ARH-ST-137
UC-11
UC-70

PRELIMINARY FEASIBILITY STUDY ON
STORAGE OF RADIOACTIVE WASTES
IN COLUMBIA RIVER BASALTS
(Two Volumes)

Volume I

Research and Engineering Division

November 1976

Prepared for the National Waste Terminal Storage Program
of the U. S. Energy Research and Development Administration
by Atlantic Richfield Hanford Company under
Contract E(45-1)-2130

Atlantic Richfield Hanford Company
Richland, Washington 99352

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	v
CONCLUSIONS	vi
RECOMMENDATIONS	viii
PROGRAM REVIEW	xi
CHAPTER I. INTRODUCTION	1
CHAPTER II. COLUMBIA RIVER BASALT	9
Summary	9
Geological Setting	11
Previous Investigations	17
Geology	21
References	27
CHAPTER III. CHEMICAL IDENTIFICATION OF BASALT FLOWS	33
Summary	33
Introduction	33
Methodology	38
Results	42
Interpretation	44
Recommendations	49
References	50
CHAPTER IV. STRATIGRAPHY OF THE PASCO BASIN	53
Summary	53
The Stratigraphic Column	53
Correlation of Yakima Basalt Members and Flows in the Pasco Basin	54
Structure and Stratigraphy	56
References	61
CHAPTER V. HYDROLOGY	62
Summary	62
Introduction	63
Surface Hydrology	64
Regional Hydrology	66

TABLE OF CONTENTS (continued)

	<u>Page</u>
CHAPTER V. HYDROLOGY (cont.)	70
The Unsaturated Zone	70
The Unconfined Aquifer	71
The Uppermost Confined Aquifers	78
Hydrology of the Lower Yakima Basalts	82
Groundwater Chemistry	93
Groundwater Modeling	95
Recommendations	101
References	103
CHAPTER VI. EXTENT OF HEAT DISSIPATION FROM RADIOACTIVE WASTES STORED IN A BASALT CAVERN	108
Summary	108
Introduction	109
Computational Techniques	110
Results	112
Recommendations	126
References	127
CHAPTER VII. GEOCHEMICAL CONSIDERATIONS	128
Summary	128
Introduction	128
Solubility	129
Stability	132
Waste Form	133
Waste Compatibility	135
Recommendations	136
References	137
CHAPTER VIII. TECTONIC STUDIES	140
Summary	140
Historic Earthquakes in the Pacific Northwest Earthquakes and Geologic Structures in the Hanford Region	141
Geodetic Surveys	147
Recommendations	157
References	158

TABLE OF CONTENTS (continued)

	<u>Page</u>
ACKNOWLEDGEMENTS	165
DISTRIBUTION	166

ABSTRACT

This report discusses geologic, hydrologic, heat transfer and rock-waste compatibility studies conducted by the Atlantic Richfield Hanford Company to evaluate the feasibility of storing nuclear wastes in caverns mined out into the Columbia River basalts. The succession of Columbia River Plateau flood basalts was sampled at various outcrops and in core holes and the samples were analyzed to develop a stratigraphic correlation of the various basalt units and sedimentary interbeds. Hydrologic tests were made in one bore hole to assess the degree of isolation in the various deep aquifers separated by thick basalt accumulations. Earthquake and tectonic studies were conducted to assess the tectonic stability of the Columbia River Plateau. Studies were made to evaluate the extent of heat dissipation from stored radioactive wastes. Geochemical studies were aimed at evaluating the compatibility between the radioactive wastes and the basalt host rocks. Data obtained to-date have allowed development of a hydrostratigraphic framework for the Columbia River Plateau and a preliminary understanding of the deep aquifer systems. Finally, the compilation of this information has served as a basis for planning the studies necessary to define the effectiveness of the Columbia River basalts for permanently isolating nuclear wastes from the biosphere.

CONCLUSIONS

The work reported here is preliminary and provides an initial framework upon which future work can be based. Work needed to determine if basalt qualifies as an acceptable geologic formation for the final storage of nuclear wastes is identified in the section on recommendations.

As a result of previous work, the geology of the Columbia River Physiographic Province is reasonably well understood. The properties of the flood basalts in this area have been studied extensively using petrographic, geophysical, and geochemical techniques. These techniques were applied primarily to the identification, characterization, and correlation of individual flows and groups of flows of the Yakima Basalts. Some individual flows and some groups of flows can be readily identified and correlated by determining their geochemical and petrographic properties. Geophysical logs can be used to support the identification and stratigraphic correlation.

The preliminary stratigraphy of the Pasco Basin has been developed from analyses of samples obtained by drilling deep core holes on the Hanford Reservation and by sampling and mapping sections exposed on the sides of anticlines and in river gorges. The formations within the Columbia River Basalt Group have been identified. These basalts represent the largest accumulation of Neogene age continental basaltic rock in the world. The Hanford Reservation lies near the center of the thickest section of these materials.

The Columbia River Basalts have also been studied with respect to tectonic deformation and behavior under stress.

Preliminary earthquake and tectonic studies have led to stability considerations which can be used for formulating criteria for the construction of a prototype facility.

Hydrologic studies of the Columbia River Basalt Physiographic Province have led to an understanding of the regional hydrologic regime. Some of the basaltic interbeds and interflow zones are aquifers isolated from one another by extensive flows. The chemical and hydrologic properties of these interbeds appear to be distinct. Some of the basalt flows are as much as 50 meters thick, and are quite impervious since nearly all joints and fractures are filled with secondary minerals such as nontronite and beidellite. These thick basalts may represent hydrologically isolated units.

The engineering feasibility of building an underground cavern into the Columbia River Basalts has not been evaluated; however, considerations are included as to the extent of heat dissipation from radioactive wastes stored in such a cavern. These studies have shown that the maximum cavern temperature decreases with (1) increasing cavern radius, (2) wider cavern spacing, (3) fewer adjacent caverns, (4) higher thermal conductivity of the surrounding medium, (5) shorter half life of the radioactive waste products, and (6) lower heat generation rates per volume of the wastes.

Geochemical studies were also initiated to identify those factors that need to be considered in order to set criteria for a waste form that is acceptable for storage in a basalt cavern. These studies attempted to identify the factors needed to evaluate the stability of various waste forms, their solubility, and their compatibility with the basalt.

RECOMMENDATIONS

The understanding thus far developed represents a preliminary base for initiating an assessment of the environmental suitability of basalts as a final storage medium for radioactive wastes.

Although the regional geology of the Columbia River Plateau is relatively well understood, additional work is needed to assess the tectonic stability of the region and evaluate the extent of regional as well as local fracturing and folding.

The stratigraphic framework must be refined with emphasis on defining the hydrostratigraphic units in detail. The stratigraphic nomenclature needs to be standardized and made compatible with the work of other investigators in nearby areas.

The geochemical, petrographic, and geophysical identification techniques require further confirmation by applying them to additional field locations and core holes. This work will help assure the accuracy of the hydrostratigraphic model for the Columbia River Plateau and the Pasco Basin.

The hydrology of the Columbia River flood basalts must be understood and the extent of interaction between various flow units and interbeds defined. The significance of head relationships and concentrations of anions and cations in deep confined aquifers must be determined. Sources of recharge and discharge of these deep aquifers must be identified and quantitatively described. Such a hydrological program can then be used to provide data for mathematical models that can predict the behavior of the

hydrologic regime under all probable stresses to assess the risk of contamination from a final radioactive storage site throughout the groundwater pathway. The extent of isolation afforded a deep cavern by the surrounding basalt is the critical hydrologic factor that needs to be determined.

Engineering studies are needed to assess the feasibility of constructing a terminal storage facility in the deep basalts. Design criteria must be developed and plans for implementation outlined. Engineering design will augment the environmental acceptability of the facility and will constitute the main thrust of the project in the final design stages should the basalts be proven environmentally acceptable for final radioactive waste storage. In addition, engineering studies are needed to assess heat dissipation and stored energy effects from the various waste forms to be stored in the cavern and to design contingency plans during the retrievable period.

Geochemical studies are fundamental to our understanding of the feasibility of long-term containment of radioactive wastes and will require substantial additional research and development effort with emphasis on selection and characterization of the solidified waste form for storage and the compatibility of such a form with the basalt host rock. Chemical reactions in a wet as well as in a dry environment will have to be considered to allow for the possibility of eventual flooding of an underground cavern. The effect of radiation on each component, including the effect of stored energy on stability, solubility, and compatibility must be understood.

All this information must then be put together into a framework that allows a full assessment of the viability

of basalt as a final storage medium for radioactive wastes while assuring environmental safety, permanent isolation, and initial retrievability. To fully accomplish this task, *in-situ* information must be gathered in a prototype underground cavern to support the information obtained from surface and bore hole studies. As part of the overall program, all release and transport mechanisms that might release radioactivity into the biosphere must be quantified.

PROGRAM REVIEW

A review of this program was held in Richland, Washington, on September 15 and 16, 1976. The Committee was composed of the following individuals:

- Dr. William S. Twenhofel - U. S. Geological Survey
- Dr. Don A. Swanson - U. S. Geological Survey
- Dr. George D. DeBuchananne - U. S. Geological Survey
- Dr. G. L. Meyer - U. S. Environmental Protection Agency
- Dr. Robert Kaufman - U. S. Environmental Protection Agency
- Mr. Jack Sceva - U. S. Environmental Protection Agency
- Mr. Arthur M. Piper - Office of Waste Isolation - Consultant
- Mr. Robert B. Laughon - Office of Waste Isolation
- Dr. Richard H. Jahns - Stanford University - Engineering Geologist
- Dr. Aaron C. Waters - University of California
- Mr. William K. Summers - Consultant-Hydrologist
- Mr. Richard B. McMullen - Nuclear Regulatory Commission

The members of the Committee were provided with draft copies of the document resulting from the subject program on August 15, 1976, and the material was orally discussed at the September 15-16, 1976, review.

Overall the Committee agreed with the results of the investigations to date. Dr. Aaron Waters, senior member of the review panel, has summarized the findings of the Committee as follows:

"The general conclusion among the conferees at the meeting on 15-16 September, 1976, is that certain stratigraphic units of basalt rock do possess chemical and physical properties which make them strong candidates among earth materials presently being considered as suitable for long-term storage of atomic wastes."

Recommendations from individual members of the Review Committee are

summarized below:

SUMMARY OF RECOMMENDATIONS FROM INDIVIDUAL REVIEWERS

Regional Geology and Tectonics

1. Prepare an up-to-date regional geologic map of the Pasco Basin with emphasis on Columbia River Basalts.
2. Conduct a program to identify and define faults, folds, and anticlines in the Pasco Basin.
3. Assess the advantages and disadvantages of the Pasco Basin versus other geologic basalt environments.
4. Conduct detailed mapping of the Wallula and Sentinel Gap Areas.
5. Conduct trenching of selected areas of the Pasco Basin to study faulting.
6. Study outcrop samples from the Lower Yakima Basalts in as many locations as possible.
7. Examine any relation between the Olympic-Wallowa lineament and local tectonics.
8. Continue the microearthquake monitoring network.
9. Continue the study of major earthquake epicenters. Assess seismic risks.
10. Study an analogous basin to determine unifying factors and develop basin-wide models.
11. Study local geomorphology and structural features.

Correlation Techniques and Stratigraphy

12. Examine further the use of fresh water logging in volcanic rocks and assess techniques for correlating geophysical logs to individual lithologic units.
13. Refine the techniques for geochemical interpretation on the Lower Yakima Basalts. Examine the extent of compositional differences.
14. Relate the presence of dikes to the history and evolution of the Pasco Basin.

Correlation Techniques and Stratigraphy (continued)

15. Attempt to correlate individual interbeds. Obtain stratigraphic information on each unit.

Hydrology

16. Study the hydraulic characteristics of individual basalt flows and interbeds.
17. Complete an additional drill hole near DC-1.
18. Develop all needed hydraulic testing techniques.
19. Test hydraulic characteristics of individual horizons penetrated by all existing drill holes.
20. Construct a model of the regional groundwater flow system.

Geochemistry

21. Develop an experimental program to assess waste-basalt compatibility.
-

CHAPTER I

INTRODUCTION

Of all the problems associated with the development of the nuclear fuel cycle, the solution to none is so complex as that of final disposal of the radioactive wastes produced by fission and transmutation reactions. This report deals with but one alternative of final disposal, namely the feasibility of storing radioactive wastes in deep, dense basalt caverns.

Disposal of radioactive wastes in this report implies the emplacement of these materials in a form completely isolated from any contact, direct or indirect, with the environment for as long as these wastes pose a hazard. Thus, the intent of final disposal is one of isolation which ultimately does not depend upon surveillance by man in order to preserve containment.

From a practical standpoint, 'final' disposal of radioactive wastes in a geologic formation is regarded as involving two phases. The first phase will allow retrieval of the waste for a limited initial period. An initial period could be extended (possibly as much as 100 years). Once this phase of the disposal ends, changes would be made in the containment configuration to provide for long-term isolation at the expense of ready retrievability. Final geologic storage thus requires a rather detailed and comprehensive knowledge of the characteristics of the stratum to be used for containment and all adjacent strata to assure both temporary retrievability and permanent isolation. Geologic studies must examine not only the integrity of the

isolation provided by the formation, but also its expected stability in the future. Hydrologic studies are needed to ascertain that no radioactive material will be transported from the containment structure through the groundwater pathway to the biosphere. Engineering design must assure the safety, integrity, and reliability of every structure and appurtenance built in connection with the geologic storage facility.

In 1968, the Atlantic Richfield Hanford Company (ARHCO) started a study to assess the feasibility of final geologic storage of Hanford, defense, radioactive waste in deep caverns constructed in the Columbia River flood basalts. The project included: geologic studies to characterize these basalts and to understand their relative stratigraphic position; preliminary hydrologic tests into the basalts and interbeds; studies to assess the release of heat resulting from the emplacement of radioactive waste in a deep cavern; studies to assess the compatibility between the waste and the host basaltic rock; and studies to assess the tectonic stability of the Hanford region (Figure 1). The entire project was suspended in 1972, before completion of interpretative work.

In early 1976 the Office of Waste Isolation, Union Carbide Corporation requested ARHCO to complete the interpretation and documentation of the early studies, inasmuch as such studies may be valuable in qualifying the Columbia River flood basalts as a viable medium for final geologic storage of commercial radioactive wastes. This report is the result of that request. The objective of the report is to summarize existing data, interpret them, and identify key issues that require resolution to qualify basalt as a viable final geologic storage medium.

FIGURE 1
 PROGRAM TO DETERMINE THE FEASIBILITY AND ACCEPTABILITY
 OF STORING RADIOACTIVE WASTES IN COLUMBIA RIVER BASALTS

The Columbia River Plateau flood basalts appear to have developed as a layered sequence of lavas that intermittently filled a gradually down-warping basin that, in later stages, began to fold into an undulation of anticlines and synclines. Initial studies were directed toward developing a hydro-stratigraphic model. To this end, methods for identifying individual basalts were developed to assure that the bottom of wells could be located at predetermined stratigraphic horizons. Work was conducted on and around the Hanford Reservation, which is situated in the Pasco Basin near the center of the Columbia River Plateau flood basalt province where the accumulation of the layered basalts is thickest, exceeding 3,000 meters in thickness.

Although the basalts are highly jointed, field and core hole evidence suggest that some of the basalt flows may be impervious to water. Inspection of basalt joints and fractures shows that secondary minerals, predominantly clays such as beidellite and nontronite, fill the joints and cracks, effectively sealing them. Further evidence of low permeability of the basalt layers is indicated by the presence of a low-pressure gas field on the slopes of Rattlesnake Mountain (on the southwest quarter of the Hanford Reservation).

Thus, preliminary characterizations suggest that the Columbia River Plateau flood basalts may provide the requisite degree of isolation needed for final storage. However, before plans can be made to store wastes in mined-out cavities, tests must be conceived, designed, and conducted to positively assure ourselves, the scientific community, and the public that the wastes cannot migrate from the final storage facilities and accumulate in hazardous concentrations in the biosphere.

This report presents the work done to assess the feasibility of final geologic storage in the Columbia River flood basalts. It includes geologic, hydrologic, engineering, and geochemical considerations. Four appendices contained in Volume II show the basic geologic and geophysical data gathered at the various field sections, type localities, and core holes. Much additional work is needed to qualify the basalts for a final storage repository. Primary factors requiring early resolution include a determination as to whether or not water moves through the basalt rock and if so, the rate at which radionuclides might be transported through the basalt layers and intercalated sediments (via pores, open fractures, and/or joints) to the biosphere. An associated factor includes a determination of the likelihood of the rock becoming fractured or the joints opening due to tectonic activity. These questions must be answered in subsequent studies prior to qualifying basalt as a final storage site.

The present report emphasizes environmental definition rather than the engineering aspects of the design of the final storage facility. Conceptually, from an engineering standpoint, such a facility may resemble the design shown in Figure 2. The facility, as noted previously, must provide for retrievability of the waste for a defined period. To build such a facility will involve shaft sinking techniques and excavation of an underground mine using ordinary mining techniques and equipment or boring methods. Waste canisters would be lowered from their shipping casks into the mine and into a shielded transporter or conveyor, one by one. The underground transportation system would deposit the canisters in the storage spaces, which could be either horizontal or vertical holes in the walls or floor.

CONCEPTUAL FINAL STORAGE AT HANFORD FOR NUCLEAR WASTES

FB S/ARHCO 10-75

FIGURE 2

The spacing of the holes is critical to keep the temperature of the underground facility below an acceptable level. During the retrievable period, provisions must be made to preserve the integrity of the waste canisters and assure easy access to them. Beyond the retrieval period, the mine rooms would probably be backfilled and permanently sealed. From the mining standpoint, such a facility design appears feasible. Many tunnels for railroad and vehicular traffic and irrigation water have been built through the Columbia River flood basalts. Experience in building these structures will be helpful in later stages of this project.

