," has been used with NRC regulations for many years. Although the Agency's intent is similar, the NRC phrase has not been used in 40 CFR Part 191 because "reasonable assurance" has come to be associated with a level of confidence that may not be appropriate for the very long-term analytical projections that are called for by 191.13. The use of a different test of judgment is meant to acknowledge the unique considerations likely to be encountered upon implementation of these disposal standards.

Assurance Requirements (Section 191.14)

In contrast to the containment requirements, the assurance requirements were developed from that point of view that there may be major uncertainties and gaps in our knowledge of the expected behavior of disposal systems over many thousands of years. Therefore, no matter how promising the analytical projections of disposal system performance appear to be, these materials should be disposed in a cautious manner that reduces the likelihood of unanticipated types of releases. Because of the inherent uncertainties associated with these long time periods, the Agency believes that the principles embodied in the assurance requirements are important complements to the containment requirements that should insure that the level of protection desired is likely to be achieved.

Each of the assurance requirements was chosen to reduce the potential harm from some aspect of our uncertainty about the future. Designing disposal systems with limited reliance on active institutional controls reduces the risks if future generations do not maintain surveillance of disposal sites. On the other hand, planning for long-term monitoring helps reduce the chances that unexpectedly poor performance of a disposal system would go unnoticed. Using extensive markers and records and avoiding resources when selecting disposal sites both serve to reduce the chances that people may inadvertently disrupt a disposal system because of incomplete understanding of its location, design, or hazards. Designing disposal systems to include multiple types of barriers, both engineered and natural, reduces the risks if one type of barrier performs more poorly than current knowledge indicates. Finally, designing disposal systems so that it is feasible for the wastes to be located and recovered gives future generations an opportunity to rectify the situation if new discoveries indicate compelling reasons (which would not be foreseeable now) to change the way these wastes are disposed of.

The proposed standards contained two other assurance requirements intended to reduce the risks of uncertainty. One of them called for these wastes to be disposed of promptly to reduce the uncertainties associated with storing these materials for indefinitely long times with methods that require active human involvement. However—after this rule was published for public comment—the NWPA was enacted, setting up mandates and procedures intended to insure development of the necessary disposal systems for spent fuel and high-level wastes. Furthermore, the Department has made substantial progress towards developing a repository for disposal of the transuranic wastes from atomic energy defense activities. Because of these steps, the Agency decided that the call for prompt disposal was no longer needed, and this assurance requirement has not been included in the final rule.

The other proposed assurance requirement deleted from the final rule is the provision that called for releases to be kept as small as reasonably achievable even when the numerical containment requirements have been complied with. This would have increased the confidence of achieving the desired level of protection even if there were major uncertainties in analytical projections of long-term isolation. However, the Agency does not believe that it is necessary to retain this assurance requirement in the final standards because of two aspects of the related rules subsequently promulgated by the NRC and DOE for disposal of spent fuel and high-level wastes.

First, NRC's 10 CFR Part 60 implemented the multiple barrier principle by requiring very good performance from two types of engineered components: A 300 to 1,000-year lifetime for waste packages during which there would be essentially no expected release of waste, and a subsequent long-term release rate from the waste form of no more than one part in 100,000 per year. The Agency fully endorses this approach and believes that it represents the best performance reasonably achievable for currently foreseeable engineered components. Second, the DOE has included a provision in its site selection guidelines (10 CFR Part 960) that calls for significant emphasis to be placed on selecting sites that demonstrate the lowest releases over 100,000 years compared to the other alternatives available. Particularly because of the longer time frame involved in this comparison, the Agency believes that this provides adequate encouragement to choose sites that provide the best isolation capabilities available. Therefore, the concept of keeping long-term releases as small as reasonably achievable has been embodied by other agencies' regulations for both the engineered and natural components of disposal systems.

The final rule incorporates the five remaining assurance requirements plus the requirement for long-term monitoring, but it makes them applicable only to disposal facilities that are not regulated by the NRC. In its comments on the proposed rule, the NRC objected to inclusion of the assurance requirements, asserting that they were not properly part of the Agency's authorities assigned by Reorganization Plan No. 3 of 1970. The Agency continues to believe that provisions such as the assurance requirements are an appropriate part of generally applicable standards where they are necessary to establish the regulatory context for numerical standards—as they are in these circumstances because of the major uncertainties involved. However, the two agencies have agreed to resolve this issue by having the Commission modify 10 CFR Part 60 where necessary to incorporate the intent of the assurance requirements, rather than have them included in 40 CFR Part 191 for NRC-licensed disposal facilities. Thus, 10 CFR Part 60 will establish the context needed for appropriate implementation of 40 CFR Part 191.

The NRC staff is preparing the appropriate revisions to Part 60 and has told the Agency that they will be published in the Federal Register for public review and comment within approximately 120 days of today's promulgation of 40 CFR Part 191. EPA has provided NRC with all of the comments received on the assurance requirements during the 40 CFR Part 191 rulemaking, and the Agency will participate in the NRC rulemaking to facilitate our objective of having the intent of all of the assurance requirements embodied in Federal regulation. Finally, the Agency will review the record and outcome of the Part 60 rulemaking to determine if any subsequent modifications to 40 CFR Part 191 are needed.

Individual and Ground Water Protection Requirements (Sections 191.15 and 191.16)

While the primary objective of both the proposed and final disposal standards has been to limit potential long-term releases from disposal systems (and the population risks associated with such releases), these two sections have been added to the final rule to provide protection for those individuals in the vicinity of a disposal system. There are a number of difficult issues involved in formulating standards for individual protection in this situation, as discussed later in the "Release Limits vs. Individual Dose Limits" section. However, after evaluating the various comments received on this topic, the Agency believes that there are also important advantages in providing for individual protection in ways compatible with the containment and assurance requirements. In discussing this issue, the SAB Subcommittee stated that: "We support the use of a population risk criteria. We believe it is impractical to provide absolute protection to every individual for all postulated events or for very long periods. On the other hand, in our view it is important that, for the first several hundred years, residents of the region immediately outside the accessible environment have very great assurance that they will suffer no, or negligible, ill effects from the repository."

The individual protection requirements in the final rule limit the annual exposure from the disposal system to a member of the public in the accessible environment, for the first 1,000 years after disposal, to no more than 25 millirems to the whole body or 75 millirems to any organs. These limitations apply to the predicted behavior of the disposal system, including consideration of the uncertainties in predicted behavior, assuming that the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. The Agency chose the limits of 25 millirem/year to the whole body and 75 millirem/year to any organ because it believes that they represent a sufficiently stringent level of protection for situations where no more than a few individuals are likely to receive this exposure. If such an individual were exposed to this level over a lifetime (which seems particularly unlikely given the localized pathways through which waste might escape from a geologic repository), the Agency estimates this would cause a 5×10^{-4} chance of incurring a premature fatal cancer.

In choosing a time period for these requirements to protect individuals nearby disposal systems, the Agency took into account concerns such as those expressed by the SAB by examining the effects of choosing different time frames. As 10,000 years was chosen for the containment requirements because it is long enough to encourage use of disposal sites with natural characteristics that enhance long-term isolation, 1,000 years was chosen for the individual protection provisions because the Agency's assessments indicate it is long enough to insure that particularly good engineered barriers would need to be used at potential sites where some ground water would be expected to flow through a mined geologic repository. Use of a time much shorter than 1,000 years would not call for substantial engineered barriers even at disposal sites with a lot of ground water flow.

On the other hand, demonstrating compliance with individual exposure limits for times much longer than 1,000 years appears to be quite difficult because of the analytical uncertainties involved. It would require predicting radionuclide concentrations—even from releases of tiny portions of the waste—in all the possible ground water pathways flowing in all directions from the disposal system, at all depths down to 2,500 feet, as a function of time over many thousands of years. At some of the sites being considered (and possibly all of them, depending upon what is discovered during site characterization) the only certain way to comply with such requirements for periods on the order of 10,000 years appears to be to use very expensive engineered barriers that would rule out any potential releases over most of this period. While such barriers could provide longer-term protection for individuals, they would not provide substantial benefits to populations because the containment and assurance requirements already reduce population risks to very small levels.

Based on all of these considerations, the Agency has decided that a 1,000-year duration is adequate for quantitative limits on individual exposures after disposal. For longer time periods, several of the qualitative assurance requirements should help to reduce the chances that individuals will receive serious radiation exposures. In addition, 40 CFR Part 191 in no way limits the future applicability of the Agency's drinking water standards (40 CFR Part 141)—which protect community water supply systems through institutional controls—or of similar standards that future generations may choose to adopt.

In assessing the performance of a disposal system with regard to individual exposures, all pathways of radioactive material or radiation from the disposal system to people shall be considered. In particular, the assessments must assume that individuals consume all of their drinking water (2 liters per day) from any portion of a "significant source of ground water" anywhere outside of the "controlled area" surrounding the disposal system. Significant sources of ground water are defined to include underground formations that are likely to be able to provide enough water for a community water system as defined in 40 CFR Part 141. (More information regarding this definition is provided later in the "Release Limits vs. Individual Dose Limits" discussion.) Formations that could only provide smaller amounts of potable water have not been included because the Agency wants to avoid discriminating against the use of low-productivity geologic formations that might provide very good long-term isolation as disposal sites. The Agency believes this is reasonable for these standards because of the very small number of such disposal facilities that are contemplated (no more than three or four over the next 100 years.) However, the Agency has no plans to use this classification for other ground water related standards, which usually affect a far greater number of situations.

The Agency has not required these individual protection provisions to assume ground water use within the controlled area because geologic media within the controlled area are an integral part of the disposal system's capability to provide long-term isolation. (But if the implementing agency plans to allow individuals to use ground water within the controlled area, such planned use would have to be considered within the pathways evaluated to determine compliance with § 191.15.) The potential loss of ground water resources is very small because of the small number of such disposal facilities contemplated. Nevertheless, the Agency has also added ground water protection requirements to the final rule (Section 191.16) that protect certain sources of ground water even within the controlled area. These ground water protection requirements are similar to the individual protection requirements because they apply to undisturbed performance for 1,000 years after disposal. However, the ground water protection requirements apply only to those Class I ground waters, as they are identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984, that meet the following three conditions: (1) They are within the controlled area or near (less than five kilometers beyond) the controlled area; (2) they are supplying drinking water for thousands of persons as of the date that the Department selects the site for extensive exploration as a potential location of a disposal system; and (3) they are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

For such Class I ground waters, § 191.16 limits the radionuclide concentrations in water withdrawn from any portion of them to no more than concentration limits similar to those established for the output of community water systems in 40 CFR Part 141. However, if the preexisting concentrations of radioactivity in the Class I aquifer already exceed any of these limits at a particular site, § 191.16 then limits any *increases* in the preexisting concentrations to these same concentration limits. The Agency believes these provisions are necessary and adequate to avoid any significant degradation of the important drinking water resources provided by these Class I ground waters.