(This page intentionally blank)

CHAPTER II
COLUMBIA RIVER BASALT

SUMMARY

The Columbia River Basalts of Miocene-Pliocene age in south central Washington represent one of the largest accumulations of continental basaltic rock in the world. The Hanford Reservation is in the western half of the Pasco Basin. The most prominent landforms of the region surrounding the Pasco Basin are the east-west trending anticlinal ridges that began to rise more than ten million years ago. The Saddle Mountains border the Pasco Basin on the north and rise to a maximum elevation of 817 meters above sea level. Two anticlinal ridges occur along the western border of the basin: Umtanum Ridge to the north and Yakima Ridge to the south. Gable Butte and Gable Mountain are outcrops along the eastern extension of Umtanum Ridge.

Very limited geological field work on the Columbia River Basalt was made before the 1930's. These early geological investigators directed their attention toward development of local and regional groundwater resources and defining the structure of a small gas field discovered on the north slope of Rattlesnake Hills in 1914.

From the late 1930's through the late 1960's, interest in the stratigraphy and structure of the Columbia River Basalts increased with the Federal construction projects of the Grand Coulee Dam, the Columbia Basin Irrigation Project, and the Hanford Works Project. These large construction projects required more detailed knowledge of the geologic and tectonic history of the Columbia River Plateau, especially in the region of the Pasco Basin.

In 1968 ARHCO undertook a study to develop a stratigraphic model of the basalts underlying the Pasco Basin. To accomplish this task, flow by flow correlations were required.

Most of the basalt within the Pasco Basin is tholeiitic basalt. The common primary constituents of the basalt are plagioclase, clinopyroxene, basalt glass (tachylyte), olivine, magnetite-ilmenite, apatite, and a mineraloid (chlorophaeite). Common alteration products formed in the basalt by diagenetic and hydrothermal activity are iron- and-magnesium clays, opal and chalcedony, calcite, celadonite, chlorite, and zeolites (heulandite, analcite, mordenite, and others). Nontronitic clays, other high-alumina clays, hydrous oxides of iron and manganese, and caliche are the main weathering products. The stratigraphy of the Pasco Basin has been developed from information obtained by drilling deep core holes on the Hanford Reservation and sampling and mapping sections exposed in river gorges.

The rocks overlying the basalts in the central part of the Pasco Basin are more than 370 meters thick. The lacustrine and fluvial Ringold Formation of late Pliocene age directly overlies the basalt. Eolian silt and glacio-fluvial sediments overlie the Ringold Formation.

The Ringold Formation, the eolian silts, and the basalt were locally eroded and truncated by a series of catastrophic floods of glacial meltwater near the close of the Ice Age 12,000 to 18,000 years ago.

GEOLOGICAL SETTING

One of the largest accumulations of continental basaltic rock is in the northwestern part of the United States in the physiographic province known as the Columbia River Plateau (Figure 1). Enormous volumes of basaltic magma welled up through fissures in the earth's crust from early Miocene to Pliocene time and spread out in broad sheets over an area conservatively estimated at two million square kilometers. The basalt magma probably had a low viscosity with very little gas trapped in the rock as evidenced by the uniformity of flow thicknesses over large areas and the limited zones of vesicular basalt within a flow. Contemporaneously with the eruption of basalts from fissures, nearby volcanoes blanketed the area with ash and ancestral rivers deposited sediments on the ground surface that in time were covered by the next flow.

The average thickness of the basalt sequence over the Columbia River Plateau is approximately 550 m; however, the greatest known thickness is in the saucer-shaped region in the northwestern part of the plateau. The Pasco Basin is the long-standing structural and topographic low point in the saucer-shaped region. The land surface near the center of the Basin is about 120 m above sea level and the underlying basalt surface is as much as 80 m below sea level.

Figure 2 shows in more detail the principal topographic features around the Pasco Basin and shows the boundary of the U. S. Energy Research and Development Administration (USERDA) Hanford Reservation. Figure 3 shows some features of the Reservation in more detail and identifies the sites of deep core holes referred to later.

(Physiographic provinces after Fenneman, 1923, as given in the U. S. Geological Survey National Atlas, 1970.)

FIGURE 1
THE COLUMBIA RIVER PLATEAU

V7607-13.27

FIGURE 2
GENERAL TOPOGRAPHY OF THE REGION

V7607-13.19

FIGURE 3
THE HANFORD RESERVATION

The most prominent landforms in the region surrounding the Pasco Basin are the anticlinal ridges that began to rise more than ten million years ago in late Miocene or early Pliocene time. The Saddle Mountains, bordering the Basin to the north, are 50 kilometers long and trend east-west. The mountains are fairly uniform in height and range from 610 to 817 m above sea level. The highest point on the crest is Wahatis Peak. Structurally, the Saddle Mountains are an asymmetric anticline with a steep northern slope and a gentle southerly slope. The axial trace of the anticline and the ridge crest of the Saddle Mountains do not generally coincide because portions of the anticline crest have been eroded.

At the western end of the Saddle Mountains the Columbia River enters the Pasco Basin through Sentinel Gap. This water gap is more than two kilometers wide and 500 m deep. Uplift of the Saddle Mountains was so gradual that the Columbia River maintained its original course by slow abrasion of the basalt surface. To the east, the Saddle Mountain structure swings slightly southeast and plunges beneath the basin fill.

Two basalt ridges occur along the western border of the Pasco Basin. The most northerly of the two is Umtanum Ridge which rises more than 1000 m above sea level. The north limb of this anticline is sharply folded and at a point near the Priest Rapids Dam, where the Columbia River impinges against this ridge, the flows are overturned (dipping 80 to 85 degrees to the south). Eastward, the main ridge plunges beneath basin fill. It crops out again near the center of the Basin as Gable Butte and Gable Mountain (Figure 2). The Yakima Ridge lies immediately south of Umtanum Ridge. The crest of this ridge to the

west of the Pasco Basin is 1,200 m above sea level and is the highest point within the Pasco Basin region. The southeastern continuation of the Yakima Ridge lies buried beneath the basin fill until it crops out as a line of isolated hills paralleling the Yakima River on its west bank above its confluence with the Columbia River.

The Rattlesnake Hills are south of the Yakima Ridge. This anticlinal structure is the most prominent topographic feature bordering the Pasco Basin. The asymmetry of this ridge is typical of most ridges in the region. The northern limb slopes 17%, whereas the southern limb slopes 5%. West of the Pasco Basin, the Rattlesnake Hills trend in an east-west direction. South of the Basin they trend southeast-northwest. Where the Rattlesnake Hills trend east-west the crest is about 1,000 m above sea level. In the short distance from the point where they turn and trend southeast-northwest, the anticline plunges sharply about 150 m/km. On the west bank of the Yakima River the anticline dies out. Southeastward from the point where the main structure dies out at the Yakima River, the extension of the Rattlesnake Hills is manifested by a series of doubly plunging anticlines or elongate domes trending toward the Horse Heaven Hills. The Rattlesnake Hills structure eventually merges with the Horse Heaven Hills to the southeast near the junction of the Snake and Walla Walla Rivers with the Columbia River.

Wallula Gap, the water gap through the Horse Heaven Hills through which the Columbia River leaves the Pasco Basin, was cut in a manner somewhat similar to Sentinel Gap in the Saddle Mountains.

Figure 4 consists of two cross sections constructed through the Pasco Basin that show the relationship of the Columbia River Basalts to the geology of the surrounding region. Generally, granitic rocks of Mesozoic age crop out to the north, the Clarno Formation of Eocene-Oligocene age crop out to the south, Eocene to Miocene metavolcanics of the Ohanapecosh and Fives Peak Formations crop out to the west, and late Paleozoic sediments and volcanics crop out to the east. The number of individual flows underlying the Pasco Basin is not known, but approximately fifty flows were identified in the core holes drilled on the Hanford Reservation and about 100 flows were tentatively identified in a deep well drilled by the Standard Oil Company of California (RSH-1) that reached a depth of 3,248 m without penetrating the base of the basalt sequence.

PREVIOUS INVESTIGATIONS

The first geological reconnaissance of the Columbia River Basalt in Washington and Oregon was made in the late 1890's and early 1900's by geologists of the U. S. Geological Survey (USGS).^[1-13] One of the principal reasons for these studies was to evaluate the groundwater resources of the semi-arid to arid region around the Pasco Basin. It was primarily in the valleys along the eastern flank of the Cascade Mountains that settlements first began to develop because of the availability of water. As people began to move away from the mountain slopes and out into the desert areas, they became more and more dependent on shallow wells for water supplies.

A major question confronting these early investigators was the source of the basalt. The relatively flat lying

FIGURE 4
REGIONAL CROSS-SECTIONS THROUGH THE PASCO BASIN
(SEE FIGURE 1 FOR CROSS SECTION LOCATIONS)

flows could be seen extending over thousands of square kilometers, but were so monotonous in nature they could not be identified and correlated between isolated outcrops using the technology available at that time. Consequently, many questions concerning structure, geologic history and the petrogenesis of the basalt flows remained unanswered.

Merriam^[14] was the first to study dikes in the Monument, Oregon area and postulated that they might be feeders for some of the Columbia River Basalt flows to the north. Fuller^[15,16] published papers describing dikes in the Cornucopia, Oregon area and used flow structures to determine general directions of movement for individual flows. These structures developed while the flow was still in the molten state and were essentially frozen in the rock when it cooled.

In the 1930's, Hammer^[17] and Glover^[18] described the gas field that had been discovered on the north slope of Rattlesnake Hills in 1914 and developed through the 1920's. During this period, Twiss^[19] developed the stratigraphy of the Saddle Mountains.

From 1940 to 1970, a number of papers were published on the Columbia River Basalt by Laval^[20], Mackin^[21-24], Waters^[25-30], and Schmincke^[31-34]. Mackin and Laval correlated the basalt flows using gross physical features observed in the field such as nature of the jointing; color of weathered surfaces; presence or absence of large and distinctive phenocrysts; shape, size and percentage of vesicles or other voids. As in correlation studies of sedimentary rocks, one of the most important clues was field determination of the exact stratigraphic position of a flow in relation to known overlying or underlying flows,

or to recognizable sedimentary interbeds between flows. Mackin stated: "recognizable stratigraphic studies in the Yakima Basalt....depend, not on tracing of any individual units, but in relations seen in sequence." [23]

These criteria serve well, and continue to be of value in local studies of small areas (less than 2,500 square kilometers) which contain good exposures. Most of the features listed above, however, do not remain constant when flows are traced for tens of kilometers. For example, jointing reflects the cooling history of the flow, and this necessarily changes with distance from the vent, thickness of the flow, nature of the surface covered (e.g., local areas of marshy ground), and whether the flow ponded quickly and then solidified from a virtually motionless fluid, or whether it continued to creep forward throughout the period of crystallization. Weathering colors also depend on many local factors such as: climate, presence or absence of an easily weathered iron-sulfide bearing mineraloid, amount of cover by lichen and mosses, local deposition of caliche on weathered surfaces, and many other variable factors.

Field criteria such as weathering and jointing are of little diagnostic value in correlating flows from one site to another unless the basalt is exposed at the land surface.

Waters [29] showed that it is possible to distinguish between certain major groups within the Columbia River Basalt using microscopic petrology supplemented by chemical analyses and careful field studies. In the last 15 years this approach has been strengthened and brought up to date by the efforts of numerous researchers. Schmincke [34]

used it to distinguish between four specific basalt flows interbedded with the Ellensburg Formation of south central Washington.

In 1968 ARHCO on behalf of the Atomic Energy Commission (now USERDA), undertook a study to develop the technology by which a credible model of the basalt structure and stratigraphy underlying the Hanford Reservation could be made. Since the start of this project, ARHCO in cooperation with the colleges and universities in the Pacific Northwest and the USGS was able to develop such a stratigraphic model. To accomplish this, five core holes were subjected to intensive study and analysis to determine properties by which individual flows (units) could be uniquely identified for correlation. The techniques used in basalt identification are discussed in the following chapter.

GEOLOGY

The Columbia River Basalt is classed as tholeiitic basalt on the basis of its chemistry and mineralogy. Not all flows within the Pasco Basin fit this classification because of their higher alkali content. The common minerals present in the basalt are plagioclase, clinopyroxene, olivine, opaque minerals (such as magnetite and ilmenite), apatite, and mineraloids (chlorophaeite). Tachylite, a basalt glass crowded with crystallites, is abundant in most flows. The plagioclase is usually labradorite where it occurs as large phenocrysts but may range from labradorite to andesine in the groundmass. Olivine is usually altered to clay minerals or Mg-chlorite. The pyroxene present is

augite and/or pigeonite. The texture is aphanitic with occasionally large phenocrysts present in some flows. Although some flows in the Pasco Basin are quite glassy, most exhibit intersertal to intergranular textures. Some show a patchy diktytaxitic ophimottling. The color of the rock is generally gray to black on a fresh surface. Some flows such as the Roza flow have reddish-orange to reddish-brown weathered surfaces that result from the oxidation of iron in iron-rich clay and mineraloid present in this flow.

The macrostructure of a flow or flow unit is illustrated in Figure 5.^[35]

Waters^[27] divided the Columbia River Basalt into two major and distinct sequences, the older Picture Gorge Basalt, cropping out in central Oregon, and the younger Yakima Basalt, well exposed in outcrops west of the Pasco Basin. In 1961 he proposed that the two sequences be formally defined as formations and that the term Columbia River Basalt be elevated to group status.^[29] Additional changes to the stratigraphy of the Columbia River Basalt have been proposed in recent years, as more and more flows have been identified by other workers. On the basis of information and knowledge gained by ARHCO on the basalts within the Pasco Basin, a significant revision will be required to clearly define the stratigraphic relationships. Figure 6 is a stratigraphic chart showing the sequence of the rock strata within the Pasco Basin. This stratigraphic chart is under revision, but for purposes of this discussion, it is used in its present form.

The basement rocks underlying the basalt are of uncertain composition. Certain rock types can be projected from around the margins of the Pasco Basin to a point

FIGURE 5
MACROSTRUCTURE OF A FLOW
(AFTER SWANSON^[35])

FIGURE 6 STRATIGRAPHY OF THE PASCO BASIN

beneath it. The basement rock types found northwest of the Pasco Basin can be inferred on the basis of our knowledge of the geological features of the region. Wells that penetrate the entire basalt sequence north of the Pasco Basin encountered sandstones and shales beneath which are probably Mesozoic granitic rocks comparable to those in the Okanogan Highlands to the north (Figure 1) and granitic rocks such as those found underlying the basalts in the Snake River Canyon upstream of the Little Goose Dam, Washington. Another possibility is that basaltic rocks older than the Columbia River basalt group underly the Pasco Basin.

Geophysical studies by Cantwell and others^[36], Skehan^[37], and McKee^[38] have led to several interpretations of the crustal structure underlying the basalts of the Pasco Basin. Cantwell et al.^[36], identified differences in deep crustal resistivity that appeared to have the same linear trend as the Olympic-Wallowa lineament (a lineament of several prominent physiographic features from the Straits of Juan De Fuca to the Wallowa Mountains in northeastern Oregon).^[39] Skehan^[37] believed these changes reflected a difference in rock type at depth, granitic rocks to the north and basaltic rocks to the south. McKee^[38] recognized that a change in rock types such as Skehan proposed did occur in the northern Cascade Mountains. He believed that the lineament was a broad zone separating those rock types and trending roughly east-west. Yates^[40] recognized a discontinuity farther east in Idaho that if projected northwestward would correspond in part with Skehan's and McKee's lineaments.

Lacustrine and fluvial sediments of the Ringold Formation overlie the Columbia River Basalt in the Pasco Basin.

Previously, downwarping in the local area was accompanied by basalt flow extrusion into the topographically and structurally low areas. The end of the fissure eruptions about 8 million years ago permitted the deposition of a continuous sequence of sediments. These were blends of sediments and volcanic ash derived from three sources: the Cascades, Okanogan Highlands, and northern Rocky Mountains.

An eolian deposit of fine sand and silt generally overlies part of the eroded surface of the Ringold Formation. This deposit is considered to be the equivalent of the Palouse soils (loesses) of eastern Washington and westernmost Idaho.^[41]

The Palouse soils, the Ringold Formation, and even the basalts were locally eroded and truncated by a sequence of catastrophic floods of glacial meltwater near the close of the Ice Age (12,000 to 18,000 years ago). These floods emanated from the Clark Fork Valley near Missoula, Montana, and resulted from the release of ice-dammed glacial Lake Missoula. Smaller floods resulted from the sudden drainage of smaller, similarly glacier-dammed lakes to the north. One of the largest floods occurred about 18,000 years ago and probably lasted a few weeks, during which an estimated more than 1000 cubic kilometers of water poured across the eastern part of Washington and into the Pasco Basin.^[42] Maximum flow rates have been estimated at 20 cubic kilometers of water per hour.

The glaciofluvial sediments deposited in the Pasco Basin are locally referred to as Pasco Gravels and Touchet Silts. Ice-rafted erratics and thin silt deposits occur up to 400 m above sea level indicating the depth of water in the Basin. A later flood, about 12,000 years ago, reached

a level of 300 m above sea level. The maximum altitude for the basin-fill deposits in the Pasco Basin is 240 m above sea level.

REFERENCES

1. I. C. Russell, Geology of the Cascade Mountains in Northern Washington, U.S. Geol. Survey 20th Ann. Rept., pt. 2, p. 83-210, 1900.
2. I. C. Russell, Geology and Water Resources of Nez Perce County, Idaho, U.S. Geol. Survey Water-Supply Paper 53 and 54, 1901.
3. I. C. Russell, A Geological Reconnaissance in Central Washington, U.S. Geol. Survey Bull. 108, 1903.
4. W. Lindgren, The Gold Belt of the Blue Mountains of Oregon, U.S. Geol. Survey 22nd Ann. Rept., pt. 11, p. 551-776, 1901.
5. G. O. Smith, Geology and Water Resources of a Portion of Yakima County, Washington, U.S. Geol. Survey Water-Supply Paper 55, 1901.
6. G. O. Smith, Geology and Physiography of Central Washington, U.S. Geol. Survey Prof. Paper 19, 1903.
7. G. O. Smith, Description of the Ellensburg Quadrangle (Washington), U.S. Geol. Survey Geol. Atlas, Ellensburg Folio, (No. 86), 1903.
8. G. O. Smith, "Anticlinal Mountain Ridges in Central Washington," Jour. Geol., v. 11, p. 166-177, 1903.
9. G. O. Smith, Mount Stuart Folio, U.S. Geol. Survey Geol. Atlas (No. 106), 1904.