Alternative Provisions for Disposal (Section 191.17)

In developing the disposal standards, the Agency has had to make many assumptions about the characteristics of disposal systems that have not been built, about plans for disposal that are only now being formulated, and about the probable adequacy of technical information that will not be collected for many years. Thus, although the Agency believes that the disposal standards being promulgated today are appropriate based upon current knowledge, we cannot rule out the possibility that future information may indicate needs to modify the standards.

In recognition of this possibility, § 191.17 of the final rule sets forth procedures under which the Administrator may develop modifications to Subpart B, should the need arise. Any such changes would have to proceed through the usual notice-and-comment rulemaking process, and § 191.17 stipulates that such a rulemaking would require a public comment period of at least 90 days, to include public hearings in affected areas of the country. Although such procedures are common practice in rulemakings of this type, they are not required by the statutes relevant to this rule (Administrative Procedures Act mandates can be satisfied by a comment period as short as 14 days). Thus, § 191.17 insures an opportunity for significant public interaction regarding any proposed changes to the disposal standards.

There are several areas of uncertainty the Agency is aware of that might cause suggested modifications of the standards in the future. One of these concerns implementation of the containment requirements for mined geologic repositories. This will require collection of a great deal of data during site characterization, resolution of the inevitable uncertainties in such information, and adaptation of this information into probabilistic risk assessments. Although the Agency is currently confident that this will be successfully accomplished, such projections over thousands of years to determine compliance with an environmental regulation are unprecedented. If—after substantial experience with these analyses is acquired—disposal systems that clearly provide good isolation cannot reasonably be shown to comply with the containment requirements, the Agency would consider whether modifications to Subpart B were appropriate.

Another situation that might lead to suggested revisions would be if additional information were developed regarding the disposal of certain wastes that appeared to make it inappropriate to retain generally applicable standards addressing all of the wastes covered by this rule. For example, the DOE is considering disposal of some defense wastes by stabilizing them in their current storage tanks, rather than relocating them to a mined repository. The Agency has not assessed the ramifications of such disposal yet, and it is certainly possible that it could be carried out in compliance with all the provisions of Subpart B being promulgated today. However, it is also possible that there may be benefits associated with such disposal that would warrant changes in Subpart B for these types of waste. If so, § 191.17 would govern the consideration of any such revisions.

Other examples of developments that might offer reasons to consider alternative provisions in the future include: The use of reactor fuel cycles or utilizations substantially-different than today's; new models of the environmental transport and biological effects of radionuclides that indicate major changes (i.e., approaching an order of magnitude) in the relative risks associated with different radionuclides and the level of protection sought by the disposal standards; or information that indicates that particular assurance requirements might not be needed in certain situations to insure adequate confidence of long-term environmental protection.

Guidance for Implementation (Appendix B)

This supplement to the final rule is based upon some of the analytical assumptions that the Agency made in developing the technical basis used for formulating the numerical disposal standards. These analytical assumptions incorporate information assembled as part of the technical basis used to develop the proposed rule. In particular, Appendix B discusses: (1) The consideration of all barriers of a disposal system in performance assessments; (2) reasonable limitations on the scope of performance assessments; (3) the use of average or "mean" values in expressing the results of performance assessments; (4) the types of assumptions regarding the effectiveness of institutional controls; and (5) limiting assumptions regarding the frequency and severity of inadvertent human intrusion into geologic repositories.

The implementing agencies are responsible for selecting the specific information to be used in these and other aspects of performance assessments to determine compliance with 40 CFR Part 191. However, the Agency believes it is important that the assumptions used by the implementing agencies are compatible with those used by EPA in developing this rule. Otherwise, implementation of the disposal standards may have effects quite different than those anticipated by EPA. The final rule to be published in the Code of Federal Regulations will include this informational appendix as guidance to the implementing agencies. Although the other agencies are not bound to follow this guidance, EPA recommends that it be carefully considered in planning for the application of 40 CFR Part 191. The Agency will monitor implementation of the disposal standards as it develops over the next several years to determine whether any changes to the rule are called for to meet the Agency's objectives for these standards.

Comments on Issues Highlighted for Public Review

The Agency particularly requested public comment on six issues associated with the proposed rule (47 FR 58196). After these comments were received, additional comments and information were requested on seven issues raised by the initial comments (48 FR 21666). Two of these seven issues (the definition of high-level waste and the use of individual dose limitations in the disposal standards) had been included among the first six issues that were highlighted. Thus, a total of eleven questions received particular attention during the public review and comment process. The following paragraphs summarize the comments received on each of these issues and the Agency's responses to them, including descriptions of any resulting changes made in the final rule.

Definition of "High-Level Waste"

Traditionally, the term "high-level waste" has meant the highly radioactive liquid wastes remaining from the recovery or uranium and plutonium in a nuclear fuel reprocessing plant, and other liquid or solid forms into which such liquid wastes are converted to facilitate managing them. This traditional use of the term has not included radioactive materials from other sources, no matter how radioactive they are. However, somewhat different definitions of high-level waste have appeared in certain laws and regulations affecting specific aspects of radioactive waste management. Most notably, some of these definitions have included unreprocessed spent fuel as the prospects for a commercial fuel reprocessing industry became more uncertain.

In the proposed rule, high-level waste was defined in the traditional sense, including spent fuel if disposed of without reprocessing. But the proposed definition also included minimum radioactivity concentrations below which such materials would not be subject to the stringent isolation requirements of 40 CFR Part 191. To identify these minimum concentrations, the maximum concentrations that the NRC determined that it would generally accept in near-surface disposal facilities under 10 CFR Part 61 (47 FR 57446) were adapted. Since this represented a modification of the traditional meaning of high-level waste, the Agency particularly sought comment on this aspect of the proposed rule.

Shortly after 40 CFR Part 191 was published for public review, the NWPA was enacted. The NWPA distinguished between spent nuclear fuel and high-level waste, and it defined high-level waste to include both: "(A) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation." This definition allow for inclusion of highly radioactive material not related to reprocessing of spent nuclear fuel, and it reflects the concept that some derivatives of nuclear fuel reprocessing may not contain sufficient radioactivity to warrant exceptional isolation.

Many of the comments regarding the proposed definition suggested that EPA adopt the definition in the NWPA, although in response to the specific questions distributed in conjunction with the Agency's public hearings, many responders thought that the Agency should define the phrase "sufficient concentrations" contained in part A of the NWPA definition. However, several commenters argued that the proposed lower limits for high-level waste concentrations had been improperly taken out of the context of 10 CFR Part 61 and could require expensive disposal of wastes with relatively small hazards.

After considering these comments and other information currently available, the Agency decided to incorporate the NWPA definition of high-level waste in the final 40 CFR Part 191 without further elaboration of the phrase "sufficient concentrations." The Agency recognizes that this introduces some uncertainty regarding the applicability of this rule. However, the Commission is now beginning a rulemaking that should assemble the technical information needed to develop a more specific definition of high-level wastes. Since the NRC definition would not necessarily apply to all the situations covered by 40 CFR Part 191 (e.g., management and storage of defense high-level wastes prior to disposal is not regulated by NRC), the Agency will follow the Commission's rulemaking to determine what appropriate elaborations of the NWPA definition should be incorporated into 40 CFR Part 191. Upon completion of the NRC rulemaking, the Agency will initiate steps to appropriately modify this rule. In addition, EPA will address disposal of any radioactive wastes that are not covered by 40 CFR Part 191 or 40 CFR Part 192 (the Agency's standards for disposal of uranium mill tailings) as it considers standards for disposal of low-level radioactive wastes (48 FR 39563).

Finally, incorporating the NWPA definition of high-level waste also includes the phrase "consistent with existing law" when describing the NRC's responsibilities to identify materials as high-level waste. Promulgation of 40 CFR Part 191 with this definition does not signify Agency acceptance or endorsement of any particular interpretation of the phrase "consistent with existing law." The Agency presumes that the Commission will specify the applicability of its existing authorities as it conducts the relevant rulemaking efforts.

The Level of Protection

In the proposed rule, the containment requirements for disposal systems limited the residual risks to no more than an estimated 1,000 premature cancer deaths over the first 10,000 years after disposal of the wastes from 100,000 metric tons of heavy metal (MTHM) used as fuel in a nuclear reactor. The Agency pointed out that a variety of mined repository designs using different combinations of geologic media and engineered controls were expected to meet these requirements. It was also estimated that the residual risks to future generations appeared to be no greater than if the uranium ore used to create the wastes had not been mined. EPA particularly asked for comment on whether it had taken an appropriate and reasonable approach in choosing this level of protection based upon these considerations.

Most of the public comments found this approach satisfactory. However, some commenters argued that the risks from unmined uranium ore did not necessarily define an acceptably low level of residual risks. They pointed out that such risks may vary from place to place (and a high-level waste repository could "redistribute" them) and that society sometimes does take measures to clean-up naturally-occurring radioactivity, implying that such natural risks are not always "acceptable."

On the other hand, some commenters felt that the level of protection sought in the proposed rule was far too stringent when compared to risks allowed and accepted by society from other activities. For example, the SAB Subcommittee recommended that the desired level of protection be relaxed by at least a factor of ten for this reason, coupled with the Subcommittee's concern that the uncertainties in analytical projections over thousands of years could make it difficult to demonstrate compliance with the proposed containment requirements.

After evaluating the public comments and updated performance assessments of geologic repositories, the Agency has retained the proposed level of protection as the basis for the long-term containment requirements in the final rule—even though it is true that long-term assessments of repository performance will encounter substantial uncertainties, as the SAB Subcommittee pointed out. Three reasons support this decision.

First, revising the performance assessments in accordance with many of the technical recommendations of the SAB has reinforced the Agency's conclusion that the proposed level of protection can reasonably be achieved by a variety of combinations of repository sites and designs—and EPA's regulatory impact analyses indicate that this level of protection can be achieved without significant effects on the cost of disposing of these wastes.

Second, comparing this level of protection with the comparable risks from equivalent amounts of unmined uranium ore continues to reinforce the Agency's belief that this is an acceptably small residual risk for future generations. Therefore, the Agency believes that this level of protection represents a reasonable basis for these disposal standards.

Third, rather than relax the level of protection, the Agency has chosen to address the uncertainties that concerned the SAB Subcommittee by adding § 191.13(b) and by providing a more detailed "Guidance for Implementation" section to replace the proposed "Procedural Requirements." For example, this guidance points out that the entire range of possible projections of releases need not meet the containment requirements. Rather, compliance should be based upon the projections that the implementing agencies believe are more realistic. Furthermore, these revisions acknowledge that the quantitative calculations needed may have to be supplemented by reasonable qualitative judgments in order to appropriately determine compliance with the disposal standards.

In retaining the proposed level of protection, the Agency emphasizes that it is making a decision applicable only to the circumstances involving disposal of spent nuclear fuel and high-level and transuranic wastes. This rule cannot be used to establish precedents such as "no incremental risk to future generations" for extrapolation to other disposal problems. For other situations, evaluations of technological feasibility and cost-effectiveness must be considered for the particular set of circumstances. If mined geologic repositories were not capable of providing such good protection, the Agency might have chosen considerably different standards.

Time Period for Containment Requirements

Many commenters addressed the 10,000-year period used for the proposed containment requirements. A few argued that this period was too long and that EPA should only be concerned with a few hundred to a thousand years. A number of commenters supported the focus on 10,000 years. However, many commenters felt that it was inappropriate for the standards to ignore the period after 10,000 years. Some suggested that the containment requirements should address periods ranging from 50,000 to 500,000 years.

In the proposed rule, the Agency indicated that 10,000 years was chosen, in part, because compliance with quantitative standards for a substantially longer period would have entailed considerably more uncertain calculations. There was no intention to indicate that times beyond 10,000 years were unimportant, but the Agency felt that a disposal system capable of meeting the proposed containment requirements for 10,000 years would continue to protect people and the environment well beyond 10,000 years. The SAB Subcommittee reviewed and supported these technical arguments for limiting the containment requirements to a 10,000-year period. Those commenters who argued for longer periods did not suggest effective ways that might compensate for the substantially greater uncertainties inherent in longer projections of disposal system performance.

However, many of the commenters and the SAB Subcommittee suggested that more qualitative or comparative assessments beyond 10,000 years might be appropriate. The Agency agreed with these comments and worked with the DOE to formulate comparative assessment provisions that have been incorporated into the final version of the Department's site selection guidelines (10 CFR Part 960). These provisions call for comparisons of the projected releases from undisturbed performance of alternative repository sites over 100,000 years to be a significant consideration in site selection. Since natural barriers are expected to provide the primary protection for such long time frames, this provision should allow for appropriate consideration of longer time periods without requiring the absolute values of these very uncertain calculations to meet a specific quantitative test. With the inclusion of this comparative test in 10 CFR Part 960, the Agency believes that no modification is needed in 40 CFR Part 191.

Use of Quantitative Probabilities in the Containment Requirements

The containment requirements in the proposed rule applied to two categories of potential releases ("reasonably foreseeable" and "very unlikely") based upon their projected probabilities of occurrence over the first 10,000 years after disposal. In its comments on the proposed rule, the NRC objected to the proposed quantitative definitions of these probabilities on the basis that calculation of such probabilities could be so uncertain that it would be impractical to determine whether the standards had been complied with. Instead, the NRC suggested substitution of qualitative terms to identify the two categories of potential releases. The wording proposed by the NRC was formulated in terms of releases that might be caused by geologic processes and events.

In the second round of comment, the Agency sought information on whether to adopt the NRC's recommended wording or to retain definitions based on quantitative probabilities. Although a number of commenters agreed with the NRC position, the preponderance of comments supported retention of the quantitative probabilities. The SAB Subcommittee strongly supported retention of the probabilistic structure, but with substantially less restrictive probabilities and with the proviso that the Agency be sure that such conditions would be ". . . practical to meet and [would] not lead to serious impediments, legal or otherwise, to the licensing of high-level waste repositories." After considering all of this information, the Agency has revised the structure of the containment requirements in several ways that will retain quantitative objectives for long-term containment while allowing the implementing agencies enough flexibility to make qualitative judgments when necessary.

First, the final rule does not use the terms "reasonably foreseeable" and "very unlikely" releases. Instead, the permissible probabilities for two different levels of cumulative releases (over 10,000 years after disposal) are now incorporated directly into the containment requirements.

Second, the numerical probabilities associated with the two release categories have been increased by an order of magnitude to reflect further assessments of the uncertainties associated with projecting the probabilities of geologic events such as fault movement.

Third, the final rule clearly indicates that comprehensive performance assessments, including estimates of the probabilities of various potential releases whenever meaningful estimates are practicable, are needed to determine compliance with the containment requirements.

Fourth, a paragraph has been added to the final containment requirements (Section 191.13) to emphasize that unequivocal proof of compliance is neither expected nor required because of the substantial uncertainties inherent in such long-term projections. Instead, the appropriate test is a reasonable expectation of compliance based upon practically obtainable information and analysis. This paragraph was patterned after a paragraph that considered similar issues in NRC's 10 CFR Part 60.

Finally, the "Guidance for Implementation" section has been added (Appendix B). This part of the rule describes the Agency's assumptions regarding performance assessments and uncertainties and should discourage overly restrictive or inappropriate implementation of the containment requirements.

The Agency believes that these revisions to the proposed rule preserve an objective framework for application of the containment requirements that requires very stringent isolation while allowing the implementing agencies adequate flexibility to handle specific uncertainties that may be encountered.

Within this framework, the possibility of inadvertent human intrusion into or nearby a repository requires special attention. Such intrusion can significantly disrupt the containment afforded by a geologic repository (as well as being dangerous for the intruders), and repositories should be selected and designed to reduce the risks from such potential disruptions. However, assessing the ways and the reasons that people might explore underground in the future—and evaluating the effectiveness of passive controls to deter such exploration near a repository—will entail informed judgment and speculation. It will not be possible to develop a "correct" estimate of the probability of such intrusion. The Agency believes that performance assessments should consider the possibilities of such intrusion, but that limits should be placed on the severity of the assumptions used to make the assessments. Appendix B to the final rule describes a set of parameters about the likelihood and consequences of inadvertent intrusion that the Agency assumed were the most pessimistic that would be reasonable in making performance assessments. The implementing agencies may adopt these assumptions or develop similar ones of their own. However, as indicated under the discussion of institutional controls, the Agency does not believe that institutional controls can be relied upon to completely eliminate the possibility of inadvertent intrusion.

Definition of "Accessible Environment"

The containment requirements limit releases to the "accessible environment" for 10,000 years after disposal. In the proposed rule, ground water within 10 kilometers of a disposal system was excluded from the definition of accessible environment. This definition was intended to reflect the concept that the geologic media surrounding a mined repository are part of the long-term containment system, with disposal sites being selected so that the surrounding media prevent or retard transport of radionuclides through ground water. Such surrounding media would be dedicated for this purpose, with the intention to prohibit incompatible activities (either those that might disrupt the disposal system or those that could cause significant radiation exposures) in perpetuity. Applying standards to the ground water contained within these geologic media surrounding a repository would ignore the role of this natural barrier, and it could reduce the incentive to search for sites with characteristics that would enhance long-term containment of these wastes. (At the same time, the Agency recognized that the institutional controls designed to reserve this area around a disposal system cannot be considered infallible, and other provisions of the rule are designed to reduce the consequences of potential failures.)

Many commenters objected to the definition of accessible environment incorporated in the proposed rule. Some recommended that all ground water, or all "potable" ground water, should be included. Others agreed that it was appropriate to exclude some ground water in the immediate vicinity of a repository, but argued that the proposed 10-kilometer distance was too long—particularly for ground water sources that were likely to be used in the future. A few commenters thought that the proposed definition was too restrictive by including all ground water beyond 10 kilometers; they suggested that poor quality ground water sources unlikely to be used in the future should not be part of the accessible environment at all.

After considering these comments, the Agency has decided to make several changes in the definition of the "accessible environment." First, the concept of a "controlled area" has been adopted from NRC's 10 CFR Part 60. This establishes an area around a disposal system that is to be identified by markers, records, and other passive institutional controls intended to prohibit incompatible activities from the area. Consistent with the proposed 40 CFR Part 191, the current NRC definition of "controlled area" limits its distance from the edge of a repository to no more than 10 kilometers. The final 40 CFR Part 191 defines "accessible environment" to include: (1) The atmosphere, land surfaces, surface waters, and the oceans, wherever they are located; and (2) portions of the lithosphere—and the ground water within it—that are beyond the controlled area.

Second, the Agency has made the definition of the "controlled area" more restrictive than that currently incorporated in 10 CFR Part 60. This revised definition limits the controlled area to a distance no greater than five kilometers from the original emplacement of wastes in a disposal system, rather than 10 kilometers. Furthermore, the revised definition limits the area encompassed by the controlled area to no more than 100 square kilometers, which is approximately the area that would be encompassed by a controlled area at a distance of three kilometers from all sides of a typical repository configuration. (A distance of five kilometers from all sides of a typical repository would correspond to an area of about 200 square kilometers, whereas a distance of ten kilometers from all sides corresponds to an area of almost 500 square kilometers.) This revised definition substantially reduces the area of the lithosphere that would have been removed from the "accessible environment" defined in the proposed rule, and it somewhat reduces the distance used in the proposed rule. The five-kilometer distance was chosen to retain reasonable compatibility with the NRC's requirement for a preemplacement ground water travel time of 1,000 years to the accessible environment (one of the 10 CFR Part 60 requirements developed in concert with the proposed rule), while still providing for greater isolation than called for by the proposed rule. This definition of the accessible environment will allow a controlled area to be established asymmetrically around a repository based upon the particular characteristics of a site.

Release Limits vs. Individual Dose Limits

The Agency believes that the containment requirements in § 191.13 will insure that the overall population risks to future generations from disposal of these wastes will be acceptably small. However, the situation with regard to potential individual doses is more complicated. Even with good engineering controls, some waste may eventually (i.e., several hundreds or thousands of years after disposal) be released into any ground water that might be in the immediate vicinity of a geologic repository. Since ground water generally provides relatively little dilution, anyone using such contaminated ground water in the future may receive a substantial radiation exposure (e.g., several rems per year or more). This possibility is inherent in collecting a very large amount of radioactivity in a small area.

The proposed rule did not contain any numerical restrictions on such potential individual doses after disposal. Rather, the proposal relied on several of the qualitative assurance requirements to greatly reduce the likelihood of such exposures. In particular, the assurance requirement calling for extensive permanent markers and records was intended to perpetuate information to future generations about the dangers of intruding into the vicinity of a repository. The assurance requirement to avoid sites with significant resources was intended to reduce the incentive to explore around a repository even if the information passed on was ignored or misunderstood. And the assurance requirements to use multiple barriers, both engineered and natural, and to keep releases as small as reasonably achievable were intended to encourage reduction of releases to ground water beyond that needed to meet the containment requirements—further reducing the potential for harmful individual exposures.

This approach to potential individual exposures was highlighted for comment when 40 CFR Part 191 was proposed. After receiving many recommendations to incorporate a limitation on individual doses after disposal, the Agency sought comment on further details of such a limitation in the second round of comments. For example, EPA asked whether such a limitation should apply to ground water use, whether it should apply only for ground water at some distance from a geologic repository or for any ground water source, and whether reliance on existing individual dose limitations (such as 40 CFR Part 141 or 10 CFR Part 20) for protection regarding ground water would be adequate.