10. F. C. Calkins, Geology and Water Resources of a Portion of East Central Washington, U.S. Geol. Survey Water-Supply Paper 118, 1905.
11. G. A. Waring, Geology and Water Resources of a Portion of South Central Washington, U.S. Geol. Survey Water-Supply Paper 316, 1913.
12. H. E. Culver, Abstract of the Report (by Solon Shedd) on the Geology and Resources of the Pasco and Prosser Quadrangles (Wash.), Washington Div. Geol. Rept. of Invest. No. 4, 1926.
13. J. T. Pardee and K. Bryan, Geology of the Latah Formation in Relation to the Lavas of the Columbia Plateau Near Spokane, Washington, U.S. Geol. Survey Prof. Paper 140, p. 1-16, 1926.
14. J. C. Merriam, A Contribution to the Geology of the John Day Basin, Univ. California Dept. Geol. Sci. Bull., v. 2, p. 269-314, 1901.
15. R. E. Fuller, "The Closing Phase of a Fissure Eruption," Am. Jour. Sci., v. 14, p. 228-230, 1927.
16. R. E. Fuller, "The Aqueous Chilling of Basaltic Lava on the Columbia River Plateau," Am. Jour. Sci., v. 21, p. 281-300, 1931.
17. A. A. Hammer, "Rattlesnake Hills Gas Field," Northwest Oil and Gas World, v. 2, no's. 5, 6, 7, 8, 9, 1931.
18. S. L. Glover, Preliminary Report on Petroleum and Natural Gas in Washington, Washington Div. Geol. Rept. Invest. No. 4, 1936.
19. S. N. Twiss, Stratigraphy of Saddle Mountains, Washington State Univ. (M.S. Thesis), 1933.

20. W. N. Laval, Stratigraphy and Structural Geology of Portions of South Central Washington, Univ. of Washington (PhD Dissertation), 1957.
21. J. H. Mackin, "Diatomite Deposits in Eastern Washington" (abst.), Northwest Sci., v. 21, p. 33, 1947.
22. J. H. Mackin, Geology of the Priest Rapids Development: Priest Rapids Hydroelectric Development, Columbia River, Washington, Grant County Public Utility District, 1955.
23. J. H. Mackin, A Stratigraphic Section in the Yakima Basalt and the Ellensburg Formation in South Central Washington, Washington Div. Mines and Geol. Rept. of Invest. 19, 1961.
24. J. H. Mackin and A. S. Cary, Origin of Cascade Landscapes, Washington Div. Mines and Geol. Information Circular No. 41, 1965.
25. A. C. Waters, "Multiple Dike Feeders of the Columbia River Basalt" (abst.), Geol. Soc. America Bull., v. 61, p. 1533, 1950.
26. A. C. Waters, "Geomorphology of South Central Washington, Illustrated by the Yakima East Quadrangle," Geol. Soc. America Bull., v. 66, p. 663-674, 1955.
27. A. C. Waters, "Two-Fold Division of the Columbia River Basalt," Geol. Soc. America Bull., v. 71, No. 12, pt. 2, p. 2082, 1960.
28. A. C. Waters, "Determining Flow Direction in Basalts," Am. Jour. Sci., Bradley Vol. C. 258-A, p. 350-366, 1960.

29. A. C. Waters, "Stratigraphic and Lithologic Variations in the Columbia River Basalt," Am. Jour. Sci., v. 259, p. 583-611, 1961.
30. A. C. Waters, Basalt Magma Types and Their Tectonic Associations; Pacific Northwest of the United States, Am. Geophys. Union, Geophys. Mon. 6, The Crust of the Pacific Basin, p. 158-170, 1962.
31. H. U. Schmincke, Petrology, Current Directions, and History of the Upper Late Yakima Basalt Flows and Interbedded Sediments, South Central Washington, Fourth Ann. Grad. Student Symposium in Geol. Sci., Univ. California, Los Angeles, April 17, 18, p. 14-15, 1964.
32. H. U. Schmincke, Petrology, Paleocurrents and Interbedded Yakima Basalt Flows, South Central Washington, The Johns Hopkins Univ. (PhD Dissertation), 1964.
33. H. U. Schmincke, "Flow Directions in Columbia River Basalt Flows and Paleocurrents of Interbedded Sedimentary Rocks, South Central Washington," Geol. Rundschau, Band 56, p. 992-1020, 1967.
34. H. U. Schmincke, "Fused Tuffs and Peperites in South Central Washington," Geol. Soc. America Bull., v. 78, No. 3, p. 319-330, 1967.
35. D. A. Swanson, "Yakima Basalt of the Tieton River Area, South Central Washington," Geol. Soc. America Bull., 78, p. 1077-1110, 1967.
36. T. P. Cantwell, Nelson, and J. Webb, "Deep Resistivity Measurements in the Pacific Northwest," Jour. Geophys. Res., v. 70, No. 8, p. 1931-1937, 1965.

37. J. W. Skehan, A Continental Oceanic Crustal Boundary in the Pacific Northwest, AFCRL-65-904, 1965.
38. B. McKee, The Olympic-Wallowa Lineament in Western and Central Washington (abst.), Geol. Soc. America Proc. Cordilleran Section 63rd Ann. Meeting, Santa Barbara, California, March 22-25, 1967.
39. E. Raisz, "The Olympic-Wallowa Lineament," Am. Jour. Sci., v. 243-A, p. 479, 1945.
40. R. G. Yates, Discontinuity in Central Idaho (abst.), Geol. Soc. America Proc. Cordilleran Section 63rd Ann. Meeting, Santa Barbara, California, March 22-25, 1967.
41. D. J. Brown, "An Eolian Deposit Beneath 200-West Area," General Electric, Hanford Atomic Products Operation, Document No. HW-67549, p. 11, 1960.
42. J. H. Bretz, H. T. U. Smith, and G. E. Neff, "Channeled Scablands of Washington: New Data and Interpretations," Geol. Soc. America Bull., v. 67, p. 957-1049, 1956.

CHAPTER III

CHEMICAL IDENTIFICATION OF BASALT FLOWS

SUMMARY

Methods of chemical and petrographic analyses of basalts were applied to the identification, characterization, and correlation of individual flows and groups of flows of the Yakima Basalts. Formally named flows and members were sampled at the type locality and chemically and petrographically analyzed. The results from the type localities were then compared with chemical and petrographic analyses of basalt from core holes and field sections. This comparison showed that some individual flows and some groups of flows can be identified and correlated by chemical and petrographic properties. Geophysical logs supported the identification.

Additional chemical data are needed to reduce the analytical error and thereby improve the precision and accuracy of the data base and to correct existing deficiencies in the data base.

Additional parameters, such as mineral compositions, isotopic compositions, and paleomagnetic polarities need to be measured and used for additional flow identification criteria and to test existing identifications and correlations.

INTRODUCTION

Recent developments in petrography and geochemistry have revealed a number of characteristics by which flows and

flow sequences can be identified. Waters^[1] made one of the first and most significant contributions toward characterizing the Columbia River Basalts. On the basis of petrographic and geochemical properties, he was able to show a major stratigraphic subdivision between basalts of lower Miocene age and of upper Miocene-lower Pliocene age. He named two formations, the Picture Gorge Basalt and the Yakima Basalt, respectively, and raised the Columbia River Basalt to group status.

Swanson^[2] demonstrated that the Yakima Basalt flows in the Tieton River area near the western margin of the Columbia River Plateau could be correlated using the modal plagioclase/pyroxene ratios of individual flows. Schmincke^[3] found significant differences in major element chemistry between certain individual flows of the Yakima Basalts. Holmgren^[4] employed $^{40}\text{K}/^{40}\text{Ar}$ age dating and paleomagnetic techniques for correlating thick flow sequences of Yakima Basalt in central Washington. Osawa and Goles^[5] demonstrated the applicability of neutron activation technology for identifying trace element variations in and between the Picture Gorge Basalt and Yakima Basalt. Myers and Brown^[6], and Wright^[7] showed that individual flows and sequences of flows can be correlated by comparing the concentrations of elements.

Other techniques for identifying Columbia River Basalts have been less successful but are still being evaluated. McKee and McKee^[8] observed differences in refractive indices of fused glass beads within the major subdivisions of the Columbia River Basalt Group but stated the method was not useful in distinguishing individual flows or flow sequences within a formation. A preliminary evaluation of the

feasibility of using Mössbauer spectra for identifying individual flows of upper Yakima Basalt has been made, but the technique needs further development before it can be applied to basalt flow identification.

An important requirement in using the techniques of geochemistry, petrography, or any other discipline to identify and correlate basalt flows is that there be no significant lateral variation within the flows of the property being measured. It is possible, for instance, that lateral (or vertical) variations within a flow could be related to distance from the vent, cooling history, chamber differentiation, rate of crystal growth, rate of crystal settling, effects of underlying topography, and conditions of extrusion.

To determine to what extent geochemistry and petrography might vary laterally within Columbia River basalt flows, two flows (later identified as the Sillusi Flow and Umatilla Flow) were sampled several times along a series of sections exposed in cliffs along the Columbia River from Sillusi Butte to Mound Pond located near Wallula Gap (Figure 1). Exposure in this area is almost continuous for about 30 kilometers; individual flows were traced visually. The results of this work indicate that geochemical and petrographic parameters within the Sillusi and Umatilla Flows do not vary significantly with distance. The flows are unique because their barium content ($\approx 3,000$ ppm) is three to eight times higher than the barium content of other flows (about 400 - 1200 ppm).

Many flows of the Columbia River basalt group have been formally named and described by previous workers at type localities designated by them.^[1,3,7,9] These type

FIGURE 1 FIELD SECTION, SILLUSI BUTTE TO MOUND POND

localities have been visited, sampled, and analyzed (Appendix A).^{*} Most of the type localities are separated from the Hanford Reservation by tens of kilometers and the intervening area is largely covered by surficial deposits that conceal the underlying stratigraphic complexities. However, some isolated exposures occur at water gaps, river canyons, and in valleys along the flanks of the anticlinal ridges. Several field sections (surface outcrops other than type localities exposing part of the stratigraphic section) have also been sampled and analyzed (Appendix B). In addition, several deep core holes have been drilled beneath the Hanford Reservation and the continuous core obtained from these holes has been sampled and analyzed (Appendix C; geophysical logs for the deep core holes are shown in Appendix D).^{*} Thus, the basalt petrographic and geochemical data bases for this report are from three sources: type localities, field sections, and core holes. Comparison of the core hole analyses with type locality analyses has permitted the basalt flows and members in the core holes to be identified by name.

In addition, comparison of the field section analyses with the type locality and core hole analyses has improved the reliability of the correlations between the core holes and type localities and permitted a better understanding of the stratigraphic complexity of the basalt sequence within the Pasco Basin. The data have been used to develop a preliminary model of the stratigraphic relationships beneath the Hanford Reservation (Chapter IV).

^{*}All of the appendices are found in Volume II of this report.

METHODOLOGY

Sampling Techniques

Field section localities were selected from areas of stratigraphic interest that gave maximum total relief, extensive basalt outcrops, and access for description and sampling.

After selection, the field sites were inspected from the air. Aerial photographs were obtained for sample documentation, structure evaluation, and reference. At each site, a lithologic description was recorded and vertical thicknesses were measured by barometric altimeter or tape. Horizontal control was established by topographic maps, aerial photographs, and Brunton compass. The lithologic description was an account of such flow features as: colonnades, entablature, vesicular zones, rubble zones, and the visual appearance of hand specimens, i.e., porphyritic, aphanitic, etc. Particular attention was paid to evidence of flow contacts such as vesicular zones, chilled margins, clastic interbeds, flow surface texture ('aa' or 'pahoehoe' surfaces), and weathering zones.

Samples were taken from the lower colonnade or basal entablature about 2 to 5 m above the base of every evident flow when possible. Multiple samples were taken from thicker flows and at points where contacts were obscured. Each sample point was documented by marking with paint and assigning a serial number. The location was marked on an aerial photograph, and on a topographic map.

Type localities were sampled in the same manner with care taken to obtain fresh unaltered samples.

The samples were prepared for chemical analysis by crushing at least 500 grams of each in an alumina jaw-crusher and splitting aliquots needed for analysis. Samples used for preparation of thin sections were also selected at that time.

Core hole samples were taken at least every 10 m near evident flow contacts. Treatment of the samples were identical to that of field sections and type localities.

Analytical Techniques

Basalt samples were analyzed for major element content by atomic absorption spectroscopy, for naturally occurring radioisotopes by gamma energy spectroscopy and for minor elements by emission spectrometry, and neutron activation analysis. A truck-mounted energy-dispersive X-ray fluorescence unit was used for field studies and core hole stratigraphic control. Basalt mineralogy was studied by electron microprobe and X-ray diffraction techniques. Some samples were age dated by $^{40}\text{K}/^{40}\text{Ar}$ methods.

Atomic Absorption

Samples for analysis by atomic absorption were crushed and pulverized to approximately 300 mesh and fused with lithium metaborate in platinum ware followed by dissolution in HCl. The method is basically applicable to both major and minor components but is a single element analysis technique in that separate dilutions are needed for most elements and only one element can be analyzed at a time. Standards must be prepared on a routine basis since they degenerate with time. Problems develop frequently if the lithium metaborate or other reagents added to the dilutions $[\text{KCl}, \text{La}(\text{NO}_3)_3]$ as ionization suppressants are not sufficiently pure. A standard rock such as the USGS-BCR-1 basalt

was normally used as a control standard. Accuracy and precision for the major elements are shown in Table I.

Accuracies and precisions in atomic absorption are limited by (1) the inability to distinguish Fe^{+2} and Fe^{+3} , (2) the lack of sensitivity for silicon analysis, a major component, (3) the need for large dilutions that introduce dilution and volumetric measurement errors, and (4) the incomplete analysis for such things as PO_4^{-3} . On atomic absorption equipment, silicon results can only be read to within one weight percent. This does not include measurement error.

TABLE I

TYPICAL ACCURACY AND PRECISION FOR
ATOMIC ABSORPTION ANALYSIS OF BCR-1
ROCK STANDARD

<u>Oxide Determined</u>	<u>Percent Recovery Of BCR-1 Standard Value</u>
SiO_2	102.3 ± 0.9
Al_2O_3	99.4 ± 1.1
Fe_2O_3	101.2 ± 1.5
CaO	96.2 ± 1.2
MgO	110.4 ± 3.4
Na_2O	102.1 ± 0.9
K_2O	103.7 ± 1.4
TiO_2	97.2 ± 2.2

Gamma Energy Analysis

Determination of naturally occurring radioactive isotopes has been described by Zimmer.^[10] Samples were analysed by an anticoincidence guarded, large volume lithium drifted germanium detector, multi-channel analyzer and

digital data reduction system. Analyses for ^{40}K , ^{226}Ra daughters, and ^{228}Th daughters were performed to a precision of 10 to 12 percent at the 95 percent confidence level in a four-hour counting period.

Emission Spectrometry

Several series of basalt samples were analyzed by an emission spectrometer quantometer to evaluate the usefulness of the method. Problems inherent with the technique were encountered and emission spectrometric analyses were discontinued.

Neutron Activation Analysis

More than 475 samples were analyzed for trace element determinations. Table II lists elements determined and analytical uncertainties. Errors listed are 1σ (standard deviation) and include counting statistics and standardization errors.

TABLE II

<u>Element</u>	<u>Concentration Range</u>		<u>Estimated 1σ Error</u>
La	10-50	ppm	$\pm 5\%$
Sm	5-15	ppm	$\pm 5\%$
Eu	1-02	ppm	$\pm 20\%$
	2-04	ppm	$\pm 10\%$
Fe	7-12	%	$\pm 5\%$
Sc	25-40	ppm	$\pm 5\%$
Cr	1-10	ppm	$\pm 30\%$
	10-50	ppm	$\pm 15\%$
	50-80	ppm	$\pm 10\%$
	80-250	ppm	$\pm 5\%$
Co	25-50	ppm	$\pm 5\%$

TABLE II (continued)

<u>Element</u>	<u>Concentration Range</u>		<u>Estimated 1σ Error</u>
Na	1-3	%	$\pm$ 2%
Th	1-3	ppm	$\pm$ 20%
	3-8	ppm	$\pm$ 10%
Hf	3-5	ppm	$\pm$ 20%
	5-12	ppm	$\pm$ 10%
Al	5-8	%	$\pm$ 5%
V	200-500	ppm	$\pm$ 10%
Mn	1,000-2,000	ppm	$\pm$ 10%

Petrography

Point counts, grain size measurements, textural description, and optical determination of plagioclase compositions were made from the basalt thin section using a petrographic microscope equipped with a mechanical stage.

Age Dating

Approximately 300 samples of Yakima Basalt were dated by the $^{40}\text{K}/^{40}\text{Ar}$ method, which is based on determining the ratio of naturally occurring radioactive potassium-40 to argon-40, the decay product.

RESULTS

Geochemical and petrographic data from the type localities, field sections, and core holes are presented in Appendices A, B, and C, respectively. Geophysical data for the deep core holes are shown in Appendix D.