The responses resulting from these questions offered a wide range of suggestions. A number of commenters opposed inclusion of an individual dose limitation for disposal on the grounds that calculations to judge compliance with such a standard would be highly speculative and not an appropriate basis upon which to judge the adequacy of a disposal system. In contrast, some other commenters argued that an individual dose standard in the 5 to 25 millirems per year range should apply to use of ground water in the accessible environment for an indefinitely long period into the future. Another group of commenters supported inclusion of some limitation on individual exposure, but only to the extent that it would not compromise the primary intent of long-term isolation and containment of the wastes.

These comments did not offer information that changed the Agency's perception of some of the problems associated with individual dose limitations for disposal. First, relying *only* upon an individual dose standard for disposal could encourage disposal methods that would enhance dilution of any wastes released. Thus, disposal sites near bodies of surface water or large sources of ground water might be preferred—which the Agency believes is an inappropriate policy that would usually increase overall population exposures.

This concern could be met by *adding* an individual dose limitation to the proposed containment requirements, rather than replacing them. However, the Agency's performance assessments of geologic repositories indicate that doses from using ground water close to a repository can become substantial (e.g., several rems per year) after a few hundred or thousand years, because the geological and geochemical characteristics of appropriate sites tend to concentrate eventual releases of wastes in any ground water that is close to the site. A study published by the National Academy of Sciences in April 1983 confirms this potential for large individual doses if flowing ground water can contact the wastes after the waste canisters are presumed to start leaking. Although it might be possible to find certain geologic settings that avoid this problem, such restrictive siting prerequisites could substantially delay development of disposal systems without providing significantly more protection to populations. Furthermore, even if reasonable limitations on individual exposure might be met at certain sites for very long times, demonstrating compliance with such limitations could be very difficult because of the additional complexities involved in estimating individual exposures rather than amounts of radioactivity released. The SAB Subcommittee report generally agreed with the technical aspects of these conclusions.

On the other hand, analyses of repository systems with good engineering controls show that they should be able to prevent significant doses from ground water use for at least a thousand years after disposal. Such protection would be compatible with both the proposed containment and assurance requirements. Accordingly, the SAB Subcommittee recommended that the Agency include a requirement limiting individual doses for the first 500 years after disposal, and one of the States that commented on the proposed rule suggested an individual dose limit for 1,000 years after disposal.

After considering all of this information, the Agency has decided to include two new sections in the final rule. The first (Section 191.15) limits exposures to members of the public after disposal, while the second (Section 191.16) limits concentrations in water withdrawn from certain important sources of ground water after disposal.

The individual protection requirements in § 191.15 limit exposures from a disposal system to individuals in the accessible environment to 25 millirems per year to the whole body and 75 millirems per year to any organ. These limits apply only to undisturbed performance of the disposal system (i.e., without any consideration of human intrusion or disruption by unlikely natural events), and they apply for the first 1,000 years after disposal. All potential pathways of radiation or radioactive material from the disposal system to people (associated with undisturbed performance) shall be considered, including the assumption that an individual drinks two liters per day of water from any "significant source of ground water" outside of the "controlled area" surrounding a disposal system. If the implementing agency plans to allow individuals to use ground water within the controlled area, such planned use would also have to be considered within the pathways evaluated to determine compliance with § 191.15.

"Significant sources of ground water" are defined to include any aquifer currently providing the primary source of water for a community water system or any aquifer that satisfies all of the following five conditions: (1) It is saturated with water containing less than 10,000 milligrams per liter of total dissolved solids; (2) it is within 2,500 feet of the land surface; (3) it has a transmissivity of a least 200 gallons per day per foot, provided that (4) each of the underground formations or parts of underground formations included within the aquifer must have an individual hydraulic conductivity greater than 2 gallons per day per square foot; and (5) it must be capable of providing a sustained yield of 10,000 gallons per day of water to a pumped or flowing well.

Although such quantitative distinctions are inevitably somewhat arbitrary, the Agency believes that they provide reasonable demarcations to identify underground formations that could meet the needs of community water systems in the future. The selected transmissivity of 200 gallons per day per foot and the sustained yield of 10,000 gallons per day roughly correspond to the size of a ground water source required to support the needs of about 20 households; this is similar to the size of the community water system considered in 40 CFR Part 141. The water quality criterion of 10,000 milligrams per liter of total dissolved solids has been used in several previous Agency regulations and is based upon congressional guidance in the legislative history of the Safe Drinking Water Act. The maximum depth criterion of 2,500 feet was chosen because almost all of the wells used to provide water to significant numbers of people do not extend below this depth. The minimum hydraulic conductivity criterion of 2 gallons per day per square foot was chosen to insure that only reasonably permeable formations are considered, rather than including unproductive formations that might be in the vicinity of a "significant source of ground water."

The ground water protection requirements in § 191.16(a) limit the concentrations in water withdrawn from any "special source of ground water" in the vicinity of a disposal system to concentrations similar to those established for the output of community water systems by 40 CFR Part 141: (1) 5 picocuries per liter of radium-226 and radium-228; (2) 15 picocuries per liter of alpha-emitting radionuclides (including radium-226 and radium-228 but excluding radon); or (3) the combined concentrations of radionuclides that emit either beta or gamma radiation that would produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems per year if an individual continuously consumed 2 liters per day of drinking water from that source of water. However, if the preexisting radionuclide concentrations in the special source of ground water already exceed any of these limits, then § 191.16(b) limits any *increases* in the preexisting concentrations to the concentration limits set in § 191.16(a). Like the individual protection requirements, the ground water protection requirements apply only for undisturbed performance of the disposal system and apply for the first 1,000 years after disposal. Unlike the individual protection requirements, the ground water requirements would apply to a "special source" if it was within the controlled area.

"Special sources" are defined to include only those Class I ground waters—to be identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984—that meet the following three conditions: (1) They are within the controlled area or near (less than five kilometers beyond) the controlled area; (2) they are supplying drinking water for thousands of persons as of the date that the Department selects the site for extensive exploration as a potential location of a disposal system; and (3) they are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

Need for the Assurance Requirements

The preceding issues dealt with the quantitative requirements of the disposal standards. While numerical standards are important to bring about appropriate selection and design of disposal systems, the Agency has long recognized that the numerical standards chosen for Subpart B, by themselves, do not provide either an adequate context for environmental protection or a sufficient basis to foster public confidence in the national program. There are too many uncertainties in projecting the behavior of natural and engineered components for many thousands of years—and too many opportunities for mistakes or poor judgments in such calculations—for the numerical requirements on overall system performance in Subpart B to be the sole basis to determine the acceptability of disposal systems for these very hazardous wastes. These uncertainties and potential errors in quantitative analysis could ultimately prevent the degree of protection sought by the Agency from being achieved. (Theoretically, it might be possible to develop adequate confidence in achieving this level of protection by choosing much more stringent numerical standards, but this could lead to substantial difficulties in implementation.) Therefore, the proposed standards also included qualitative assurance requirements chosen to ensure that cautious steps are taken to reduce the problems caused by these uncertainties. The proposed rule emphasized that the assurance requirements were an essential complement to the quantitative containment requirements that were selected.

In its comments on the proposed rule, the NRC argued that the assurance requirements were not properly part of the Agency's generally applicable standards. The Commission agreed that the overall numerical performance standards were not sufficient, but suggested that its regulations and procedures were the appropriate vehicle to provide the necessary confidence that the inherent uncertainties would not compromise environmental protection. The Agency believes that it does have the authority to give regulatory expression to the context within which it has chosen to establish one set of numerical standards rather than another. However, because it might not be appropriate to exercise this authority, the Agency sought public comment on the need for the assurance requirements in the second round of comments.

The preponderance of comments received on this question strongly supported retention of the assurance requirements in 40 CFR Part 191. In particular, virtually all of the various State governments that commented on the rule described the assurance requirements as an essential part of the regulations governing disposal of these wastes. Subsequently, two of these States, Nevada and Minnesota, petitioned the Commission to incorporate the assurance requirements proposed as part of 40 CFR Part 191 into its own rules (50 FR 18267).

Based upon these comments, the Agency and the NRC have reached an agreement that should accomplish the desired regulatory goals while avoiding the jurisdictional issue. EPA has included the assurance requirements in the final rule, modified as appropriate in response to other comments. However, these requirements will not be applicable to disposal facilities to be licensed by the Commission. Instead, as discussed previously, the NRC staff plans to propose modifications to 10 CFR Part 60, developed in consultation with EPA, for public review and comment within approximately 120 days to insure that the objectives of all of the assurance requirements in 40 CFR Part 191 will be accomplished through compliance with 10 CFR Part 60. The Agency has provided the Commission with all of the comments received by EPA regarding the assurance requirements, so that the NRC can use them in its rulemaking. In addition, the Agency will participate in the NRC rulemaking to facilitate incorporation of the principles of all of the assurance requirements in Federal regulation. Finally, the Agency will review the record and outcome of the Part 60 rulemaking to determine if any subsequent modifications to 40 CFR Part 191 are needed.

Approach Toward Institutional Controls

The Agency particularly sought comment on its proposed approach to reliance on institutional controls. The proposed rule limited reliance on "active institutional controls" (such as controlling access to a disposal site, performing maintenance operations, or cleaning up releases) to a reasonable period of time after disposal, described as on the order of a "few hundred years." On the other hand, "passive institutional controls" (such as permanent markers, records, archives, and other methods of preserving knowledge) were considered to be at least partially effective for a longer period of time.

Few commenters argued with the distinction between active and passive institutional controls, or with the amount of reliance the proposed rule envisioned for passive controls. However, many commenters felt that "a few hundred years" was too long a period to count on active controls. Accordingly, the final rule limits reliance on active institutional controls to no more than 100 years after disposal. This was the time period the Agency considered in criteria for radioactive waste disposal that were proposed for public comment in 1978 (43 FR 53262), a period that was generally supported by the commenters on that proposal. After this time, no contribution from any of the active institutional controls can be projected to prevent or limit potential releases of wasts from a disposal system.

The concept of passive institutional controls has now been incorporated into the definition of "controlled area" that is used to establish one of the boundaries for applicability of the containment requirements and the individual protection requirements in the final rule. Because the assumptions made about the effectiveness of passive institutional controls can strongly affect implementation of the containment requirements, the Agency's intent has been elaborated in the "guidance for implementation" section. The Federal Government is committed to retaining control over disposal sites for these wastes as long as possible. Accordingly (and in compliance with one of the assurance requirements), an extensive system of explanatory markers and records will be instituted to warn future generations about the location and dangers of these wastes. These passive controls have not been assumed to prevent all possibilities of inadvertent human intrusion, because there will always be a realistic chance that some individuals will overlook or misunderstand the markers and records. (For example, exploratory drilling operations occasionally intrude into areas that clearly would have been avoided if existing information had been obtained and properly evaluated.) However, the Agency assumed that society in general will retain knowledge about these wastes and that future societies should be able to deter systematic or persistent exploitation of a disposal site.