Type locality geochemical data (Appendix A) are summarized in Table III. These geochemical data supported by

TABLE III

Analyses by Atomic Absorption Corrected for % Volatility (Heated to 900°C)												Analyses by Neutron Activation															
		SiO ₂ %	Al ₂ O ₃ %	FeO %	MgO %	CaO %	Na ₂ O %	K ₂ O %	TiO ₂ %	MnO %	SrO %	P ₂ O ₅ %	Ba ppm	M/Ba1 %	Na %	La ppm	Sm ppm	Fe %	Co ppm	Sc ppm	Cr ppm	Eu ppm	Th ppm	Tb ppm	Hf ppm	Ta ppm	
Ice Harbor II (Type Locality)	A1424	48.7	11.8	16.6	4.9	9.2	2.5	1.2	3.4				1286	98.4	1.79	74	19.5	13.1	39	39	40	5.4	5.4			11.0	
	A1426	50.0	11.4	16.9	4.8	9.0	2.6	1.2	3.4				1252	99.3													
	A1427	50.2	11.5	16.7	4.5	9.4	2.8	1.1	3.6				1299	99.7													
Ice Harbor I (Type Locality)	A1423	51.9	13.0	13.8	7.0	10.8	2.4	0.7	3.2				813	102.9													
	A1425	49.9	12.8	13.8	7.0	10.5	2.2	0.8	3.2				891	100.3	1.78	38	9.9	11.1	45	42	162	3.3	3.1			6.4	
Ward Gap (Type Locality)	A1276	54.0	13.3	14.2	4.9	8.4	2.5	1.1	3.0	0.21	0.017		611	101.6	1.82	34	7.4	10.1	43	31	22	3.0	5.7	1.7	7.7	2.3	
	A1277	52.3	13.1	15.4	4.6	8.4	2.6	1.1	2.8	0.22	0.018		659	100.5	1.76	34	7.5	11.2	42	31	23	2.6	5.2	1.2	6.5	2.3	
	A1278	51.0	12.7	15.2	4.7	8.5	2.5	1.2	2.8	0.21	0.018		597	99.0	1.79	36	7.8	10.9	40	28	24	2.9	6.7	1.6	7.1	2.1	
Elephant Mountain (Type Locality)	A1393	52.8	12.5	14.8	4.2	8.5	2.4	0.9	3.2	0.23	0.03	0.52	709	100.1	1.87	37	9.0	11.5	48	33	27	2.9	6.2			6.3	
	A1394	53.0	12.6	15.0	4.0	8.8	2.4	0.9	3.3	0.21	0.03	0.45	685	100.0													
	A1395	53.1	12.8	14.6	4.0	8.7	2.4	0.9	3.3	0.24	0.03	0.56	702	100.0													
	A1396	52.8	12.6	14.4	4.0	8.5	2.4	1.1	3.2	0.22	0.02	0.48	712	99.0													
	A1397	52.9	12.7	14.7	4.2	9.0	2.5	1.2	3.2	0.24	0.03	0.44	705	101.0													
Pomona (Type Locality)	A1266	52.6	14.4	11.0	7.6	9.7	2.4	0.7	1.6	0.19	0.016		637	100.3	1.59	21	4.5	8.1	40	32	100	1.7	5.2	1.0	3.1	1.1	
	A1267	52.8	14.9	11.0	8.2	10.4	2.3	0.7	1.6	0.19	0.017		405	102.1	1.64	20	5.0	8.0	41	33	102	1.3	4.6	1.3	3.2	0.9	
	A1268	51.8	14.3	11.1	7.9	10.3	2.5	0.7	1.6	0.18	0.016		435	100.5	1.69	19	4.6	7.8	43	33	103	1.7	4.8	0.9	3.0	1.0	
	A1269	52.8	14.7	10.9	7.9	10.2	2.4	0.8	1.6	0.18	0.016		433	101.6	1.61	19	5.1	8.2	41	33	106	1.3	6.0	1.3	3.4	1.0	
	A1270	52.3	14.6	10.8	7.5	10.4	2.6	0.5	1.5	0.17	0.016		575	100.4	1.66	18	4.5	8.0	43	34	104	1.7	6.8	0.8	2.9	1.1	
Gable Mountain (Esquatzel) (Type Locality) (Core Wells) DDH-1, DB-1, DB-2, DDH-3)	K1005	52.7	13.2	14.1	4.2	7.0	2.9	1.5	2.8				558	98.4													
	K1025	53.4	13.2	13.0	4.2	7.2	2.9	1.3	2.6				663	97.6													
	K1026	53.4	13.2	13.4	4.1	7.3	2.9	1.3	2.6				674	98.2													
	A1037	52.7	13.4	13.2	4.2	7.2	2.7	2.0	2.4				790	97.9													
	A1038	52.7	13.1	13.8	4.0	8.7	2.6	1.5	2.6				639	99.2													
	A1039	52.5	12.9	13.4	4.1	8.0	2.7	1.5	2.6				690	97.8													
	A2017	55.5	13.0	15.3	4.3	7.6	2.7	1.8	2.9				605	103.2	1.91	38	11.4	11.0	45	31	8.3	2.3	8.6	1.0	5.8	2.2	
	A2018	55.0	13.8	14.5	4.2	8.0	2.8	1.6	2.5				642	102.5	2.09	37	8.4	10.9	42	27	9.1	2.3	9.0	1.2	6.2	2.2	
	A2019	54.0	13.3	14.9	3.9	7.4	2.6	1.7	2.6				713	100.6	2.05	38	8.2	10.5	42	28	5.0	2.5	8.2	1.1	5.0	2.0	
	II	D1007	53.6	13.1	11.5	4.0	7.9	2.9	1.6	2.6	0.17		0.32	813	97.8	1.98	36	7.1	9.2	40	27	26	2.1	8.1		6.9	
I	D1008	53.3	13.4	11.8	4.0	7.8	3.0	1.6	2.7	0.18		0.32	926	98.2	1.96	36	7.0	9.3	39	27	21	2.1	8.9		7.1		
	D1009	54.0	13.3	12.2	4.0	7.8	3.2	1.7	2.8	0.18		0.33	909	99.6	1.99	36	7.1	9.8	42	28	11	1.9	9.5		7.5		
	D2009	54.1	13.0	11.2	3.7	7.4	3.0	1.6	2.5	0.18		0.28	847	97.1	2.26	42	8.3	11.1	48	31	8	2.7	9.5		9.6		
	D1010	53.2	14.7	12.6	4.1	8.2	3.0	1.4	3.0	0.18		0.31	921	100.8	1.95	34	7.0	10.0	45	29	23	2.0	7.4		6.3		
Huntzinger (Type Locality)	A1301	52.6	15.4	10.7	6.9	9.0	2.4	1.0	1.6				585	99.7	1.74	24	5.7	8.0	41	28	163	1.8	6.4	0.9	4.6	1.0	
	A1302	52.6	15.5	10.8	7.2	9.0	2.4	1.0	1.6				497	100.2	1.79	24	6.2	8.1	41	28	181	1.6	6.2	0.9	4.3	1.0	
	A1303	52.6	15.6	10.6	7.2	9.1	2.4	1.0	1.7				603	100.2	1.75	25	5.8	8.1	42	28	173	2.1	6.5	1.2	5.0	1.1	
	A1304	52.6	15.3	10.8	7.1	9.1	2.4	1.0	1.6				531	99.9	1.76	23	6.1	8.1	43	27	188	1.6	6.4	1.1	4.4	1.0	
	A1305	52.9	15.2	10.6	6.8	9.0	2.6	1.0	1.6				603	99.9	1.86	25	5.8	7.7	40	27	168	1.7	6.3	0.7	5.1	0.9	
(Core Well DH-4)	A4010	53.1	13.9	11.0	5.9	9.2	2.4	0.9	1.8	0.17	0.030		789	98.6	1.63	35	5.8	7.9	38	27	111	1.5	5.1	0.96	5.6	1.0	
	A4011	51.9	14.6	11.5	6.3	9.3	2.4	0.9	1.6	0.18	0.028		666	98.7	1.55	33	5.5	7.7	40	26	125	1.7	2.2	1.1	5.6	1.6	
	A4012	50.4	16.0	10.1	9.5	10.6	2.3	0.1	1.3	0.17	0.025		472	100.5	1.46	13	3.0	6.8	42	30	295	1.1	0.43	0.84	3.5	0.82	
	A4013	50.6	15.9	10.2	9.1	10.7	2.2	0.3	1.4	0.17	0.026		375	100.6	1.46	13	3.2	6.9	45	28	269	1.0	0.90	0.45	2.8	1.0	
	A4014	51.6	15.3	10.8	7.7	9.8	2.4	0.8	1.6	0.17	0.028		531	100.3	1.68	26	4.7	7.7	39	26	173	1.4	1.3	0.88	5.0	1.2	
	A4015	52.1	14.2	11.7	6.1	9.0	2.4	1.4	1.7	0.17	0.030		791	98.9	1.72	35	5.9	8.1	37	26	97	1.7	2.8	1.2	7.1	1.7	
	Wahluke (Warden?) (Core Well DH-4)	A4016	53.5	14.0	11.7	5.1	8.2	2.8	2.0	1.8	0.19	0.029		1089	99.4	1.82	45	7.2	8.5	37	25	31	1.7	3.0	1.1	7.1	1.7
A4017	53.7	13.8	12.4	5.4	8.2	2.8	1.9	1.8	0.18	0.030		1011	100.2	1.80	42	6.3	8.9	38	26	41	2.1	3.4	1.4	7.9	1.7		
Sillusi-Umatilla (Type Locality)	A1214	54.2	13.2	12.6	3.6	5.8	3.4	2.9	2.4				4119	98.1													
	A1216	56.6	14.2	12.4	2.6	6.0	3.2	2.6	2.6				3541	100													

selected petrographic and geophysical data have been used for identification, characterization, and correlation of basalt flows and sequences of flows. Table IV shows the results of $^{40}\text{K}/^{40}\text{Ar}$ age dating. Problems were experienced with reliability of results due to alteration of the minerals in the basalt. This alteration caused a loss of argon from the original minerals as well as a loss of potassium and the formation of secondary minerals. The loss of argon would generally lead to younger than actual dates. All samples were examined by thin section to evaluate suitability for dating, and only those with fresh or only moderate alteration were used.

INTERPRETATION

The results shown in Table III combined with the geophysical logs (Appendix D) and the petrographic information were used to identify individual flows. The main identifying features are shown in Table V. The geochemical "signature" stresses compositional differences. The petrographic description emphasizes petrographic differences between members and between flows within members. The geophysical log responses reflect differences in physical and chemical properties of rock and the entrained fluid.

The geochemical data appear to give the most promising single means for identifying individual flows and members. Table VI summarizes one scheme for arranging geochemical criteria in such a manner that flows or members can be identified using a chemical analysis. It must be emphasized that Table VI was constructed using the currently available type locality chemical data only (Table III). It merely shows one scheme by which geochemical data can be

STRATIGRAPHIC UNIT	RANGE OF DATES IN MILLIONS OF YEARS	PROBABLE DATE
ICE HARBOR I FLOW	7.9-11.3	8.5
ELEPHANT MT. MEMBER	8.1-12.0	9.5
POMONA MEMBER	7.7-13.3	10.5
GABLE MT. MEMBER	10.3-12.9	
HUNTZINGER FLOW	10.8-12.9	
WAHLUKE FLOW	12.7	12.7
UMATILLA MEMBER	12.0-15.0	14.1
PRIEST RAPIDS IV FLOW	13.1-16.2	14.9
PRIEST RAPIDS I, II & III FLOWS	11.9-15.5	
ROZA MEMBER	12.5-16.3	

V7608-27.2

TABLE IV
RADIOGENIC AGES OF BASALT FLOWS

TABLE V
MAIN. IDENTIFYING GEOCHEMICAL, PETROGRAPHIC,
AND GEOPHYSICAL SIGNATURES OF INDIVIDUAL STRATIGRAPHIC UNITS

Stratigraphic Unit		Geochemical Signature Based on Type Locality Data (all oxide values are in percent)	Petrographic Description	Geophysical Description
ICE HARBOR MEMBER	ICE HARBOR II	MgO < 5.8, TiO ₂ ≥ 2.2, K ₂ O < 1.4 FeO ≥ 16.4 and TiO ₂ ≥ 3.3	sparse plagioclase phenocrysts, rare Fe-Ti oxide phenocrysts	(Not present in any boreholes)
	ICE HARBOR I	MgO ~ 7, TiO ₂ > 3.1	phenocrysts of plagioclase, augite and olivine up to 2 cm.	Dense. Porosity and moisture grades from top to center of the flow. Natural gamma radioactivity is lower than most basalts (similar to Pomona II and Priest Rapids IV).
ELEPHANT MOUNTAIN MEMBER	LEVEY* INTERBED	Tuff and Tuffaceous Sandstone		Low density, high porosity and moisture. High natural gamma radioactivity.
	WARD GAP	MgO < 5.8, TiO ₂ > 2.8, K ₂ O ≤ 1.4, FeO < 16.4, TiO ₂ /MgO < 0.75, Cr 20-25 ppm, La 34-36 ppm	High apatite content, scattered pyroxene microphenocrysts and plagioclase microphenocrysts rich in pyroxene inclusions	Low density at top and bottom grading to medium density. Porosity and moisture grades from top and bottom decreasing to the center of the flow. Natural gamma radioactivity is lower than that of the Middle Yakima Basalt and greater than that of Pomona.
	ELEPHANT MOUNTAIN	MgO < 5.8, TiO ≥ 2.2, K ₂ O < 1.4, FeO < 16.4, TiO ₂ /MgO ≥ 0.75, CaO Average > 8.5	Similar to the Ward Gap	Low density at top grading rapidly to high density. Porosity and moisture grades from top to bottom, decreasing with depth. Natural gamma radioactivity increases with depth and is equal to or greater than that of the Middle Yakima Basalt.
POMONA MEMBER	RATTLESNAKE RIDGE INTERBED	Sandstone, tuffaceous sandstone and clay; equivalent to the upper Ellensburg to the west and upper Beverly to the northeast		Low density. High porosity and moisture. High natural gamma radioactivity.
	POMONA I* AND II*	MgO > 5.8, TiO ₂ < 2.2, Cr 100-106 ppm, Sc 32 - 36 ppm	Plagioclase phenocrysts up to 2 mm crowded with inclusions of pyroxene, glass, and mineraloid, and having an inclusion-free rim; plagioclase/ pyroxene ratio 0.9-1.1	<u>Pomona II</u> High density with gradational density at top. Porosity and moisture decreases with depth through 50% to 75% of the flow thickness then increases in the bottom 15% of the flow thickness. Natural gamma radioactivity lower than that of Pomona I. Natural gamma radioactivity of Pomona and Huntzinger flows is lowest of all Yakima Basalts. <u>Pomona I</u> High density, decreasing slightly toward bottom. Low porosity and moisture, increasing slightly toward bottom. Low natural gamma radioactivity but slightly higher than Pomona II and Huntzinger.
GABLE MOUNTAIN (ESQUATZEL ?) MEMBER *	SELAH INTERBED	Tuff and tuffaceous sandstone equivalent to the lower Beverly to the northeast		Low density layered interbed with density lowest in the center. High porosity and moisture. High natural gamma radioactivity that increases stepwise with depth.
	GABLE MOUNTAIN I* AND II* (ESQUATZEL ?)	MgO < 5.8, TiO ₂ ≥ 2.2, K ₂ O ≥ 1.4, Th > 7.3 ppm	Plagioclase phenocrysts up to 3 cm (Thin sections of this flow have not yet been studied).	<u>Gable Mountain II</u> Moderate density increasing to high density with depth. Low porosity and moisture decreasing with depth. High natural gamma radioactivity. <u>Gable Mountain Tuff</u> Low to medium density increasing with depth. Medium interstitial porosity and moisture. Medium natural gamma radioactivity that peaks and then decreases with depth. <u>Gable Mountain I</u> Low density (for basalt). High porosity and moisture increasing slightly with depth. Medium natural radioactivity.
HUNTZINGER MEMBER	COLD CREEK* INTERBED	Sandstone with tuff, sand, and gravel		Low density, high porosity and moisture. Medium to high natural gamma radioactivity.
	HUNTZINGER	MgO ≥ 5.8, TiO ₂ < 2.2, Cr 163- 188 ppm, Sc 27-28 ppm	Ophimottled texture locally well- developed, concentration of olivine toward base of the flow in thick sections	High density at top to medium density at bottom, generally in two or more steps. High porosity but low moisture. Natural gamma radioactivity is lowest of all basalt flows in upper portion but increases significantly toward base.
	WAHLUKE* (WARDEN ?)	MgO < 5.8, TiO ₂ < 2.2, K ₂ O ≥ 1.6	Not yet studied	Erratic density medium to high. Porosity and moisture increases gradationally from center to top and bottom. Natural gamma radioactivity is high and increases gradationally with depth.

TABLE V
MAIN IDENTIFYING GEOCHEMICAL, PETROGRAPHIC,
AND GEOPHYSICAL SIGNATURES OF INDIVIDUAL STRATIGRAPHIC UNITS
(Continued)

Stratigraphic Unit	Geochemical Signature Based on Type Locality Data (all oxide values are in percent)		Petrographic Description	Geophysical Description
UMATILLA MEMBER	SILLUSI AND UMATILLA	Ba $\geq$ 3000 ppm	Plagioclase/pyroxene ratio is 2.5-6.0, high compared to other Yakima basalt flows.	Sillusi Low density at top of flow increasing to high density in 15 to 20 feet. High porosity and high moisture decreasing abruptly to moderate to low. High natural gamma radioactivity exceeded only by its companion, the Umatilla. Umatilla High density, low porosity, low moisture. High natural gamma radioactivity. (Gable Mt. II, Wahluke, Sillusi and Umatilla have highest gamma radioactivity of all basalt flows).
PRIEST RAPIDS MEMBER	MABTON INTERBED	Sandstone with some gravel		Low density, high porosity, high moisture. Natural gamma radioactivity tends to be lowest of all interbeds and lower than many basalt flows.
	PRIEST RAPIDS IV	MgO 6.0-6.5, TiO ₂ $\geq$ 2.2 Cr > 70 ppm, Chemically different from the other Priest Rapids	Very rare plagioclase phenocrysts	High density. High porosity and moisture near bottom. Low natural gamma radioactivity at top of flow grading to medium at bottom.
	PRIEST RAPIDS III II I	MgO < 5.8, TiO ₂ $\geq$ 2.8 K ₂ O $\leq$ 1.4, FeO < 16.4, TiO ₂ /MgO < 0.75, Cr $\leq$ 20 ppm, La 20-32 ppm, Chemically similar to Roza and Frenchman Springs Flows	Very rare plagioclase phenocrysts	Thickness and presence varies from borehole to borehole. Tends toward very high and consistent density when flows are thick. Low porosity and moisture. Medium natural gamma radioactivity.
	QUINCY INTERBED	Sandstone with clay and diatomaceous material		Low density, high porosity, high moisture, high natural gamma radioactivity in limited locations (not always distinguishable from adjacent basalt)
ROZA MEMBER	ROZA	MgO < 5.8, TiO ₂ 2.4-3.2, K ₂ O $\leq$ 1.4, FeO < 16.4, TiO ₂ /MgO < 0.75 and Cr > 30 ppm. Chemically similar to Priest Rapids I, II, III, and Frenchman Springs Flows	Abundant 5-10 mm, lath-shaped euhedral plagioclase phenocrysts; olivine microphenocryst content $\leq$ 0.5%	Density is variable within flows ranging from medium to high. Porosity and moisture is also variable ranging from low to high. Natural gamma radioactivity is medium.
FRENCHMAN SPRINGS MEMBER	SQUAW CREEK	Diatomite		Not distinguishable (moderate density, high porosity, high moisture).
	SENTINEL GAP	MgO < 5.8, TiO ₂ 2.6-2.7, K ₂ O < 1.4, FeO 14.4-14.9, TiO ₂ /MgO < 0.75 and Cr 18-29 ppm. Chemically similar to Priest Rapids I, II, and III.	Sparse plagioclase phenocrysts; olivine content 1.5-3.5%	Density is variable within flows ranging from medium to high. Porosity and moisture is also variable ranging from low to high. Natural gamma radioactivity is medium.
	SAND HOLLOW	Chemically similar to Roza and Priest Rapids I, II, and III.	Sparse plagioclase phenocrysts; olivine content 2-5%	Density is variable within flows ranging from medium to high. Porosity and moisture is also variable ranging from low to high. Natural gamma radioactivity is medium.
	GINKO	MgO < 5.8, TiO ₂ $\geq$ 2.7, K ₂ O < 1.4, FeO 14.7-15.2, TiO ₂ /MgO < 0.75, Cr 17-33 ppm	Abundant plagioclase glomeroporphyrictic clots up to 2.5 mm in diameter. Negligible olivine microphenocrysts compared to Roza	Density is variable within flows ranging from medium to high. Porosity and moisture is also variable ranging from low to high. Natural gamma radioactivity is medium.
VANTAGE SANDSTONE FORMATION*		Weakly cemented sandstone		Low density, high porosity, high moisture. Natural gamma radioactivity is consistently high in all boreholes.
MUSEUM MEMBER		MgO < 5.8, TiO ₂ < 2.2, K ₂ O < 1.6, Sa $\sim$ 4.7, Co $\sim$ 39 ppm.	Sparse inclusion-rich plagioclase microphenocrysts, ophimottled texture, diktytaxitic cavities. Plagioclase/pyroxene ratio 1.23-1.54	Very uniform. High density, low porosity, low moisture.
ROCKY COULEE MEMBER		MgO < 5.8, TiO ₂ < 2.2, K ₂ O < 1.6, Sa 5.4-5.9 ppm, Co 34-36 ppm.	Not completed	Very uniform. High density, low porosity, low moisture.

*Informally used name stratigraphic rank

TABLE VI
 CRITERIA FOR GEOCHEMICAL IDENTIFICATION USING
 TYPE LOCALITY DATA (TABLE III) ONLY

1. <u>Check for Barium</u>	
a) If Barium ≥ 3000 ppm	Sillusi - Umatilla
b) If Barium < 3000 ppm	Upper, Middle or Lower Yakima Basalt except the Sillusi-Umatilla
2. <u>Check for MgO and TiO₂</u>	
a) If MgO ≥ 5.8 and TiO ₂ ≥ 2.2	
i MgO 6.0-6.5 and Cr > 70 ppm	Priest Rapids IV
ii MgO ~ 7.0 and TiO ₂ > 3.1	Ice Harbor I
b) If MgO ≥ 5.8 and TiO ₂ < 2.2	
i Cr 163-188 ppm, Sc 27-28 ppm	Huntzinger
ii Cr 100-106 ppm, Sc 32-34 ppm	Pomona
c) If MgO < 5.8 and TiO ₂ < 2.2	
i If K ₂ O ≥ 1.6	Wahluke (Warden?)
ii If K ₂ O < 1.6	
aa) Samarium ~ 4.7 ppm Cobalt ~ 39 ppm	Museum
bb) Samarium 5.4-5.9 ppm Cobalt 34-36 ppm	Rocky Coulee
d) If MgO < 5.8 and TiO ₂ ≥ 2.2	
i If K ₂ O > 1.4 Thorium > 7.3	Gable Mountain (Esquatze?)
ii If K ₂ O ≤ 1.4	
aa) If FeO ≥ 16.4 and TiO ₂ ≥ 3.3	Ice Harbor II
bb) If FeO < 16.4	
bb-1 If TiO ₂ /MgO ≥ 0.75 CaO average $> 8.5\%$	Elephant Mountain
bb-2 If TiO ₂ /MgO < 0.75	
If TiO ₂ ≥ 2.8 and Cr < 25 ppm	
a If Cr ≥ 20 , La 34-36 ppm, CaO average $\leq 8.5\%$	Hard Gap
b If Cr ≤ 20 La, 20-32 ppm	Priest Rapids I, II, III
If TiO ₂ ≥ 2.8 and Cr > 25 ppm	Roza
If TiO ₂ < 2.8 and Cr < 25 ppm	
a If average FeO ≤ 14.8	Sentinel Gap
b If average FeO > 14.8	Ginkgo
If TiO ₂ < 2.8 and Cr > 25 ppm	
a If Cr > 40 ppm	Roza or Sand Hollow
b If Cr < 40 ppm	
If average FeO ≤ 14.8	Sentinel Gap
If average FeO > 14.8	Ginkgo

These flows are
apparently very
similar in
chemistry. Dis-
tinguishing them
from each other
is difficult
using chemical
data alone.

used to identify flows; other schemes have also been used. This approach cannot be used as a sole criteria by itself for identifying flows and members because the data base on which the scheme is based is insufficient, i.e., a particular flow or member may not have been sampled sufficiently and chemically analyzed at its type locality to adequately measure the range of variability of the chemical constituents within the flow or member. Consequently, a multi-criteria approach has been used in the actual identification of flows and members in the core holes: geochemical, petrographic, and geophysical data are all used and combined with stratigraphic relationships to arrive at the most likely name for a particular flow or member. The names and correlations are given in Chapter IV.

The age dating information (Table IV) shows that the most recent basalt flow is about 8.5 million years B.P. (before present), and that the ages increase progressively in all core holes down to the Roza, which is about 15 million years B.P. (Table IV). The apparent ages of the samples below the Roza range in erratic fashion from about 11 to 15 million years B.P. Investigations as to the cause for the erratic relationship between potassium-40 and argon-40 revealed that the variation in apparent age increased as the glass content increased and was highly erratic in those samples in which the glass had altered to palagonite.

RECOMMENDATIONS

The geochemical characterization criteria supported by petrographic and geophysical studies should be applied to future stratigraphic studies in the Columbia River flood basalts.

Additional chemical data are needed to reduce the analytical error and thereby improve the accuracy and reliability of the data base, and to correct existing deficiencies in the data base.

Additional parameters, such as mineral compositions, isotope compositions, and paleomagnetic polarities need to be measured and used for additional flow identification criteria and to test existing identifications and correlations.

REFERENCES

1. A. C. Waters, "Stratigraphic and Lithologic Variations in the Columbia River Basalt," Am. Jour. Sci., 259, p. 583-611, 1961.
2. D. A. Swanson, "Yakima Basalt of the Tieton River Area," South Central Washington, Geol. Soc. America Bull., 78, p. 1077-1110, 1967.
3. H. U. Schmincke, "Stratigraphy and Petrography of Four Upper Yakima Basalt Flows in South Central Washington," Geol. Soc. America Bull., 78, p. 1385-1422, 1967.
4. D. A. Holmgren, K/Ar Dates and Paleomagnetism of the Type Yakima Basalt, Central Washington, Proceedings of the Second Columbia River Basalt Symposium, Eastern Washington State College Press, Cheney, Washington, p. 189-199, 1970.
5. M. Osawa and G. G. Goles, Trace Element Abundances in Columbia River Basalts, Proceedings of the Second Columbia River Basalt Symposium, Eastern Washington State College Press, Cheney, Washington, p. 55-71, 1970.

6. C. W. Myers and D. J. Brown, "Stratigraphy of the Yakima Basalt in the Pasco Basin, Washington," Geol. Soc. America, Abstracts with Programs, 5-1:80, 1973.
7. T. L. Wright, D. A. Swanson, and J. J. Grolier, "Chemical Variations Related to the Stratigraphy of the Columbia River Basalt," Geol. Soc. America Bull., 84, 371-386, 1973.
8. B. McKee and P. McKee, Refraction Index Data For Fused Glass from Basalt of the Columbia Plateau, Proceedings of the Second Columbia River Basalt Symposium, Eastern Washington State College Press, Cheney, Washington, p. 39-49, 1970.
9. J. H. Mackin, A Stratigraphic Section in the Yakima Basalt and the Ellensburg Formation in South Central Washington, Washington Division of Mines and Geology, Invest. Report, 19:45, 1961.
10. W. H. Zimmer, "An Anticoincidence Guarded, (Li) Detector for Environmental Level Gamma Energy Analysis," US-AEC Report, ARH-SA-101, Atlantic Richfield Hanford Company, September 1971.

CHAPTER IV

STRATIGRAPHY OF THE PASCO BASIN

SUMMARY

The stratigraphy of the Pasco Basin as it is currently understood is based on the correlation of basalt flows, members, and interbeds which have been identified and traced using their geochemical, petrographic, and geophysical properties.

The stratigraphy has been generalized because of the limited number of sample points; nonetheless, the data appear to be self-consistent in a broad sense over a relatively large area.

THE STRATIGRAPHIC COLUMN

The approximate ages, stratigraphic positions, and descriptions of the rocks within the Pasco Basin are summarized in the chart shown in Figure 6, Chapter II, and in Table V, Chapter III. This stratigraphic chart is under revision, but for purposes of this discussion, it is used in its present form.

The Yakima Basalt Formation of the Columbia River Basalt Group, has been subdivided^[1] into three informal stratigraphic units: the lower Yakima Basalt, the middle Yakima Basalt, and the upper Yakima Basalt. Sedimentary interbeds are intercalated with the basalts. In the Pasco Basin more than ten sedimentary interbeds have been identified in deep core holes. One of these interbeds, the Vantage Sandstone, has been informally given formational

status by ARHCO researchers (Figure 6, Chapter II and Table V, Chapter III), because of the marked difference between the chemistry of the basalts above and below.

The middle and upper Yakima Basalts, which occur stratigraphically above the Vantage Sandstone, are divided into nine members. Each member consists of one or more individual basalt flows. The lower Yakima Basalt flows, which occur stratigraphically below the Vantage Sandstone, can be divided into at least two stratigraphic units (chemical types) on the basis of marked differences in chemistry. The lowermost unit, the LOW Mg - HIGH K chemical type, consists of at least 20 flows identified in core holes DH-4 and DH-5. The uppermost unit, the HIGH Mg chemical type, consists of 7 to 13 flows, also identified in DH-4 and DH-5. In addition, surface outcrops of these two units have been identified at Sentinel Gap, Selah Butte, and Umtanum Ridge (Figure 2, Chapter II).

Two flows in the bottom of DDH-3, the LOW Ti - LOW K chemical type on Figure 6, Chapter II, may not be lower Yakima Basalt, their affinity to other Columbia River Basalt Group units is unknown.

CORRELATION OF YAKIMA BASALT MEMBERS AND FLOWS IN THE PASCO BASIN

The geochemical, petrographic, and geophysical properties that characterize and distinguish the members and certain individual flows of the Yakima Basalt in the Pasco Basin have been discussed (Chapter III, Tables III and V). These properties plus stratigraphic relationships were used to correlate basalt units from their type localities to the field sections and between the core holes. A common

procedure for establishing correlations was as follows: type locality geochemical and petrographic data were used to establish criteria by which basalt units could be characterized as uniquely as possible (Table V and Table VI, Chapter III), their geochemical and petrographic data from flows in the core holes were compared with the type locality data until the best possible correlation was found. A good correlation was not always found and some correlations remain questionable. Correlations of basalt units stratigraphically below the Vantage Sandstone horizon are generally more questionable than correlations of basalt units stratigraphically above the Vantage Sandstone horizon because of the overall chemical and petrographic similarity of the basalt units below the Vantage Sandstone. Geophysical criteria were also used to establish correlations between core holes; this probably makes the correlations of the basalt units between the core holes stronger than the correlations between the core holes and the type localities.

The importance of stratigraphic relationships cannot be emphasized enough. For example, if analysis A2108 from core hole DDH-3, is taken through the scheme shown on Table VI of Chapter III, the basalt from which this analysis was made might be mistakenly identified as the Wahluke flow of the Huntzinger Member (this is a common mistake for those using single criteria for the identification). However, examination of the stratigraphic position of the flow from which sample A2108 was taken readily reveals that it cannot possibly be correlative with the Wahluke flow. The Wahluke flow is stratigraphically above the Vantage Sandstone horizon (easily identified by the sharp contrast in $\text{TiO}_2\%$ in flows above and below) and between the Pomona and Umatilla Members (also easily identified). The flow from which sample

A2108 was taken, however, is below the Vantage Sandstone horizon and within the LOW Mg - HIGH K chemical type (Figure 6, Chapter II).

One of the nine members above the Vantage Sandstone could be uniquely identified on the basis of a single element (barium in concentrations exceeding 3000 ppm for the Umatilla Member). The two flows that comprise this member can also be distinguished in the field sections and core holes on the basis of lithologic and petrographic differences. Most flows within the remaining members can be distinguished from one another on the basis of their minor element and major oxide concentrations as noted in the preceding chapter.

Two distinct horizons were observed where a marked contrast in the chemical composition of the flows above and below the horizon occurs. One horizon, as noted above, is the Vantage Sandstone. All of the flows below this horizon contain less than 1.8% TiO_2 and most flows above contain 2.4-2.6% TiO_2 . The second horizon identified is from 7 to 12 flows below the Vantage Sandstone in DH-4 and DH-5. In this horizon a chemical change occurs in the concentration of MgO and K_2O within the flows. This is the contact between the HIGH Mg chemical type and the LOW Mg - HIGH K chemical type.

STRUCTURE AND STRATIGRAPHY

A map showing the contours on the surface of the basalt in the Pasco Basin is given in Figure 1. This map also shows the position of sections constructed through the Pasco Basin (Figures 2 and 3). The major synclinal and

FIGURE 1
 MAP SHOWING THE CONTOURS ON THE
 SURFACE OF THE BASALT IN THE PASCO BASIN

FIGURE 2
GENERALIZED CROSS SECTION A-A'
PARALLEL TO THE MAIN AXIS OF THE PASCO BASIN

FIGURE 3

GENERALIZED CROSS SECTION B-B'
NORMAL TO THE MAIN AXIS OF THE PASCO BASIN

V7607-13.30

anticlinal axes can be inferred from the shape of the contour lines.

The general trend in the structures shown in the western portion of the region is east-west. In the eastern portion, the structural trend changes to a southeasterly direction. The Rattlesnake Hills, Yakima Ridge, Umtanum Ridge-Gable Mountain, and Saddle Mountains all tend to converge with the Horse Heaven Hills near Wallula Gap.

Two geologic cross-sections show the relationship of the several basalt members of the Columbia River Basalt Group to each other (Figures 2 and 3). Cross-section A-A' parallels the main axis of the Pasco Basin and section B-B' is normal to it.

The cross-sections show that the youngest member (Ice Harbor) is apparently restricted to the eastern part of the Pasco Basin. The next youngest member (Elephant Mountain) has been identified in outcrops on or near the crest of the Horse Heaven Hills, Rattlesnake Mountain, Gable Mountain, and Saddle Mountain. West of the Hanford Reservation, Umtanum Ridge rises to an elevation of more than 1000 m above sea level and the basalt capping the crest of the ridge is either the Roza Member or the Frenchman Springs Member. It is not known whether Umtanum Ridge was one of the first anticlines to develop in the region and flows younger than the Roza Member are not found there because of nondeposition, or whether Umtanum Ridge formed later and flows younger than the Roza Member were eroded from the crest. Eastward along the Umtanum Ridge-Gable Mountain structure the members capping the crest of the structure are progressively younger.

Five basalt units have been identified over most of the Pasco Basin: (1) the LOW Mg - HIGH K chemical type, (2) the LOW Mg chemical type, (3) the Frenchman Springs Member, (4) the Roza Member, and (5) the Pomona Member. The number of flows or flow units within these members changes significantly across the basin. For example, five flows occur within the Frenchman Springs Member and seven flows within the HIGH Mg Member on the south flank of Saddle Mountain; however, in core hole DDH-3 near the center of the Pasco Basin, 12 flows occur in the Frenchman Springs Member and 13 flows in the HIGH Mg chemical type unit. Conversely, the Umatilla and Gable Mountain Members are present in core hole DDH-3 but have not been found on Saddle Mountain.