The Agency also assumed that passive institutional controls should reduce the chance of inadvertent intrusion compared to the likelihood if no markers and records were in place. Specific judgments about the chances and consequences of intrusion should be made by the implementing agencies when more information about particular disposal sites and passive control systems is available. The parameters described in the "guidance for implementation" represent the most severe assumptions that the Agency believed were reasonable to use in its analyses to evaluate the feasibility of compliance with this rule (analyses that are summarized in the BID). The implementing agencies are free to use other assumption if they develop information considered adequate to support those judgments.

The role envisioned for institutional controls in this rulemaking has been adapted from the general approach the Agency has followed in its activities involving disposal of radioactive wastes since the initial public workshops conducted in 1977 and 1978. The Agency's overall objective has been to protect public health and the environment from disposal of radioactive wastes without relying upon institutional controls for extended periods of time—because such controls do not appear to be reliable enough over the very long periods that these wastes remain dangerous. Instead, the Agency has pursued standards that call for isolation of the wastes through the physical characteristics of disposal system siting and design, rather than through continuing maintenance and surveillance. This principle was enunciated in the general criteria published for public comment in 1978 (43 FR 53262), and it has been incorporated into the Agency's standards for disposal of uranium mill tailings (48 FR 590, 48 FR 45926).

This approach has been tailored to fit two circumstances associated with mined geologic repositories. First, 40 CFR Part 191 places containment requirements on a broad range of potential unplanned releases as well as the expected behavior of the disposal system. Therefore, determining compliance with the standards involves performance assessments that consider the probabilities and consequences of a variety of disruptive events, including potential human intrusion. Not allowing passive institutional controls to be taken into account to some degree when estimating the consequences of inadvertent human intrusion could lead to less protective geologic media being selected for repository sites. The Agency's analyses indicate that repositories in salt formations have particularly good capabilities to isolate the wastes from flowing ground water and, hence, the accessible environment. However, salt formations are also relatively easy to mine and are often associated with other types of resources. If performance assessments had to assume that future societies will have no way to ever recognize and limit the consequences of inadvertent intrusion (from solution mining of salt, for example), the scenarios that would have to be studied would be more likely to eliminate salt media from consideration than other rock types. Yet, this could rule out repositories that may provide the best isolation, compared to other alternatives, if less pessimistic assumptions about survival of knowledge were made.

The second circumstance that the Agency considered in evaluating the approach towards institutional controls taken in this rule is the fact that the mined geologic repositories planned for disposal of the materials covered by 40 CFR Part 191 are different from the disposal systems evisioned for any other types of waste. The types of inadvertent human activities that could lead to significant radiation exposures or releases of material from geologic repositories appear to call for much more intensive and organized effort than those which could cause problems at, for example, an unattended surface disposal site. It appears reasonable to assume that information regarding the disposal system is more likely to reach (and presumably deter) people undertaking such organized efforts than it is to inform individuals involved in mundane activities.

These considerations led the Agency to conclude that a limited role for passive institutional controls would be appropriate when projecting the long-term performance of mined geologic repositories to judge compliance with these standards. However, such assumptions would not necessarily be applicable to other Agency actions where different issues are involved.

Avoiding Sites With Natural Resources

The proposed rule contained an assurance requirement that would have prohibited use of sites where there is a reasonable expectation that future exploration for scarce or easily accessible resources might occur. The comments received on this issue generally agreed that sites with resources should be avoided. However, some commenters suggested that the requirement should be more restrictive, to include "potentially accessible" resources. Other commenters argued that the Agency should be less restrictive regarding sites with possible resource potential—discouraging but not prohibiting their use—because other attributes of the site might overcome the relative disadvantages presented by resource potential.

After considering these comments, the Agency agreed with the latter viewpoint. This judgment was reinforced by the belief that disposal sites should be chosen after comparative evaluation of a variety of alternatives, and the proposed assurance requirement could have inhibited this process. Therefore, this assurance requirement has been revised in the final rule to identify resource potential as a disincentive but not as an outright prohibition for site selection. Instead, the revised assurance requirement states that places with resource potential shall not be used "unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future."

This wording implies a qualitative comparison, because the Agency is not aware of quantitative formulas comprehensive enough to provide adequate comparisons to govern site selection. However, the Agency does not intend that sites with resource potential can be used merely upon identification of a few features that might be more favorable than at a site without significant resources. Rather, sites with resources should only be used if it is reasonably certain that they would provide better *overall* protection than the practical alternatives that are available.

The following example illustrates the effect of the change in this assurance requirement. When discussing the proposed assurance requirement, the Agency implied that disposal in salt domes might not be acceptable because such formations seemed more likely than others to attract exploration in the future. The modification of this assurance requirement in the final rule means that salt domes should not be peremptorily removed from consideration, but should be compared against all of the characteristics of alternative sites in terms of the overall environmental protection expected.

Long-Term Monitoring

The proposed rule addressed active institutional controls over a disposal site only in a negative sense—to prohibit reliance upon them for more than a few hundred years after disposal. The Agency's intent was to be sure that long-term protection of the environment did not depend upon positive actions by future generations. Almost all commenters agreed with this intent, although many suggested a shorter period of reliance was appropriate (see the preceding discussion under "Approach Towards Institutional Controls").

However, several commenters (including most of the States) also urged addition of a requirement for long-term monitoring of a repository after disposal. This view did not deny the need to select and design disposal systems without depending upon active controls in the future. However, it broadened this perspective by arguing that a disposal system so designed should still be monitored for a long time after disposal to guard against unexpected failures.

The Agency had not considered this viewpoint in developing the proposed rule. Accordingly, further information on this idea was sought during the "second round" of public comment, and the Agency surveyed the capabilities and expectations of long-term monitoring approaches. Evaluating this information led the Agency to several conclusions:

(1) Perhaps most importantly, the techniques used for monitoring after disposal must not jeopardize the long-term isolation capabilities of the disposal system. Furthermore, plans to conduct monitoring after disposal should never become an excuse to relax the care with which systems to isolate these wastes must be selected, designed, constructed, and operated.

(2) Monitoring for radionuclide releases to the accessible environment is not likely to be productive. Even a poorly performing geologic repository is very unlikely to allow measurable releases to the accessible environment for several hundreds of years of more, particularly in view of the engineered controls needed to comply with 10 CFR Part 60. A monitoring system based only on detecting radionuclide releases—a system which would almost certainly not be detecting anything for several times the history of the United States—is not likely to be maintained for long enough to be of much use.

(3) Within the above constraints, however, there are likely to be monitoring approaches which may, in a relatively short time, significantly improve confidence that a repository is performing as intended. Two examples are of particular interest. One involves the concept of monitoring ground water sources at a variety of distances for benign tracers intentionally released to the ground water in the repository; this approach can evaluate the delay involved in ground water movement from the repository to the environment and can serve to validate expectations of the performance expected from the system's natural barriers. Another concept involves monitoring the small uplift of the land surface over the repository in order to validate predictions of the system's thermal behavior. Both of these approaches can be carried out without enhancing pathways for the wastes to escape from the repository.

Based on these conclusions and the public comments on this question, the Agency has included a provision for long-term monitoring after disposal in the assurance requirements of the final rule: "Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring." This new provision is consistent with the overall intent of the assurance requirements: To take prudent and cautious steps necessary to minimize the risks posed by the inherent uncertainties in expectations of the future. Beyond this broad mandate, however, the Agency has not specified the details of a monitoring program. That is properly left to the implementing agencies. Furthermore, the precise objectives of an appropriate monitoring program probably should not be spelled out until much more information is gathered about the characteristics and expected behavior of specific sites and designs.

Ability To Recover Wastes After Disposal

The proposed rule included an assurance requirement that recovery of these wastes be feasible for "a reasonable period of time" after disposal. The Agency specifically sought comment on whether this was a desirable provision, since it would rule out certain disposal concepts, such as deep-well injection of liquid wastes. The comments received were split about evenly between those who thought the provision should be retained and those who thought it was detrimental to the overall rule. Many of those who opposed the requirement argued that it would encourage designing a geologic repository to make retrieving waste relatively easy—which might compromise the isolation capabilities of the repository or which might encourage recovery of the waste to make use of some intrinsic value it might retain (the potential energy content of spent nuclear fuel, for example).

The intent of this provision was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated. EPA reiterates the statement in the preamble to the proposal that *any* current concept for a mined geologic repository meets this requirement *without* any additional procedures or design features. For example, there is no intent to require that a repository shaft be kept open to allow future recovery. To meet this assurance requirement, it only need be technologically feasible (assuming current technology levels) to be able to mine the sealed repository and recover the waste—albeit at substantial cost and occupational risk. The Commission's requirements for multiple engineered barriers within a repository (10 CFR Part 60) adequately address any concerns about the feasibility of recovering wastes from a repository.

Therefore, this provision should not have any effect upon plans for mined geologic repositories. Rather, it is intended to call into question any other disposal concept that might not be so reversible—because the Agency believes that future generations should have options to correct any mistakes that this generation might unintentionally make. Almost all of the commenters agreed with the validity of this objective. Accordingly, the Agency has decided to retain this assurance requirement in the final rule as proposed.

Health Impacts of 40 CFR Part 191

Waste Management and Storage. Waste management and storage activities conducted in accordance with Subpart A would limit the maximum risk to a member of the public in the general environment to a 5×10^{-4} chance of incurring a premature fatal cancer over a lifetime. Of course, a risk this large would exist only for an individual continuously exposed to the full amount of the dose limits over his or her lifetime. Because the Agency believes that such continuous exposure is very unlikely, the actual risks to individuals are expected to be much lower. It is theoretically possible under the final rule that an individual could be exposed to 25 millirems per year (to the whole body) from *both* an NRC-licensed facility and a DOE facility not licensed by NRC, for a total of 50 millirem/year. However, the Agency believes that this is particularly improbable and does not foresee a significant public health impact from this possibility.

Waste Disposal. A disposal system complying with Subpart B would confine almost all of the radioactive wastes to the immediate vicinity of the repository for a very long time. Because the wastes would be so well isolated from the environment, the Agency is confident that any risks to future populations would be very small. Similarly, risks to most future individuals would also be very small (and effectively zero in almost all cases)—except for the possibility that an individual in the distant future might use ground water from the vicinity of a repository. In this case, there is a chance that such an individual might receive a substantial exposure. The following paragraphs describe the possible health impacts of the residual risks from a disposal system that would be in compliance with 40 CFR Part 191.

Population Risks: With regard to exposure of populations, the Agency has estimated the potential long-term health risks to future generations from various types of mined geologic repositories using very general models of environmental transport and a linear, nonthreshold dose-effect relationship between radiation exposures and premature deaths from cancer. Food chains, ways of life, and the size and geographical distributions of populations will undoubtedly change over a 10,000-year period. Unlike geological processes, factors such as these cannot be usefully predicted over such long periods of time. Thus, in making these health effects projections, the Agency found it necessary to depend upon very general models of environmental pathways and to assume current population distributions and death rates. The SAB Subcommittee evaluated these models carefully, and, although a number of specific changes were recommended for particular parameters, the Subcommittee endorsed the general approach. As a consequence of using these generalized models, EPA's projections are intended to be used primarily as a tool for comparing the performance of one waste disposal system to another and for comparison of the risks of waste disposal with those of undisturbed ore bodies. The results of these analyses should not be considered a reliable projection of the "real" or absolute number of health effects resulting from compliance with the disposal standards.

These health risk models were used to assess the long-term health risks from several different model repositories containing the wastes from 100,000 MTHM—which could include all existing wastes and the future wastes from all currently operating reactors. The Agency estimates that this quantity of waste, when disposed of in accordance with the proposed standards, would cause no more than 1,000 premature deaths from cancer in the first 10,000 years after disposal: an average of no more than one premature death every 10 years. Most of the model repositories considered had projected population risks at least a factor of ten below this, or about 100 deaths over 10,000 years. The projections for the actual repositories that are constructed are expected to be closer to this lower figure. Any such increase in the number of cancer deaths would be very small compared to today's incidence of cancer, which kills about 350,000 people per year in the United States. Similarly, any such increase would be much less than the approximately 6,000 premature cancer deaths per year that the same linear, non-threshold dose-effect relationship predicts for the nation due to natural background radiation.

Individual Risks: With regard to exposures of individuals, the Agency examined the potential doses to persons who might use ground water from the immediate vicinity of a repository at various times in the future. For these analyses, only the expected undisturbed performance of a repository was considered (e.g. there was no evaluation of exposures that might occur if a repository was disrupted by movement of a fault). In most of the cases studied, no exposures occurred for more than one thousand years after disposal. After that, these analyses predict that significant exposures (on the order of a few rems per year in the vicinity of the repository over the next several thousands of years) may appear for some of the geologic media considered. These projections are similar to those contained in the April 1983 report published by the National Academy of Sciences. The BID contains more detailed descriptions of the Agency's individual dose calculations.

Intergenerational Risk: As described earlier, the Agency has chosen to rely on provisions that limit risks to populations as the primary standards for the long-term performance of disposal systems. Although the projections of the residual population risk are clearly very small, the discontinuity between when the wastes are generated and when the projected health effects manifest themselves made it difficult to determine what level of residual risk should be allowed by these disposal standards. The difficulty arose because most of the benefits derived in the process of waste production fall upon the current generation, while most of the risks fall upon future generations. Thus, a potential problem of intergenerational equity with respect to the distribution of risks and benefits became apparent. This problem is sometimes referred to as the intergenerational risk issue, and it is not unique to the disposal of high-level radioactive wastes. If the Agency tried to insure that these standards fully satisfied a criterion of intergenerational equity with respect to the distribution of risks and benefits, it might appear that no risk should be passed on to future generations. This is a condition which the Agency believes cannot be met by disposal technologies foreseeable within this century. However, there is one particular factor which has reinforced EPA's decision about the reasonableness of the risks permitted under the disposal standards. This is the following evaluation of the risks associated with undisturbed uranium ore bodies. Additionally, for the purpose of comparing the risks permitted under the standards to other radiation risks which people are currently exposed to, a brief discussion of the risks from other natural sources of radiation is also included.

Uranium Ore: Most uranium ore in the United States occurs in permeable geologic strata containing flowing ground water. Radionuclides in the ore, particularly uranium and radium, continuously enter this ground water. EPA estimated the potential risks from these undisturbed ore bodies using the same generalized environmental models that were used for releases from a waste repository. The effects associated with the amount of ore needed to produce the high-level wastes that would fill the model geologic repository can vary considerably. Part of this variation corresponds to actual differences from one ore body to another; part can be attributed to uncertainties in the assessment. After revising the population risk models in accordance with the recommendations of the SAB Subcommittee, these estimates of the risks from unmined ore bodies ranged from about 10 to more than 100,000 excess cancer deaths over 10,000 years. Thus, leaving the ore unmined appears to present a risk to future generations comparable to the risks from disposal of wastes covered by these standards.

Variations in Natural Background: Radionuclides occur naturally in the earth in very large amounts, and are produced in the atmosphere by cosmic radiation. Everyone is exposed to natural background radiation from these natural radionuclides and from direct exposure to cosmic radiation. Individual exposures average about 100 millirems per year, with a range of about 60 to 200 millirem/year. These natural background radiation levels have remained relatively constant for a very long time. According to the same linear, nonthreshold dose effect relationship used in EPA's other analyses, an increase of one millirem per year (about one percent) in natural background in the United States would result in about 60 additional deaths per year, or 600,000 over a 10,000-year period.

Natural Radionuclide Concentrations in Ground Water: One source of this exposure to natural background radiation comes from naturally occurring radionuclides found in ground water. Radium is the most important of the naturally occurring radioactive materials likely to occur in public water supply systems, but uranium is also found in ground waters due to its natural occurrence. Surveys of radionuclides in ground water systems indicate: a United States range of 0.1 to 50 picocuries (pCi) per liter for radium-226 (with isolated sources exceeding 100 pCi/liter); up to 74 pCi/liter for all alpha-emitting radionuclides other than uranium (although most of the alpha-emitting concentrations are below 3 pCi/liter); and up to 650 pCi/liter for total uranium concentrations. Elevated radium-226 concentrations are found along the Atlantic coastal region and the Midwest; low levels are usually found in the treated water supplies in the western States. Elevated uranium and alpha-emitting radionuclide concentrations are generally limited to the Rocky Mountain region and Maine and Pennsylvania in the east.

The Agency's primary drinking water regulations (40 CFR Part 141) limit the contamination levels for radium-226 and radium-228 to 5 pCi/liter and the levels for total alpha-emitting contamination (excluding radon and uranium) to 15 pCi/liter. Elevated concentrations of radium in drinking water are generally a problem associated with smaller community water systems, with an estimated 500 systems exceeding 5 pCi/liter. The Agency's risk assessments indicate that continuous consumption of water containing the maximum amount of radium allowed may cause between 0.7 and 3 cancers per year per million exposed persons.

Environmental Impacts

A Draft Environmental Impact Statement (EIS) was prepared for the proposed rule, in accordance with the Agency's procedures for the voluntary preparation of EIS's (30 FR 37419). However, section 121(c) of the NWPA subsequently exempted this action from preparation of an EIS under section 102(2)(C) of the National Environmental Policy Act of 1969 (NEPA) and from any environmental review under subparagraph (E) or (F) of section 102(2) of the NEPA. Accordingly, a Final EIS has not been prepared for promulgation of this rule. The potential health impacts of this action are summarized above, and much of the information that would have been contained in a Final EIS is documented in the Background Information Document that accompanies this final version of 40 CFR Part 191.

Regulatory Impacts

This rule was submitted to the Office of Management and Budget (OMB) for review as required by Executive Order 12291. The final rule has not been classified as a "major rule" in accordance with the guidelines provided by the Executive Order. Any comments received from OMB and EPA's responses to those comments are available for public inspection in the docket cited above under the heading "ADDRESSES."

The Agency has had to take an unusual approach in considering the regulatory impacts of this proposed action—as required by Executive Order 12291. In most cases, a regulation concerns an ongoing activity and may be considered a burden whose costs should be judged against the regulatory benefits. Here, it was not possible to quantify the costs and benefits of this action compared to the consequences of no regulation because there is no specific "baseline" program to consider. The appropriate regulations must be established before the regulated activity can even begin. Thus, the typical perspectives on costs and benefits are altered. Instead, the Agency evaluated how the costs of commercial waste management and disposal might change in response to different levels of protection from the containment requirements. Similar evaluations were not performed for the wastes from atomic energy defense activities because sufficient information was not available.

To evaluate the effects of different levels of protection, EPA considered the performance of different repository designs in several different geologic media. The costs of the various engineering controls that might be needed to meet different levels of protection were estimated. In addition, allowances were made for the increased research and development costs that might be needed to demonstrate compliance with the standards if projected performance for a particular disposal system indicated releases less than an order of magnitude below the long-term radionuclide release limits in § 191.13.

Since the regulatory impact analyses that supported the proposed rule were performed, the NRC has promulgated minimum requirements for the engineered barriers of a disposal system (in 10 CFR Part 60), more data concerning disposal sites being considered by the Department have become available, and the Agency has reviewed its performance assessments to reduce overestimates of long-term risks in accordance with the SAB review. After evaluating all of this new information, the Agency believes that there need not be any significant additional costs to the national program for disposal of commercial wastes caused by retaining the proposed level of protection in the final rule, compared to the costs of choosing levels considerably less stringent. In other words, all of the disposal sites being evaluated by the Department, assuming compliance with the existing requirements of 10 CFR Part 60, are expected to be able to meet these disposal standards without additional precautions beyond those already planned.

List of Subjects in 40 CFR Part 191

Environmental protection, Nuclear energy, Radiation protection, Uranium, Waste treatment and disposal.

Regulatory Flexibility Certification

In accordance with the Regulatory Flexibility Act of 1980, 5 U.S.C. 605(b), the Administrator hereby certifies that this rule will not have any significant impact on small businesses or other entitites, and that a Regulatory Flexibility Analysis is not required. This rule will affect only a small number of facilities, most of which are or will be operated by the United States Government.

Dated: August 15, 1985.

Lee M. Thomas,

Administrator.

A new Part 191 is hereby added to Title 40, Code of Federal Regulations, as follows:

SUBCHAPTER F—RADIATION PROTECTION PROGRAMS

PART 191—ENVIRONMENTAL RADIATION PROTECTION STANDARDS FOR MANAGEMENT AND DISPOSAL OF SPENT NUCLEAR FUEL, HIGH-LEVEL AND TRANSURANIC RADIOACTIVE WASTES

Subpart A—Environmental Standards for Management and Storage

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191.01 Applicability.
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191.03 Standards.
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Subpart B—Environmental Standards for Disposal

191.11 Applicability.
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191.15 Individual protection requirements.
191.16 Ground water protection requirements.
191.17 Alternative provisions for disposal.
191.18 Effective date.
Appendix A Table for Subpart B
Appendix B Guidance for Implementation of Subpart B

Authority: The Atomic Energy Act of 1954, as amended; Reorganization Plan No. 3 of 1970; and the Nuclear Waste Policy Act of 1982.

Subpart A—Environmental Standards for Management and Storage

§ 191.01 Applicability.

This Subpart applies to:

(a) Radiation doses received by members of the public as a result of the management (except for transportation) and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at any facility regulated by the Nuclear Regulatory Commission or by Agreement States, to the extent that such management and storage operations are not subject to the provisions of Part 190 of title 40; and

(b) Radiation doses received by members of the public as a result of the management and storage of spent nuclear fuel or high-level or transuranic wastes at any disposal facility that is operated by the Department of Energy and that is not regulated by the Commission or by Agreement States.

§ 191.02 Definitions.

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of Part 190.

(a) "Agency" means the Environmental Protection Agency.