REFERENCES

1. T. L. Wright, J. J. Crolrier, D. A. Swanson, "Chemical Variations Related to the Stratigraphy of the Columbia River Basalt," Geol. Soc. Amer. Bull., v. 84, p. 371-386, 1973.

CHAPTER V

HYDROLOGY

SUMMARY

The hydrology of the Hanford Reservation has been studied extensively in recent years.^[1] The area is underlain by an unconfined aquifer composed of sediment of the Ringold Formation and glaciofluvial material. The unconfined aquifer overlies a series of confined aquifers including portions of the Lower Ringold Formation and interbeds of the Columbia River Basalt Group. The confined aquifers above the Vantage Sandstone (see Chapter on "Stratigraphy" for nomenclature) are termed the uppermost confined aquifers.

Studies at Hanford have centered on the unconfined and uppermost confined aquifers. The hydraulic conductivity of the former is much greater than that of the latter. Flow in all of these aquifers is greatly affected by the behavior of the Columbia River where they discharge their waters. The unconfined aquifer flow pattern has been affected by waste disposal operations at Hanford. The water table has risen under waste disposal sites and contaminants resulting from waste processing have been found in samples from the unconfined aquifer. Total water flow through this aquifer in the Hanford area is small.

The uppermost confined aquifers within the Hanford Reservation are locally unimportant except for the Mabton Interbed and the Quincy Interbed. The latter has not been studied within the Hanford Reservation. Recharge into these aquifers appears to occur at the ridges and plateaus

fringing the Pasco Basin. They are probably connected to the unconfined aquifer in areas where the basalts have been subjected to deformation and warping.

The hydraulic properties of the basalt flows and interbeds of the lower Yakima Basalts within the Hanford Reservation have been studied at only one site (Well ARH-CD-1, Figure 8). The lithology of these beds has been studied using geophysical data. The hydraulic conductivity of all beds sampled below the Vantage Sandstone is very small, especially for the dense basalts. The flows proper appear to act as barriers separating the various interbeds. The geochemistry of the waters in the lower Yakima Basalts appears to be controlled by the nature of the sedimentary interbeds and not the basalts themselves. Their composition appears to show an equilibrium with albite. Flow rates are very slow, thus supporting the low hydraulic conductivity values.

Some mathematical models are available for describing the hydrologic regime underlying the Hanford Reservation, especially the unconfined aquifer. A preliminary model of cavern leakage is available but has not been tested.

Additional information in the field of hydrology is needed to qualify basalts at Hanford as a viable medium for geologic storage. Such a program requires additional regional and local studies and development and testing of mathematical models.

INTRODUCTION

To demonstrate conclusively the feasibility of a proposed terminal storage project for nuclear wastes in the

Columbia River flood basalt requires that the hydrologic conditions in the prospective host rocks, the regional, and local groundwater flow regimes be known in unprecedented detail. This chapter summarizes the information currently available on the hydrology of the Hanford Reservation and points out the areas where additional information is needed.

SURFACE HYDROLOGY

The surface water bodies located within the boundaries of the Hanford Reservation consist of the Columbia River, various ditches, and ponds in and near the 200 Areas, and three ponds located in the 300 Area (Figure 1). Two ephemeral streams, Cold and Dry Creeks, appear only for a short time after a heavy rainfall or snowmelt. The Yakima River borders part of the Reservation's southern boundary.

The surface hydrology of the Hanford Reservation has been studied extensively.^[1-4] These studies include not only an analysis of the Columbia and Yakima Rivers, but also investigations as to the nature of a number of ditches and ponds that are used for the disposal of low-level radioactive liquid wastes, certain industrial wastes, and cooling waters from various processes. A complete list of the ditches and ponds, together with their physical dimensions and radioactive inventories, is given in the "Final Environmental Statement, Waste Management Operations, Hanford Reservation, Richland, Washington."^[1]

Average annual precipitation at Hanford is 15.9 centimeters. November, December, and January contribute 42 percent of the total; whereas July, August, and September contribute only 10 percent. A slight secondary maximum in

FIGURE 1

SURFACE WATER AREAS ON THE HANFORD SITE

precipitation occurs in early summer. About 45 percent of all precipitation during the months of December through February is in the form of snow. Runoff is essentially negligible.

The maximum expected yearly rainfall over the next 1,000 years is about 46 cm (a three-fold increase of the average yearly precipitation).

The probable maximum 24-hour precipitation that can be expected in the Hanford region at least once in a million years is 28 cm.^[5] The maximum recorded 24-hour precipitation has been 4.85 cm. Even the 28 cm, 24-hour downpour would not cause appreciably significant flooding of the 200 Areas.^[1]

REGIONAL HYDROLOGY

The regional geology of the Hanford Reservation, as discussed in preceding chapters, has been extensively studied and documented.^[1] From a hydrologic standpoint the area is composed of a series of confined aquifers (primarily basaltic interbeds of the Columbia River Group) overlain by an unconfined aquifer formed by permeable beds in the upper and middle Ringold and in the Pasco Gravels. Table I summarizes the hydrologic characteristics of the various stratigraphic horizons.

During the Tertiary Period the Columbia Plateau was the scene of numerous lava outpourings emanating from extensive fissure systems. The viscous fluids covered the surrounding terrain and flowed into the regional low areas such as the Pasco Basin. As basining continued, thick sections of basalt accumulated in these low regions.

TABLE I
HYDROSTATIGRAPHIC CHARACTERISTICS OF THE PASCO BASIN

GEOLOGIC TIME SCALE			GEOLOGIC CHARACTERISTICS					HYDROGEOLOGY	
ERA	PERIOD	EPOCH	RADIOGENIC DATE YEARS B.P.	STRATIGRAPHIC	BED OR FLOW UNIT	LITHOLOGIC CHARACTER	THICKNESS IN METERS	HYDROLOGIC CHARACTER	AQUIFER
CENOZOIC	QUATERNARY	HOLOCENE				SANDS, SILTS, GRAVELS & CLAYS MODIFIED BY WIND EROSION	DUNES TO 20	OCCUR EVERYWHERE ABOVE THE WATER TABLE	DRY
			6,600	ALLUVIUM, COLLUVIUM & EOLIAN SEDIMENTS	MAZAMA ASH	ASH FALL, CRATER LAKE, OREGON	.2-.3		
			10,000		GLACIER PEAK ASH	ASH FALL, GLACIER PEAK, WASHINGTON	.05		
			12,500						
		PLEISTOCENE	> 12,000 < 18,000	GLACIOFLUVIATILE SANDS & GRAVELS	ST. HELENS ASH	ASH FALL, MT. ST. HELENS, WASHINGTON	.05	OCCUR ABOVE THE WATER TABLE EXCEPT BETWEEN THE HIGH TERRACE PLATEAUS & THE COLUMBIA RIVER HAS VERY HIGH TRANSMISSIVITY & STORAGE	OCCASIONALLY AN UNCONFINED AQUIFER OR DRY
					TOUCHET SILTS	FINE GRAINED FACIES OF THE GLACIOFLUVIATILE DEPOSITS, BEDDED IN QUIET WATER			
			40,000		PASCO GRAVELS	PREDOMINANTLY COARSE GRAINED GRAVELS, COBBLES & SANDS WITH CUT & FILL STRUCTURE	0-120		
	TERTIARY	PLIOCENE		RINGOLD FORMATION	PALOUSE SOIL	CALCAREOUS SAND, & SILT EOLIAN DEPOSIT, MAINLY DERIVED FROM RINGOLD FM	0-25	OCCUR EVERYWHERE ABOVE THE WATER TABLE	DRY
					UPPER RINGOLD	LOCALLY CAPPED BY CALICHE, MOSTLY WELL-BEDDED FLUVIAL SILTS & SANDS WITH SOME GRAVELS	0-125	SAND & GRAVEL BEDS HAVE VERY HIGH HYDRAULIC CONDUCTIVITY & STORAGE SOME BEDS OF SILTY CLAY OR CLAY ARE ESSENTIALLY IMPERMEABLE	UNCONFINED AQUIFER
					MIDDLE RINGOLD	SANDS & GRAVELS, WELL SORTED, COMPACT BUT VARIABLY CEMENTED	0-125		
			1,000,000 1,500,000		LOWER RINGOLD	SILTS & CLAYS WITH INTERBEDDED GRAVELS & SANDS CLAY IS CHARACTERISTICALLY BLUE BUT MAY BE GREEN, BROWN OR TAN	0-125		
		MIOCENE		COLUMBIA RIVER BASALT GROUP	UPPER AND MIDDLE YAKIMA	BASALT FLOWS AND INTERBEDS, TUFF & TUFFACEOUS SANDSTONE	0-700	FLOWS ARE DENSE VERTICAL HYDRAULIC CONDUCTIVITY IN THE FLOW IS MODERATE DUE TO SHRINKAGE CRACKS HORIZONTAL HYDRAULIC CONDUCTIVITY & TRANSMISSIVITY OF INTERBEDDED SEDIMENTS IS MODERATE	<div> <div>CONFINED SYSTEMS</div> <div> AQUICLUDE AQUIFER AQUITARD AQUIFER AQUITARD AQUIFER </div> </div>
					VANTAGE SANDSTONE	WEAKLY CEMENTED SANDSTONE	0-10		
			11,000,000 15,000,000		LOWER YAKIMA	BASALT FLOWS & INTERBEDS	0-500		

Between periods of lava outpourings the existing basalt surfaces were subjected to various degrees of weathering and erosion. As a consequence, varying amounts of sediments accumulated on some of the basalt surfaces prior to being covered by later flows. Such sedimentary deposits now act as confined aquifers and are, in many cases, good water-producers. Confined groundwater present in these sedimentary interbeds may originate as far away as the Cascade Mountains to the west.

During Pliocene time the number and size of fissure eruptions decreased markedly and finally ceased. Even though the volcanic activity ceased, basining continued and was apparently accompanied by a regional north-south compression. As a result of the compressional forces acting on the basalt rocks, a number of east-west trending anticlinal ridges (e.g., Saddle Mountains) were formed in the western part of the Columbia Plateau. The rise of these ridges had a significant effect on the course of the Columbia River. Where the Columbia River was able to erode the basalt at a rate equal to or faster than the anticlinal ridges were rising, little change in the course of the Columbia River occurred. Where the ridges rose faster than the water was able to erode, the river was temporarily halted and the water formed a lake behind the ridges. As basining continued, such lacustrine and fluvial deposits continued to fill the Pasco Basin and covered the previously deposited basalts. These sedimentary deposits constitute the Ringold Formation. The upper portion of the formation presently comprises the steep cliffs exposed just east of the Columbia River, known as the White Bluffs.

The total thickness of the Ringold Formation in the Pasco Basin is about 330 m. It is characterized by clay

separating gravel lenses in the lower section, cemented gravels in the middle, and silts and sands in the upper part of the section. The Ringold sediments are well- to poorly- sorted and show a wide range of cementation. Locally the coarse muds and gravels possess a high permeability and are capable of storing vast quantities of groundwater. The clay and silty clay beds are generally impermeable under hydraulic gradients of ordinary magnitude. The water table over the western portion of the Hanford Reservation lies at the top of the Ringold Formation. However, between the high terrace plateaus and the Columbia River the water table rises above the Ringold sediments and intersects overlying permeable glaciofluvial deposits.^[1]

The gravel zones in the lower Ringold tend to constitute local confined aquifer systems overlain by clay zones and underlain by clay or basalt. The upper part of the Ringold and, in places, the overlying glaciofluvial sediments constitute the major unconfined aquifer underlying the Hanford Reservation.

Above the water table lies the unsaturated or vadose zone. This zone is composed of eolian and glaciofluvial material.

The critical factor that controls the nature of the unconfined aquifer within the Hanford Reservation is the extent of the Columbia River downcutting that took place during Ringold and post-Ringold times. Sizable paleochannels of high permeability were formed as a result of such downcutting. The nature and location of the paleochannels have been studied using a gravity survey.^[6]

THE UNSATURATED ZONE

The unsaturated (vadose) zone has been defined by the U.S. Geological Survey's Committee on Redefinition of Groundwater Terms^[7] as:

"...the zone between the land surface and the water table. Characteristically, this zone contains liquid water under less than atmospheric pressure, and water vapor and air or other gases usually at atmospheric pressure. In parts of this zone, interstices may be temporarily or permanently filled with water. Perched water bodies may exist within the unsaturated zone."

On the Hanford Reservation the thickness of the unsaturated zone varies from less than 1 m to more than 100 m.

The movement of water in the unsaturated zone is influenced by the physical properties of the sediments in two ways: (1) the size and structural arrangement of the sediment particles determine the space configuration through which the water moves, and (2) the interaction between the sediments and the water gives rise to water-moving forces. In sediments where pores are completely filled with water, the fluid is a single phase. Where water does not completely fill the pores, the water potential depends on the gravitational field and on the absorptive forces associated with the interfacial boundaries in the sediments. Where air partially fills the soil pores, with water occupying the remaining void space, a two-phase flow can take place. As the percentage of liquid water decreases, it occupies the smaller and smaller capillaries that exist between soil particles.

During the period August 1, 1973 through July 31, 1974, Hanford experienced 170 percent of normal rainfall. At a field test site located south of the 200 East Area, rainfall moisture penetration is measured by means of a lysimeter.^[8] The 170 percent of normal rainfall penetrated less than 6 m into the sediments. All moisture from rainfall during this rain year appears to have now evaporated to the atmosphere. In fact, the data indicate that more moisture has evaporated from the ground than was put in by rainfall during this rain year. The current lysimeter data show that Hanford sediments below a depth of about 9 m are extremely dry. In this desiccated zone the ability of the sediments to transmit water is significantly reduced.

THE UNCONFINED AQUIFER

The unconfined aquifer consists of both glaciofluvial and Ringold sand and gravel deposits. Since these materials are very heterogeneous, greater lithologic differences often appear within a given bed than between beds. The top of the aquifer at any one time is the water table^[9] (Figure 2). The unconfined aquifer bottom is the basalt bedrock in some areas and silt/clay zones of the Ringold Formation in other areas (Figure 3). The unconfined aquifer bottom has been determined using information from hundreds of wells drilled at Hanford. The hydraulic characteristics of the unconfined aquifer are quite variable and are summarized in Table II. The storage coefficient is not sufficiently well-known to plot its areal distribution; however, as a result of pump testing^[10] and from geologic studies, one can plot a map of the vertically averaged hydraulic conductivity distribution of the Hanford

FIGURE 2
HANFORD RESERVATION WATER TABLE MAP - DECEMBER 1975

FIGURE 3
UNCONFINED AQUIFER BOTTOM (OBTAINED FROM WELL SAMPLE DATA)

unconfined aquifer (Figure 4). There is a zone of high hydraulic conductivity apparent between Gable Butte and Gable Mountain down through the middle of the Reservation.

TABLE II

A. Hydraulic Conductivity of the Unconfined
Aquifer Material

Interval Tested	Hydraulic Conductivity	
	ft/day	m/day
Glaciofluviatile	500-20,000	150 - 5,100
Glaciofluviatile and Ringold	100- 1,000	30 - 300
Ringold (including clay)	1- 200	0.3- 60

B. Transmissivity of the Unconfined Aquifer

Region	Transmissivity	
	ft ² /day	m ² /day
North of Gable Butte and Gable Mountain	4,000- 25,000	370- 2,300
On the flank of Gable Butte and Gable Mountain and along paleochannels	40,000-600,000	3,700-56,000
Other areas of the Reservation	2,000- 40,000	185- 3,700

C. Storage Coefficient

Through the Reservation It Ranges from 0.05 to 0.4.

The impermeable boundaries of the unconfined aquifer within the Hanford Reservation and vicinity are the Rattlesnake Hills, Yakima Ridge, and Umtanum Ridge to the west and southwest (Figure 4). Gable Mountain and Gable Butte, as well as other small areas of basalt, outcrop above the water table and impede groundwater flow. The Yakima River recharges the unconfined aquifer along its reach from Horn Rapids to Richland. The Columbia River forms a hydraulic potential boundary in the Pasco Basin which is mainly a

FIGURE 4
VERTICALLY AVERAGED HYDRAULIC CONDUCTIVITY
DISTRIBUTION IN THE UNCONFINED AQUIFER

discharge boundary for the aquifer. However, the groundwater flow from 1 to 3 miles inland from the Columbia River is affected by seasonal river stage fluctuations.^[1]

The flow pattern that originally prevailed in the unconfined aquifer prior to waste discharges was primarily to the east and northeast with discharge into the Columbia River.^[1] Natural recharge occurs at the foot of Rattlesnake Hills and Yakima Ridge. Surficial flow sinks into the floor of the valley at the foot of and paralleling Rattlesnake Hills. Probably the underflow is to a great extent interrupted by a buried extension of Yakima Ridge which parallels Rattlesnake Hills at a distance of about 3 kilometers and which rises above the water table.

As a result of waste disposal activity at Hanford, the above-described natural groundwater pathways have been superimposed by three synthetic flow systems: (1) the 200 West Area, (2) the 200 East Area, and (3) Gable Mountain Pond (Figure 5).

The 200 West Area receives approximately one-third of the liquid disposed of at Hanford. Piezometers show that the flow from this area underflows that of the 200 East Area.^[11]

The flow systems of the 200 East Area and Gable Mountain Pond receive about two-thirds of the liquid waste disposed of at the Hanford Reservation. The input of these areas forms two 'local' flow systems within the 'intermediate' flow system of the 200 West Area. The Gable Mountain Pond flow system underflows the small system that results from recharge on Gable Mountain.

FIGURE 5
HANFORD RESERVATION REGIONAL FLOW SYSTEM

THE UPPERMOST CONFINED AQUIFERS

The uppermost confined aquifers consist of the lower Ringold Formation and the sedimentary interbeds of the upper and middle Yakima Basalts.^[12] From a hydrologic standpoint, locally the only important confined aquifers are the Mabton and Quincy Interbeds. The Mabton Interbed is below the Umatilla Member and atop the Priest Rapids Member of the Columbia River Basalt Group (refer to the chapter on 'Stratigraphy' for nomenclature). The Mabton Interbed locally ranges in thickness from 15 to 40 m. Interbeds within the middle Yakima Basalts are known to be productive aquifers but their hydraulic properties have not been studied.

The head in the uppermost confined aquifers is measured at periodic intervals in wells within the Hanford Reservation and its vicinity. Figure 6 shows the shape of the average head surface of these aquifers that gives an approximate picture of the regional flow system in these aquifers. Flow lines are perpendicular to equal head contours. In the Reservation variations in head between the various uppermost confined aquifers are only pronounced near the Columbia River (Figure 7), and in the Cold Creek Valley (Figure 1). Recharge into these aquifers appears to occur at the ridges and plateaus fringing the Pasco Basin with the discharge being toward the Columbia River. The entire eastern third of the Hanford Reservation appears to be a discharge area for the uppermost confined aquifers.

The hydraulic properties of the uppermost confined aquifers have been studied and reported by various investigators.^[1,12,13] Table III summarizes these properties.

FIGURE 6
AVERAGE HEAD SURFACE OF THE UPPERMOST CONFINED AQUIFERS

FIGURE 7

V7606-9.13

WATER LEVELS FOR THE UPPERMOST CONFINED AQUIFERS

TABLE III
HYDRAULIC CHARACTERISTICS OF THE UPPERMOST CONFINED AQUIFERS

Well Number	Transmissivity		Hydraulic Conductivity		Other Properties
	ft ² /day	m ² /day	ft/day	m/day	
LOWER RINGOLD					
699-84-35P	4	0.4	0.11	0.03	The porosity for the uppermost confined aquifers ranges between 0.3 and 0.4 (30 to 40%). The vertical hydraulic conductivity in the interbeds ranges between 5 x 10 ⁻⁴ m/day and 20 x 10 ⁻⁴ m/day. The storage coefficient approaches the compressibility of water.
699-24-1P	90	8.3	5	1.5	
699-S11-E12	40	3.7	0.5	0.15	
699-20-E12P	350	32	7	2.1	
Mean	120	11	3	0.91	
Range	4-350	0.4-32	0.11-7	0.03-2.1	
RATTLESNAKE RIDGE					
199-B3-2P	3.5	0.3	0.25	0.08	The storage coefficient approaches the compressibility of water.
199-H4-2	3	0.3	0.3	0.09	
699-14-E6Q	600	55	30	9.1	
Mean	200	18	10	3.0	
Range	3-600	0.3-55	0.25-30	0.08-9.1	
MABTON					
DH-8 Range	600-2000	55-180	20-60	5.0-20.0	

The uppermost confined aquifers are interconnected in places to the overlying unconfined aquifer. This is the case in areas where the basalts have been subjected to extensive warping, deformation, and differential erosion such as along the anticlinal axis that runs from Umtanum Ridge to Gable Mountain. In the vicinity of this anticline where the basalt flows are severely tilted and where the ancestral Columbia River has deeply eroded the flows, both the unconfined aquifer and the uppermost confined aquifers appear to be in hydraulic equilibrium.

HYDROLOGY OF THE LOWER YAKIMA BASALTS

From the standpoint of assessing the feasibility of establishing a permanent geologic repository of immobilized high-level waste at Hanford, the hydrology of the lower Yakima Basalts is of utmost importance. Geologic information on the lower Yakima Basalts is available from field studies ^[13,15] and from several wells within and adjacent to the Hanford Reservation (DDH-3, DH-4, DH-5, RSH-1, and ARH-DC-1) (Figure 8). Hydrologic tests have been conducted only in Well ARH-DC-1. This well lies on the north flank of the Cold Creek Syncline (Figure 8). The rock units dip southward in this area. The rocks analyzed appear to be structurally uncomplicated and exhibit a normal stratigraphic succession.

The lithology of the section of ARH-DC-1 has been interpreted using cores, geophysical, and drilling logs. On the geophysical logs competent, dense basalt shows a high electrical resistivity and density while sedimentary horizons show a low electrical resistivity and density.

Cutting and Drilling Rate logs can also be used to distinguish sections of resistant basalt from softer sediments.

Figure 9 shows a portion of several geophysical and drilling logs taken in Well ARH-DC-1. The Vantage Sandstone Formation shows as a very thin washout zone at a depth of about 625 m below the land surface. Below the Vantage Sandstone is the lower Yakima series of basalt flows and interbeds. Of special interest is the 'Umtanum' interval found at a depth of 915 m. Cores and geophysical logs of this interval demonstrate it to be a very tight, dense, glassy basalt flow nearly 60 m thick.

Direct measurements of head were taken in 1969 in discrete water-bearing zones in Well ARH-DC-1. These measurements were made using packers operated by a tool carried on a string of tubing that extends to the surface. The tubing can be connected hydraulically to the isolated zone after setting the packers, and the head in the zone can be measured as a depth-to-water in the tubing. Results are shown in Figure 10. Intervals tested in the lower Yakima Basalts down to 1310 m tend to either have the same head as intervals tested above this formation or have slightly lower heads. These intervals have very low permeabilities and since they were tested within one day after drilling was suspended, the heads may not have recovered from production of water during drilling.

Swabbing and injection tests were conducted by the USGS in Well ARH-DC-1 to determine the transmissivity and storage coefficient of selected intervals downhole.^[13] Laboratory analyses of hydraulic conductivity, porosity, compressive and tensile strength were obtained on five core samples from the lower Yakima Basalts (Table IV). The data obtained from these tests combined with lithologic information allow a definition of the hydraulic properties of

FIGURE 8

LOCATION OF WELL ARH-DC-1 IN RELATION TO THE
MAIN TECTONIC FEATURES OF THE HANFORD RESERVATION

FIGURE 9
PORTION OF SOME GEOPHYSICAL LOGS TAKEN IN
ARH-DC-1 DEPICTING THE LOWER YAKIMA BASALTS

APPROXIMATE UNDISTURBED GROUNDWATER HEAD FOR
ISOLATED WATER-BEARING ZONES IN WELL ARH-DC-1 (1969)

TABLE IV

SUMMARY OF LABORATORY ANALYSES OF ROCK CORES FROM TEST WELL ARH-DC-1

Core number	Depth (feet)		Hydraulic conductivity	Porosity (percent)	Compressive strength (unconfined)			Tensile strength (Reichmuth test)		
	From	To			Kgm cm ⁻²	Moisture content (vol. percent)	Sample diameter (cm)	Kgm cm ⁻²	Moisture content (vol. percent)	Sample diameter (cm)
6-----	2,381.4	2,384.6	1.3x10 ⁻⁸ cm/sec	9.8	1/738	6.2	5.38	28	6.2	5.38
			3.68x10 ⁻⁵ ft/day							
			2.76x10 ⁻⁴ gpd/ft ²					2/816	2.7	2.52
7-----	2,779.0	2,779.8	2.1x10 ⁻⁸ cm/sec	10.5	1892	3.8	2.52	300	3.6	2.53
			5.96x10 ⁻⁵ ft/day							
			4.46x10 ⁻⁴ gpd/ft ²		2425	4.0	2.52	339		2.53
8-----	2,946.8	2,950.1	1.1x10 ⁻⁸ cm/sec	3/25.4	240	28.6	5.37	60	28.5	5.38
			3.12x10 ⁻⁵ ft/day							
			2.34x10 ⁻⁴ gpd/ft ²							
13-----	3,127.1	3,128.0	6.7x10 ⁻⁹ cm/sec	2.1	1006	2.0	2.52	150	1.9	2.52
			1.9x10 ⁻⁵ ft/day							
			1.42x10 ⁻⁴ gpd/ft ²		3219	1.9	2.53	229	1.5	2.53
28-----	4,285.0	4,285.5	1.4x10 ⁻⁸ cm/sec	10.9	----	----	----	---	----	----
			3.97x10 ⁻⁵ ft/day							
			2.98x10 ⁻⁴ gpd/ft ²							

1/ Sample failed along a partially penetrating fracture surface not visible in the original specimen.

2/ Value undoubtedly too high as the result of using value of compressive strength from first specimen in calculation of tensile strength for second specimen.

3/ Porosity determined on small specimen apparently more dense than those used for other physical tests on Core 8.

the four basic lithology types found in the lower Yakima Basalts. Table V shows the typical hydraulic conductivity, transmissivity, effective porosity, and storage coefficient found for dense basalt, vesicular basalt, fractured basalt, and sedimentary interbeds in the lower Yakima Basalts at Well ARH-DC-1.

In 1972 five isolated piezometers (Figure 11) were installed in Well ARH-DC-1. Water level measurements have been taken during the past four years in these piezometers. Results are shown in Table VI and in Figure 12. The results point out a potential interconnection of the basalt and interbeds above 888 m. The flow regimes below 970 m appear connected down to 1480 m. Separating these two flow regimes lies the 'Umtanum' flow unit. At ARH-DC-1 the difference in head between the upper and lower flow regimes is presently about 2 m with the flow direction being apparently from the lower to the upper flow regime.

Little is known about the direction of migration of groundwater through the deep basalts and interbeds. Groundwater movement is influenced by both depositional structure of the rock and tectonic structures, chiefly folds and faults.

La Sala and Doty^[13] discuss the effect of tectonics on groundwater flow through the deep basalts and interbeds and the potential recharge and discharge areas. Their investigations, however, are based on meager data and the results remain unsubstantiated. It is clear, however, that the regional flow systems in the lower Yakima Basalts are extensive although probably the amount of water extractable from any one unit is likely to be small within the Hanford Reservation.

TABLE V
RANGE OF HYDROLOGIC PROPERTIES OF LOWER YAKIMA BASALT FLOWS AND INTERBEDS

	Hydraulic Conductivity		Transmissivity		Effective Porosity ^a	Storage Coefficient
	ft/day	m/day	ft ² /day	m ² /day	Dimensionless	Dimensionless
Dense basalt	1x10 ⁻⁵ -3x10 ⁻³	3x10 ⁻⁶ -9x10 ⁻⁴	1x10 ⁻⁴ -3x10 ⁻¹	9x10 ⁻⁶ -3x10 ⁻²	0.1-1	1x10 ⁻⁵ -1x10 ⁻⁶
Vesicular basalt	1x10 ⁻³ -1x10 ⁻²	3x10 ⁻⁴ -3x10 ⁻³	1x10 ⁻² -1	9x10 ⁻⁴ -9x10 ⁻²	5	<1x10 ⁻⁴
Fractured, weathered or brecciated basalt	3x10 ⁻³ - 5	3x10 ⁻⁴ -1.5	1x10 ⁻² -500	9x10 ⁻⁴ -46	10	<1x10 ⁻³
Interbed	3x10 ⁻³ -10	9x10 ⁻⁴ -3	3x10 ⁻² -100	3x10 ⁻³ - 9	20	<1x10 ⁻²

^aVolume percent.

V7607-13.12

FIGURE 11
PIEZOMETERS INSTALLED IN ARH-DC-1

TABLE VI
SUMMARY RECORD OF DEPTHS TO WATER BELOW THE LAND SURFACE IN
FEET AND METERS FOR PIEZOMETERS IN ARH-DC-1

Measurement Date	Piezometer Tube									
	1		2		3		4		5	
	ft	m	ft	m	ft	m	ft	m	ft	m
06/29/72	157.33	47.95	158.03	48.16	158.39	48.28	141.37	43.09	163.00	49.68
07/06/72	157.05	47.87	157.71	48.07	158.10	48.19	142.33	43.38	162.82	49.63
07/13/72	157.02	47.86	157.63	48.05	158.00	48.16	143.40	43.71	162.94	49.66
07/20/72	156.91	47.83	157.50	48.01	157.90	48.13	144.24	43.96	163.00	49.68
08/10/72	157.07	47.87	158.00	48.16	158.38	48.27	146.42	44.63	162.78	49.62
08/17/72	157.34	47.96	158.21	48.22	158.58	48.34	147.18	44.86	162.88	49.65
08/24/72	157.27	47.94	158.00	48.16	158.42	48.29	147.75	45.03	162.82	49.63
08/30/72	157.45	47.99	158.17	48.21	158.52	48.32	148.28	45.20	162.30	49.47
09/07/72	157.25	47.93	157.88	48.12	158.26	48.24	148.81	45.36	162.81	49.62
09/21/72	156.97	47.84	157.57	48.03	157.94	48.14	149.69	45.63	162.83	49.63
09/28/72	157.52	48.01	157.75	48.08	158.07	48.18	150.29	45.81	163.06	49.70
10/05/72	157.36	47.96	157.88	48.12	158.25	48.23	150.80	45.96	163.22	49.75
12/30/74	155.73	47.47	156.26	47.63	156.67	47.75	158.90	48.43	162.56	49.55
04/18/75	155.28	47.33	155.60	47.43	156.35	47.66	163.70	49.90	162.24	49.45
09/03/75	155.39	47.36	155.69	47.45	156.44	47.68	164.08	50.01	162.30	50.69
12/06/75	155.59	47.42	155.47	47.39	156.50	47.70	164.96	50.28	163.37	49.80

FIGURE 12
HYDROGRAPHS OF DEPTHS TO WATER BELOW THE LAND SURFACE IN
FEET AND METERS FOR PIEZOMETERS IN ARH-DC-1

GROUNDWATER CHEMISTRY

The chemistry of the waters in the various aquifers underlying the Hanford Reservation is not as well understood as the hydraulic properties of these aquifers. Complete chemical analyses are available from some wells penetrating the unconfined aquifer^[1,16], the uppermost confined aquifer^[1], and the lower Yakima Basalts^[1,13,17] (ARH-DC-1). Table VII summarizes these results. The waters from the three aquifers are quite distinct. The unconfined aquifer is characterized by waters high in calcium and magnesium and can be described as calcium-magnesium-sulfate-bicarbonate waters. On the other hand, the waters in the lower Yakima Basalts are sodium-chloride-carbonate waters which are very low in both calcium and magnesium. Waters in the uppermost confined aquifers are intermediate in nature and can be described as calcium-sodium-bicarbonate waters.

Generally, waters from basalt aquifers are characterized by high ratios of calcium-to-sodium and of magnesium-to-calcium, a relatively high silica content and a relatively low fluoride content. The waters in both the uppermost confined aquifers and the lower Yakima Basalts are atypical basalt waters and thus appear to come from the sedimentary interbeds and not the basalts proper. This point is further supported by the silica values. La Sala and Doty^[13] noted that the silica content indicates near-equilibrium with a silica phase having properties similar to those of chalcedony or cristobalite. The silica probably comes into solution from feldspars and other minerals but at a concentration higher than that at which it would be in equilibrium with quartz.

TABLE VII
AVERAGE COMPOSITION OF WATERS FROM AQUIFERS
UNDERLYING THE HANFORD RESERVATION
(Numbers in Parentheses Denote the Range of Values Found)

	<u>Unconfined Aquifer</u>	<u>Uppermost Confined Aquifers</u>	<u>Lower Yakima Basalt Formation</u>
Sodium (mg/liter)	29 (16-64)	40 (4.1-122)	168 (134-182)
Calcium (mg/liter)	48 (31-72)	15 (1-18)	0.5 (0.2-0.8)
Magnesium (mg/liter)	12 (7.1-14)	7 (0-11)	0.1 (0-0.1)
Chloride (mg/liter)	13 (3.1-24)	16 (3.8-81)	90 (68-98)
Sulphate (mg/liter)	58 (20-150)	9 (0-29)	14 (10-21)
Bicarbonate (mg/liter)	172 (115-315)	152 (93-180)	56 (2-164)
Carbonate (mg/liter)	0 (0)	3 (0-15)	87 (16-125)
Hardness, total (mg/liter)	170 (110-220)	66 (3-96)	2 (1-2)
Potassium (mg/liter)	6.8 (4.6-13)	9.0 (4.5-17)	4.0 (3.0-5.9)
pH	8.0 (7.5-8.1)	8.0 (7.2-8.7)	9.6 (8.9-9.9)

In the waters obtained from the lower Yakima Basalts, sodium is the predominant cation present. These waters appear to be in equilibrium with a feldspar of about equal calcium and sodium content. The low calcium in solution probably results from the high bicarbonate content of the water that causes calcite to precipitate from solution.

Waters from the unconfined aquifer contain chloride in concentrations generally present in meteoric waters. The high chloride content of the waters from the lower Yakima Basalts is atypical of basalt waters.

The USGS^[13] analyzed the carbon-14 content of the bicarbonate dissolved in water from the uppermost confined aquifers in ARH-DC-1. The measured carbon-14 content has been adjusted for the dilution effects of carbonate mineral solution using the carbon-13 value of bicarbonate.^[18] The adjusted age is about 13,000 years before the present. Deuterium/hydrogen and oxygen-18/oxygen-16 ratios for waters from the lower Yakima Basalts also suggest that these waters were recharged at about the end of glaciation when a cooler climate prevailed. On the other hand, waters in the unconfined aquifer are of recent origin.

GROUNDWATER MODELING

In order to assess the potential migration of contaminants from a deep, high-level waste geologic storage facility, one must construct mathematical models capable of describing the extent of contaminant migration from the facility and assessing the overall risk. In addition, models must be available that can be used to describe the local and regional hydrology and to analyze the effect of stresses

applied to the groundwater system. The models available to date on migration out of a repository are very preliminary and have not been tested with field data. The groundwater flow and transport codes available at Hanford are primarily applicable to the unconfined aquifer but could be extended to treat multiaquifer systems including the deeper basalts.

To date models for describing groundwater and contaminant movement in the unsaturated zone and the unconfined aquifer have been developed and tested against analytical solutions and field data. The testing provided confidence in the mathematical methods and the approach used. Verification with field data showed areas where data coverage was inadequate and pointed up the need for development of a technique to compute uncertainties in the output based on known uncertainties in the input data. Additional data and work are needed to reduce the uncertainty in the model predictions.