(b) "Administrator" means the Administrator of the Environmental Protection Agency.

(c) "Commission" means the Nuclear Regulatory Commission.

(d) "Department" means the Department of Energy.

(e) "NWPA" means the Nuclear Waste Policy Act of 1982 (Pub. L. 97-425).

(f) "Agreement State" means any State with which the Commission or the Atomic Energy Commission has entered into an effective agreement under subsection 274b of the Atomic Energy Act of 1954, as amended (68 Stat. 919).

(g) "Spent nuclear fuel" means fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

(h) "High-level radioactive waste," as used in this Part, means high-level radioactive waste as defined in the Nuclear Waste Policy Act of 1982 (Pub. L. 97–425).

(i) "Transuranic radioactive waste," as used in this Part, means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) High-level radioactive wastes; (2) wastes that the Department has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this Part; or (3) wastes that the Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.

(j) "Radioactive waste," as used in this Part, means the high-level and transuranic radioactive waste covered by this Part.

(k) "Storage" means retention of spent nuclear fuel or radioactive wastes with the intent and capability to readily retrieve such fuel or waste for subsequent use, processing, or disposal.

(l) "Disposal" means permanent isolation of spent nuclear fuel or radioactive waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such fuel or waste. For example, disposal of waste in a mined geologic repository occurs when all of the shafts to the repository are backfilled and sealed.

(m) "Management" means any activity, operation, or process (except for transportation) conducted to prepare spent nuclear fuel or radioactive waste for storage or disposal, or the activities associated with placing such fuel or waste in a disposal system.

(n) "Site" means an area contained within the boundary of a location under the effective control of persons possessing or using spent nuclear fuel or radioactive waste that are involved in any activity, operation, or process covered by this Subpart.

(o) "General environment" means the total terrestrial, atmospheric, and aquatic environments outside sites within which any activity, operation, or process associated with the management and storage of spent nuclear fuel or radioactive waste is conducted.

(p) "Member of the public" means any individual except during the time when that individual is a worker engaged in any activity, operation, or process that is covered by the Atomic Energy Act of 1954, as amended.

(q) "Critical organ" means the most exposed human organ or tissue exclusive of the integumentary system (skin) and the cornea.

§ 191.03 Standards.

(a) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities regulated by the Commission or by Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from: (1) Discharges of radioactive material and direct radiation from such management and storage and (2) all operations covered by Part 190; shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other critical organ.

(b) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities for the disposal of such fuel or waste that are operated by the Department and that are not regulated by the Commission or Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from discharges of radioactive material and direct radiation from such management and storage shall not exceed 25 millirems to the whole body and 75 millirems to any critical organ.

§ 191.04 Alternative standards.

(a) The Administrator may issue alternative standards from those standards established in 191.03(b) for waste management and storage activities at facilities that are not regulated by the Commission or Agreement States if, upon review of an application for such alternative standards:

(1) The Administrator determines that such alternative standards will prevent any member of the public from receiving a continuous exposure of more than 100 millirems per year dose equivalent and an infrequent exposure of more than 500 millirems dose equivalent in a year from all sources, excluding natural background and medical procedures; and

(2) The Administrator promptly makes a matter of public record the degree to which continued operation of the facility is expected to result in levels in excess of the standards specified in 191.03(b).

(b) An application for alternative standards shall be submitted as soon as possible after the Department determines that continued operation of a facility will exceed the levels specified in 191.03(b) and shall include all information necessary for the Administrator to make the determinations called for in 191.04(a).

(c) Requests for alternative standards shall be submitted to the Administrator, U.S. Environmental Protection Agency, 401 M Street, SW., Washington, DC 20460.

§ 191.05 Effective date.

The standards in this Subpart shall be effective on November 18, 1985.

Subpart B—Environmental Standards for Disposal

§ 191.11 Applicability.

(a) This Subpart applies to:

(1) Radioactive materials released into the accessible environment as a result of the disposal of spent nuclear fuel or high-level or transuranic radioactive wastes;

(2) Radiation doses received by members of the public as a result of such disposal; and

(3) Radioactive contamination of certain sources of ground water in the vicinity of disposal systems for such fuel or wastes.

(b) However, this Subpart does not apply to disposal directly into the oceans or ocean sediments. This Subpart also does not apply to wastes disposed of before the effective date of this rule.

§ 191.12 Definitions.

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of this Part.

(a) "Disposal system" means any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal.

(b) "Waste," as used in this Subpart, means any spent nuclear fuel or radioactive waste isolated in a disposal system.

(c) "Waste form" means the materials comprising the radioactive components of waste and any encapsulating or stabilizing matrix.

(d) "Barrier" means any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.

(e) "Passive institutional control" means: (1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.

(f) "Active institutional control" means: (1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance.

(g) "Controlled area" means: (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.

(h) "Ground water" means water below the land surface in a zone of saturation.

(i) "Aquifer" means an underground geological formation, group of formations, or part of a formation that is capable of yielding a significant amount of water to a well or spring.

(j) "Lithosphere" means the solid part of the Earth below the surface, including any ground water contained within it.

(k) "Accessible environment" means: (1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area.

(l) "Transmissivity" means the hydraulic conductivity integrated over the saturated thickness of an underground formation. The transmissivity of a series of formations is the sum of the individual transmissivities of each formation comprising the series.

(m) "Community water system" means a system for the provision to the public of piped water for human consumption, if such system has at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.

(n) "Significant source of ground water," as used in this Part, means: (1) An aquifer that: (i) Is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface; (iii) has a transmissivity greater than 200 gallons per day per foot, provided that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than 2 gallons per day per square foot; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of this Subpart.

(o) "Special source of ground water," as used in this Part, means those Class I ground waters identified in accordance with the Agency's Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that the Department chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the NWPA); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

(p) "Undisturbed performance" means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

(q) "Performance assessment" means an analysis that: (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable.

(r) "Heavy metal" means all uranium, plutonium, or thorium placed into a nuclear reactor.

(s) "Implementing agency," as used in this Subpart, means the Commission for spent nuclear fuel or high-level or transuranic wastes to be disposed of in facilities licensed by the Commission in accordance with the Energy Reorganization Act of 1974 and the Nuclear Waste Policy Act of 1982, and it means the Department for all other radioactive wastes covered by this Part.

§ 191.13 Containment requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

(1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

(b) Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13 (a) will be achieved.

§ 191.14 Assurance requirements.

To provide the confidence needed for long-term compliance with the requirements of 191.13, disposal of spent nuclear fuel or high-level or transuranic wastes shall be conducted in accordance with the following provisions, except that these provisions do not apply to facilities regulated by the Commission (see 10 CFR Part 60 for comparable provisions applicable to facilities regulated by the Commission):

(a) Active institutional controls over disposal sites should be maintained for as long a period of time as is practicable after disposal; however, performance assessments that assess isolation of the wastes from the accessible environment shall not consider any contributions from active institutional controls for more than 100 years after disposal.

(b) Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring.

(c) Disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location.

(d) Disposal systems shall use different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included.

(e) Places where there has been mining for resources, or where there is a reasonable expectation of exploration for scarce or easily accessible resources, or where there is a significant concentration of any material that is not widely available from other sources, should be avoided in selecting disposal sites. Resources to be considered shall include minerals, petroleum or natural gas, valuable geologic formations, and ground waters that are either irreplaceable because there is no reasonable alternative source of drinking water available for substantial populations or that are vital to the preservation of unique and sensitive ecosystems. Such places shall not be used for disposal of the wastes covered by this Part unless the favorable characteristics of such places compensate for their greater likelihood of being disturbed in the future.

(f) Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.

§ 191.15 Individual protection requirements.

Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual dose equivalent from the disposal system to any member of the public in the accessible environment to exceed 25 millirems to the whole body or 75 millirems to any critical organ. All potential pathways (associated with undisturbed performance) from the disposal system to people shall be considered, including the assumption that individuals consume 2 liters per day of drinking water from any significant source of ground water outside of the controlled area.

§ 191.16 Ground water protection requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the radionuclide concentrations averaged over any year in water withdrawn from any portion of a special source of ground water to exceed:

(1) 5 picocuries per liter of radium-226 and radium-228;

(2) 15 picocuries per liter of alpha-emitting radionuclides (including radium-226 and radium-228 but excluding radon); or

(3) The combined concentrations of radionuclides that emit either beta or gamma radiation that would produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems per year if an individual consumed 2 liters per day of drinking water from such a source of ground water.

(b) If any of the average annual radionuclide concentrations existing in a special source of ground water before construction of the disposal system already exceed the limits in 191.16(a), the disposal system shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not increase the existing average annual radionuclide concentrations in water withdrawn from that special source of ground water by more than the limits established in 191.16(a).

§ 191.17 Alternative provisions for disposal.

The Administrator may, by rule, substitute for any of the provisions of Subpart B alternative provisions chosen after:

(a) The alternative provisions have been proposed for public comment in the Federal Register together with information describing the costs, risks, and benefits of disposal in accordance with the alternative provisions and the reasons why compliance with the existing provisions of Subpart B appears inappropriate;

(b) A public comment period of at least 90 days has been completed, during which an opportunity for public hearings in affected areas of the country has been provided; and

(c) The public comments received have been fully considered in developing the final version of such alternative provisions.

§ 191.18 Effective date.

The standards in this Subpart shall be effective on September 19, 1985.

Appendix A—Table for Subpart B

TABLE 1.—RELEASE LIMITS FOR CONTAINMENT REQUIREMENTS

[Cumulative releases to the accessible environment for 10,000 years after disposal]

Radionuclide	Release limit per 1,000 MTHM or other unit of waste (see notes) (curies)
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or -232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

Application of Table 1

Note 1: *Units of Waste.* The Release Limits in Table 1 apply to the amount of wastes in any one of the following:

(a) An amount of spent nuclear fuel containing 1,000 metric tons of heavy metal (MTHM) exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM;

(b) The high-level radioactive wastes generated from reprocessing each 1,000 MTHM exposed to a burnup between 25,000 MWd/MTHM and 40,000 MWd/MTHM;

(c) Each 100,000,000 curies of gamma or beta-emitting radionuclides with half-lives greater than 20 years but less than 100 years (for use as discussed in Note 5 or with materials that are identified by the Commission as high-level radioactive waste in accordance with part B of the definition of high-level waste in the NWPA);

(d) Each 1,000,000 curies of other radionuclides (i.e., gamma or beta-emitters with half-lives greater than 100 years or any alpha-emitters with half-lives greater than 20 years) (for use as discussed in Note 5 or with materials that are identified by the Commission as high-level radioactive waste in accordance with part B of the definition of high-level waste in the NWPA); or

(e) An amount of transuranic (TRU) wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years.

Note 2: *Release Limits for Specific Disposal Systems.* To develop Release Limits for a particular disposal system, the quantities in Table 1 shall be adjusted for the amount of waste included in the disposal system compared to the various units of waste defined in Note 1. For example:

(a) If a particular disposal system contained the high-level wastes from 50,000 MTHM, the Release Limits for that system would be the quantities in Table 1 multiplied by 50 (50,000 MTHM divided by 1,000 MTHM).

(b) If a particular disposal system contained three million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by three (three million curies divided by one million curies).

(c) If a particular disposal system contained both the high-level wastes from 50,000 MTHM *and* 5 million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 1 multiplied by 55:

$$\frac{50{,}000 \text{ MTHM}}{1{,}000 \text{ MTHM}} + \frac{5{,}000{,}000 \text{ curies TRU}}{1{,}000{,}000 \text{ curies TRU}} = 55$$

Note 3: *Adjustments for Reactor Fuels with Different Burnup.* For disposal systems containing reactor fuels (or the high-level wastes from reactor fuels) exposed to an average burnup of less than 25,000 MWd/MTHM or greater than 40,000 MWd/MTHM, the units of waste defined in (a) and (b) of Note 1 shall be adjusted. The unit shall be multiplied by the ratio of 30,000 MWd/MTHM divided by the fuel's actual average burnup, except that a value of 5,000 MWd/MTHM may be used when the average fuel burnup is below 5,000 MWd/MTHM and a value of 100,000 MWd/MTHM shall be used when the average fuel burnup is above 100,000 MWd/MTHM. This adjusted unit of waste shall then be used in determining the Release Limits for the disposal system.

For example, if a particular disposal system contained only high-level wastes with an average burnup of 3,000 MWd/MTHM, the unit of waste for that disposal system would be:

$$1{,}000 \text{ MTHM} \times \frac{(30{,}000)}{(5{,}000)} = 6{,}000 \text{ MTHM}$$

If that disposal system contained the high-level wastes from 60,000 MTHM (with an average burnup of 3,000 MWd/MTHM), then the Release Limits for that system would be the quantities in Table 1 multiplied by ten:

$$\frac{60{,}000 \text{ MTHM}}{6{,}000 \text{ MTHM}} = 10$$

which is the same as:

$$\frac{60{,}000 \text{ MTHM}}{1{,}000 \text{ MTHM}} \times \frac{(5{,}000 \text{ MWd/MTHM})}{(30{,}000 \text{ MWd/MTHM})} = 10$$

Note 4: *Treatment of Fractionated High-Level Wastes.* In some cases, a high-level waste stream from reprocessing spent nuclear fuel may have been (or will be) separated into two or more high-level waste components destined for different disposal systems. In such cases, the implementing agency may allocate the Release Limit multiplier (based upon the original MTHM and the average fuel burnup of the high-level waste stream) among the various disposal systems as it chooses, provided that the total Release Limit multiplier used for that waste stream at all of its disposal systems may not exceed the Release Limit multiplier that would be used if the entire waste stream were disposed of in one disposal system.

Note 5: *Treatment of Wastes with Poorly Known Burnups or Original MTHM.* In some cases, the records associated with particular high-level waste streams may not be adequate to accurately determine the original metric tons of heavy metal in the reactor fuel that created the waste, or to determine the average burnup that the fuel was exposed to. If the uncertainties are such that the original amount of heavy metal or the average fuel burnup for particular high-level waste streams cannot be quantified, the units of waste derived from (a) and (b) of Note 1 shall no longer be used. Instead, the units of waste defined in (c) and (d) of Note 1 shall be used for such high-level waste streams. If the uncertainties in such information allow a range of values to be associated with the original amount of heavy metal or the average fuel burnup, then the calculations described in previous Notes will be conducted using the values that result in the smallest Release Limits, except that the Release Limits need not be smaller than those that would be calculated using the units of waste defined in (c) and (d) of Note 1.

Note 6: *Uses of Release Limits to Determine Compliance with 191.13* Once release limits for a particular disposal system have been determined in accordance with Notes 1 through 5, these release limits shall be used to determine compliance with the requirements of 191.13 as follows. In cases where a mixture of radionuclides is projected to be released to the accessible environment, the limiting values shall be determined as follows: For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide as determined from Table 1 and Notes 1 through 5. The sum of such ratios for all the radionuclides in the mixture may not exceed one with regard to 191.13(a)(1) and may not exceed ten with regard to 191.13(a)(2).

For example, if radionuclides A, B, and C are projected to be released in amounts Q_a, Q_b, and Q_c, and if the applicable Release Limits are RL_a, RL_b, and RL_c, then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$\frac{Q_a}{RL_a} + \frac{Q_b}{RL_b} + \frac{Q_c}{RL_c} < 1$$

Appendix B—Guidance for Implementation of Subpart B

[Note: The supplemental information in this appendix is not an integral part of 40 CFR Part 191. Therefore, the implementing agencies are not bound to follow this guidance. However, it is included because it describes the Agency's assumptions regarding the implementation of Subpart B. This appendix will appear in the Code of Federal Regulations.]

The Agency believes that the implementing agencies must determine compliance with §§ 191.13, 191.15, and 191.16 of Subpart B by evaluating long-term predictions of disposal system performance. Determining compliance with § 191.13 will also involve predicting the likelihood of events and processes that may disturb the disposal system. In making these various predictions, it will be appropriate for the implementing agencies to make use of rather complex computational models, analytical theories, and prevalent expert judgment relevant to the numerical predictions. Substantial uncertainties are likely to be encountered in making these predictions. In fact, sole reliance on these numerical predictions to determine compliance may not be appropriate; the implementing agencies may choose to supplement such predictions with qualitative judgments as well. Because the procedures for determining compliance with Subpart B have not been formulated and tested yet, this appendix to the rule indicates the Agency's assumptions regarding certain issues that may arise when implementing §§ 191.13, 191.15, and 191.16. Most of this guidance applies to any type of disposal system for the wastes covered by this rule. However, several sections apply only to disposal in mined geologic repositories and would be inappropriate for other types of disposal systems.

Consideration of Total Disposal System. When predicting disposal system performance, the Agency assumes that reasonable projections of the protection expected from all of the engineered and natural barriers of a disposal system will be considered. Portions of the disposal system should not be disregarded, even if projected performance is uncertain, except for portions of the system that make negligible contributions to the overall isolation provided by the disposal system.

Scope of Performance Assessments. Section 191.13 requires the implementing agencies to evaluate compliance through performance assessments as defined in § 191.12(q). The Agency assumes that such performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. Furthermore, the performance assessments need not evaluate in detail the releases from all events and processes estimated to have a greater likelihood of occurrence. Some of these events and processes may be omitted from the performance assessments if there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

Compliance with Section 191.13. The Agency assumes that, whenever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with § 191.13 into a "complementary cumulative distribution function" that indicates the probability of exceeding various levels of cumulative release. When the uncertainties in parameters are considered in a performance assessment, the effects of the uncertainties considered can be incorporated into a single such distribution function for each disposal system considered. The Agency assumes that a disposal system can be considered to be in compliance with § 191.13 if this single distribution function meets the requirements of § 191.13(a).

Compliance with Sections 191.15 and 191.16. When the uncertainties in undisturbed performance of a disposal system are considered, the implementing agencies need not require that a very large percentage of the range of estimated radiation exposures or radionuclide concentrations fall below limits established in §§ 191.15 and 191.16, respectively. The Agency assumes that compliance can be determined based upon "best estimate" predictions (e.g., the mean or the median of the appropriate distribution, whichever is higher).

Institutional Controls. To comply with § 191.14(a), the implementing agency will assume that none of the active institutional controls prevent or reduce radionuclide releases for more than 100 years after disposal. However, the Federal Government is committed to retaining ownership of all disposal sites for spent nuclear fuel and high-level and transuranic radioactive wastes and will establish appropriate markers and records, consistent with § 191.14(c). The Agency assumes that, as long as such passive institutional controls endure and are understood, they: (1) can be effective in deterring systematic or persistent exploitation of these disposal sites; and (2) can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the implementing agency. However, the Agency believes that passive institutional controls can never be assumed to eliminate the chance of inadvertent and intermittent human intrusion into these disposal sites.

Consideration of Inadvertent Human Intrusion into Geologic Repositories. The most speculative potential disruptions of a mined geologic repository are those associated with inadvertent human intrusion. Some types of intrusion would have virtually no effect on a repository's containment of waste. On the other hand, it is possible to conceive of intrusions (involving widespread societal loss of knowledge regarding radioactive wastes) that could result in major disruptions that no reasonable repository selection or design precautions could alleviate. The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). Therefore, inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed by the implementing agencies. Furthermore, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.

Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories. The implementing agencies should consider the effects of each particular disposal system's site, design, and passive institutional controls in judging the likelihood and consequences of such inadvertent exploratory drilling. However, the Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations, or more than 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations. Furthermore, the Agency assumes that the consequences of such inadvertent drilling need not be assumed to be more severe than: (1) Direct release to the land surface of all the ground water in the repository horizon that would promptly flow through the newly created borehole to the surface due to natural lithostatic pressure—or (if pumping would be required to raise water to the surface) release of 200 cubic meters of ground water pumped to the surface if that much water is readily available to be pumped; and (2) creation of a ground water flow path with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time—not the permeability of a carefully sealed borehole.

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Attachment - 7

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PROGRAM REVIEW

TECHNICAL ASSISTANCE IN GEOCHEMISTRY (B0287)

AND

LABORATORY EVALUATION OF RETARDATION PARAMETERS (B0290)

SILVER SPRING, MD

OCTOBER 16-17, 1985

October 16, 1985

8:30 AM	Overview of B0287 and B0290 Projects	S. K. Whatley
8:45 AM	Status and Plans for Technical Assistance in Geochemistry	S. K. Whatley
9:00 PM	Concerns Relative to the Applicability of the Yucca Mountain Sorption Information for Site Performance Assessment	A. D. Kelmers
9:30 AM	BREAK	
9:45 AM	Status of Laboratory Evaluations:	
	I. Sorption of Uranium, Neptunium, and Technetium on Basalt	R. E. Meyer
	II. Geochemical Modeling	G. K. Jacobs
	III. Plans for Yucca Mountain Evaluations	R. E. Meyer
11:30 AM	LUNCH	
12:45 PM	Summary of Topical Reports:	J. G. Blencoe
	I. BWIP Geochemical Conditions	
	[redacted]	
1:30 PM	Application of Radionuclide Sorption Information for Prediction of Retardation in Fracture-Flow Systems	A. D. Kelmers
2:15 PM	BREAK	
2:30 PM	Progress Report on Catalog of Natural Analogs	D. G. Brookins
3:00 PM	Demonstration of ORNL Document Data Base for Geochemical Information	G. K. Jacobs/ R. M. Gove
4:00 PM	Discussion	

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September 23, 1985

Dave:

Please find enclosed a revised agenda for the Program Review. Look it over and give me a call if you want to make any changes. If possible by Tuesday, because I will be in Los Alamos the rest of the week.

Thanks.

Gary

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