In general, the Hanford Reservation modeling is divided into four categories: (1) unsaturated zone analysis capability, (2) saturated unconfined groundwater analysis capability, (3) transport capability, and (4) leakage from a deep storage cavern. The unsaturated and saturated portions of the groundwater system were considered separately in order to develop feasible models. The transport phenomena were assumed to be affected by, but not to affect, the convective flow patterns.

The model development effort is separated into three major categories: data models, hydraulic models, and contaminant transport models. Data models are used to calculate input characteristics required for operation of the hydraulic and transport models. The hydraulic models utilize the

groundwater movement calculated by the hydraulic models with soil-waste reactions for predicting the contaminant movement rate. The groundwater convective transport is simulated independent of waste movement. Figure 13 lists the models and their respective functions as well as input data requirements and output information.

A major data model, the Transmissivity Iterative Routine (TIR) has been developed for calculating the hydraulic conductivity distribution in highly heterogeneous aquifers where characterization by field measurement alone would be prohibitive. The method is based on the numerical integration of the Boussinesq equation for the transmissivity along instantaneous streamtubes of flow. Testing of the computer program on a synthetic surface identified a set of control parameters that resulted in a maximum computational error of $\pm 5\%$. This maximum error occurred as streamtubes passed near stagnation points where the groundwater gradients and radius of curvature were small. Two versions of the program, steady and transient, were implemented on the Hanford unconfined aquifer. Although the earlier steady version was a limited program, the verification by comparison of computed and observed groundwater potentials assuming steady conditions, while far from perfect, was encouraging, and the resultant distribution represented a substantial improvement over the previous version.^[19]

The results of limited sensitivity analyses on the Hanford unconfined aquifer indicated that, in general, the flow in the aquifer is sufficiently greater than the rate of storage to make the calculation of the hydraulic conductivity relatively insensitive to the storage coefficient. A good average estimate is that a 100 percent error in either storage coefficient or temporal rate of change will

FIGURE 13
HYDROLOGIC MODELS

result in a 20 percent error in the calculated hydraulic conductivity measurement because of the extreme sensitivity of the calculated hydraulic conductivity generated for certain streamtubes. The agreement of calculated hydraulic conductivities of the reference lines and analysis of pump test data support these observations. Details of the model assumptions, limitations, error, and sensitivity analyses are contained in a recent report.^[19]

The basic hydraulic models are the Variable Thickness Transient Groundwater Model (VTT)^[20] and the Partially Saturated Transient Flow Model (PST).^[21] The VTT Model was developed to predict the changing height of the water table (phreatic surface) throughout the unconfined aquifer underlying the Hanford Reservation. It provides for the simulations of two-dimensional flow in an unconfined aquifer. The model utilizes the nonlinear transient Boussinesq equation with the appropriate initial and boundary conditions. The heterogeneous permeability distribution input can be calculated by the TIR Model. A successive line over-relaxation technique with unequal time steps is used for numerical solution.

The PST Model includes a mathematical description and computer program to simulate transient Darcian transport of a fluid in heterogeneous partially saturated porous media.^[21] The objective of the model is to assess movement of groundwater in the unsaturated zone. The model involves the solution of the basic two-dimensional equation of flow in the unsaturated region.^[21]

A transport model^[22,23] based on ion exchange has been developed for use with the PST and VTT Models for predicting movement and distribution of contaminants in groundwater

systems. Based on the two-dimensional form of the diffusion-convection equation, the model considers variable dispersion coefficients, variable media thickness, and sink and/or source terms. The model has two major components: the macroion segment handles dissolved minerals that are typically present in groundwater systems, and the microion segment predicts movement of the contaminants that are normally present in trace quantities (in comparison with the naturally occurring materials). The model combines the compound problem of multicomponent transport with simultaneous chemical reactions and includes the general transport mechanisms of advection, dispersion, and sorption, as well as radioactive decay. Each segment can be run as a separate model.

A preliminary model of fluid movement from a deep underground storage cavern has been developed.^[24,25] This model is aimed at giving:

1. The expected location of the fluid during movement from an area of release to a remote outflow boundary.
2. The expected elapsed time between fluid release and arrival at the boundary.
3. The expected fluid flow rate across the outflow boundary as it varies with time.

This cavern outflow model considers flow in a stratum of uniform thickness, of constant permeability, and of uniform porosity. The lateral flow in the stratum results from a uniform gradient upon which the cavern leakage (a completely penetrating line source) is superimposed.

Therefore only two-dimensional lateral flow in the stratum is considered by the initial model. This model has not been tested to date.

RECOMMENDATIONS

To demonstrate conclusively the outcome of a proposed project for final storage of nuclear wastes in the Columbia River flood basalt requires that the hydrologic conditions in the prospective host rocks be known in unprecedented detail and precision.

The Committee on Radioactive Waste Management of the National Academy of Sciences^[26] has indicated the type of information needed to make an adequate hydrologic assessment. They have noted:

1. "To guide underground exploration ... investigations must produce definitive information as to the three-dimensional characteristics of ... rock units ... Particularly important is information on (a) the fluid transmissivity ... (b) the hydraulic gradients ... (c) the ion exchange capacities, ... (d) the chemical reactions between the waste and the potential host rocks, and (e) regional stress fields ..."
2. "The (Committee on Radioactive Waste Management, Panel on Bedrock Disposal) concludes that no reasonable amount of exploration from the land surface can conclusively demonstrate the safety of waste storage in deep vaults. Essential for such a demonstration is *in situ* inspection and testing of the rock in which vaults might be constructed.

Obtaining such information requires not only regional hydrogeologic studies of the flood basalts but also coring and detailed studies of the locality where the shaft leading to the vault and the vault itself are to be built. These studies should assure that the following standards be met:

1. "Whatever method is adopted (for terminal waste disposal) ... it (must) be capable of protecting the biosphere from these wastes for not less than 1,000 years."^[26]
2. "The excavated vault (must) remain structurally sound so long as access may be necessary."^[27]
3. "Waste toxins (must) not reach the biosphere in concentrations exceeding the permissible maximum for public drinking water."^[27]
4. "No waste constituents (must) reach beyond a prededicated containment zone within the basalt so long as these constituents exceeded 'permissible' concentrations."^[27]

Studies to date at Hanford have concentrated on understanding the geologic framework and history of deposition of the Columbia River flood basalts. Hydrologic information on the unconfined aquifer is abundant; however such is not the case with the hydrology of the deep basalt flows. Hydrologic data for the lower Yakima Basalts are available from only one well (ARH-DC-1). Additional data are needed to elucidate the regional flow regime in these basalts. A comprehensive program to demonstrate the feasibility of a proposed terminal storage project in the flood basalts must be aimed at (1) characterizing the hydrology of the lower Yakima Basalts and assessing the extent of interaction

between the basalts and adjacent strata; (2) developing and using mathematical models to predict the behavior of the hydrologic regime under all possible stresses; and (3) assessing the risk of contamination from a terminal storage facility through the groundwater pathway.

REFERENCES

1. Environmental Statement of Waste Management Operations, Hanford Reservation, Richland, Washington, ERDA-1538, United States Energy Research and Development Administration, 1975.
2. Waste Resources Data for Washington, Part 1, Surface Records, 1972, U. S. Department of Interior, Geological Survey, 1973.
3. J. K. Soldat, A Compilation of Basic Data Relating to the Columbia River, US-AEC Report HW-69369, General Electric Company, Richland, Washington, 1962.
4. Water Resources Data for Washington, Part 2, Water Records, 1972, U. S. Department of Interior, Geological Survey, 1973.
5. Probable Maximum Precipitation, Northwest States U. S. Department of Commerce, Environmental Sciences Services Administration, Weather Bureau, Hydro-Meteorological Report No. 43, Washington, D.C., November 1966.
6. R. A. Deju and B. H. Richard, A Regional Gravity Investigation of the Hanford Reservation, CA-168-RAD-6, Raul A. Deju Associates, April 1975.

7. Definition of Selected Groundwater Terms, A Report of the Committee on Redefinition of Groundwater Terms, U. S. Geological Survey Open File Report, August 1970.
8. R. E. Isaacson et al., Soil Moisture Transport in Arid Site Vadose Zones, US-ERDA Report ARH-2983, Atlantic Richfield Hanford Company, Richland, Washington October 1974.
9. Water Table Measurement Data Maps--December 1975, H-2-38396 Rev. 1, Atlantic Richfield Hanford Company.
10. R. A. Deju, The Hanford Field Testing Program, CA-168-RAD-3, Raul A. Deju Associates, September 1974.
11. W. K. Summers and R. A. Deju, A Preliminary Review of the Regional Hydrology of the Hanford Reservation, CA-168-RAD-4, Raul A. Deju Associates, Richland, Washington, June 1974.
12. R. K. Ledgerwood and R. A. Deju, Hydrology of the Uppermost Confined Aquifers Underlying the Hanford Reservation, US-ERDA Report ARH-SA-253, Atlantic Richfield Hanford Company, March 5, 1976.
13. A. M. La Sala, Jr. and G. C. Doty, Preliminary Evaluation of Hydrologic Factors Related to Radioactive Waste Storage in Basaltic Rocks at the Hanford Reservation, Washington, U. S. Geological Survey Open-File Report, 1971.
14. J. W. Bingham and M. J. Grolier, "The Yakima Basalt and Ellensburg Formation of South Central Washington," U. S. Geological Survey Bulletin, 1224-G, p. 15.
15. Completion Report, Exploratory Hole ARH-DC-1, Fenix and Scisson, Inc. Tulsa, Oklahoma, 1969.

16. J. R. Raymond, D. A. Myers, J. J. Fox, V. L. McGhan, P. M. Schrotke, Environmental Monitoring Report on Radiological Status of the Ground Waste Beneath the Hanford Site January-December 1974, AEC-ERDA Report BNWL-1970, Battelle Pacific Northwest Laboratories, Richland, Washington, March 1976.
17. A. M. La Sala, Jr., G. C. Doty, and F. J. Pearson, Jr., A Preliminary Evaluation of Regional Groundwater Flow in South Central Washington, U. S. Geological Survey Administrative Report, p. 55, 1972.
18. F. J. Pearson, Jr. and B. B. Hanshaw, Sources of Dissolved Carbonate Species in Groundwater and Their Effects on Carbon-14 Dating, Symposium on Use of Isotopes in Hydrology, International Atomic Energy Agency, Vienna, Proceedings, p. 271-286, 1970.
19. D. B. Cearlock, K. L. Kipp, and D. R. Friedrichs, The Transmissivity Iterative Calculations Routine-Theory and Numerical Implementation, US-AEC Report BNWL-1706, Battelle Pacific Northwest Laboratories, 1974.
20. K. L. Kipp, A. E. Reisenauer, C. R. Cole, and C. A. Bryan, Variable Thickness Transient Groundwater Flow Model Theory and Numerical Implementation, US-ERDA Report BNWL-1703, Battelle Pacific Northwest Laboratories, 1976.
21. A. E. Reisenauer, D. B. Cearlock, and C. A. Bryan, Partially Saturated Transient Groundwater Flow Model Theory and Numerical Implementation, US-AEC Report BNWL-1713, Battelle Pacific Northwest Laboratories, 1972.

22. R. G. Baca, S. W. Ahlstrom, A. Brandstetter, P. J. Serne, and R. C. Routson, Transport Model Theory and Computer Implementation, US-AEC Report BNWL-1715, Battelle Pacific Northwest Laboratories, 1973.
23. S. W. Ahlstrom and R. G. Baca, Transport Model User's Manual, US-AEC Report BNWL-1716, Battelle Pacific Northwest Laboratories, 1974.
24. Z. C. Motteler, Steady Contaminant Flow from a Cylindrical Tank into a Deep Stratum with Variable Permeability, CSC-7008-2, Computer Sciences Corporation, Richland, Washington, p. 43, 1970.
25. R. W. Nelson, R. T. Toyooka, and D. A. Moe, An Initial Model of Fluid Movement from Deep Underground Storage Caverns, CSC-7006-01, Computer Sciences Corporation, p. 31, 1970.
26. An Evaluation of the Concept of Storing Radioactive Wastes in Bedrock Below the Savannah River Plant Site, National Academy of Sciences, Washington, D.C., 1972.
27. Hypothetical Prototype Sites of Repositories for Radioactive Wastes: Flood Basalt, A. A. Piper Report to Oak Ridge National Laboratories, April 1975.

CHAPTER VI

EXTENT OF HEAT DISSIPATION FROM RADIOACTIVE WASTES STORED IN A BASALT CAVERN

SUMMARY

Several computational techniques have been developed to study the effect of different variables on the maximum cavern temperature reached as a result of storage of radioactive wastes. The computer programs TALUS and DIBUW were developed to allow the calculation of these temperatures under many conditions. These programs are based on an equation to calculate the temperature as a function of time from a line heat-generation source. Studies were made using these programs to calculate the effect on cavern temperature of various parameters. These studies have shown that the maximum transient cavern temperature decreases with:

(1) increasing cavern radius, (2) wider cavern spacing, (3) fewer adjacent caverns, (4) higher thermal conductivity of the surrounding medium, (5) decreasing quantities of shorter half-life radioactive waste products, and (6) lower heat generation rates per volume of the wastes.

Calculations in these studies were based on the assumption that the basalt was a "perfect" medium. However, the basalt layers surrounding the cavern have different thermal properties, and ground water is present between and within some of these layers. If this water is heated and a large temperature rise occurs, the geologic stability of the basalt might be affected. Future calculations should take into account that the surrounding basalt layers are not infinite media with constant thermal properties and temperatures.

INTRODUCTION

One of the factors that must be considered in assessing the feasibility of geologic storage in basalt of high-level radioactive wastes in solid form is the dissipation of heat produced by the wastes. Temperatures in the storage cavern and access tunnels will have to be kept below a level dictated by the melting point of the waste, the devitrification temperature of the glass (if the waste is in glass form), and the temperature limit for concrete bore-hole seal integrity.

Over a period of years after the waste is in a storage mode, the temperature will rise, passing through a maximum that is a function of the following variables: (1) the half lives of the various radionuclides in the waste, (2) heat generation of the fission products, (3) the thermal properties of the basalt, (4) the size of the caverns, (5) the spacing of the caverns, (6) the number of adjacent caverns, (7) the geometric layout of adjacent caverns, and (8) the filling time of each cavern with respect to surrounding caverns. To assess the feasibility of using basalt as a geologic storage site for high-level radioactive waste, the effects the above variables have on cavern temperature changes were studied. These studies included the development and testing of different computational methods and corresponding computer programs for determining the maximum transient cavern temperature.

COMPUTATIONAL TECHNIQUES

To determine the cavern temperature at a specified time, a computer program TALUS (Temperature Around a Line Underground Source) has been developed. This program was used to calculate the temperature rise in an infinite cylinder at a given radial distance from the center of the continuous line source using the equation:^[1]

$$V = \sum_{i=1}^m \frac{Q_i}{\pi \rho c a^2} e^{-\lambda_i t} \left\{ \frac{1}{\lambda_i} \left[e^{\lambda_i t} \operatorname{erf} \frac{b}{\sqrt{4\kappa t}} - 1 + e^{(\lambda_i t - b^2/4\kappa t)} R w \left(\sqrt{\lambda_i t} + \frac{jb}{\sqrt{4\kappa t}} \right) \right] \right. \\ \left. + \sum_{n=1}^{\infty} \frac{J_0(\alpha_n r)}{(\lambda_i - \kappa \alpha_n^2) J_0^2(\alpha_n a)} \left[e^{(\lambda_i - \kappa \alpha_n^2)t} \operatorname{erf} \frac{b}{\sqrt{4\kappa t}} - 1 + \cosh \left(b \sqrt{\frac{|\lambda_i - \kappa \alpha_n^2|}{\kappa}} \right) \right. \right. \\ \left. \left. + \frac{1}{2} e^{-b \sqrt{|\lambda_i - \kappa \alpha_n^2|/\kappa}} \operatorname{erf} \left(\sqrt{|\lambda_i - \kappa \alpha_n^2|} t - \frac{b}{\sqrt{4\kappa t}} \right) - \frac{1}{2} e^{b \sqrt{|\lambda_i - \kappa \alpha_n^2|/\kappa}} \operatorname{erf} \left(\sqrt{|\lambda_i - \kappa \alpha_n^2|} t + \frac{b}{\sqrt{4\kappa t}} \right) \right] \right\}$$

WHERE

V = TEMPERATURE RISE IN INFINITE CYLINDER AT A RADIAL DISTANCE, r , FROM THE CENTER OF THE CONTINUOUS LINE SOURCE, °F

Q_i = HEAT GENERATION OF i th NUCLIDE AT TIME OF BURIAL OF WASTE, Btu/hr-ft

ρc = VOLUME HEAT CAPACITY OF MEDIUM, Btu/ft³·°F

a = RADIUS OF INFINITE CYLINDER, ft

λ_i = DECAY CONSTANT OF i th NUCLIDE, hr⁻¹

t = TIME AFTER BURIAL OF WASTE, hr

$2b$ = LENGTH OF LINE SOURCE, ft

κ = THERMAL DIFFUSIVITY OF MEDIUM, ft²/hr

$Rw(\)$ = REAL PART OF COMPLEX ERROR FUNCTION $w(z)$, DIMENSIONLESS

$j = \sqrt{-1}$

α_n = POSITIVE ROOTS OF $J_1(\alpha a)$, EXCLUDING $\alpha_n = 0$

r = RADIAL DISTANCE FROM CENTER OF INFINITE CYLINDER, ft

This equation is for a line source of finite length $2b$ in a medium of finite radius a . Computations are made for a radius r corresponding to the cavern wall. Radioactive decay is assumed to occur with a decay constant λ_i .

The TALUS program is used to calculate the maximum temperature for a single line heat-generation source and the corresponding time since waste burial. Several line sources, analogous to two- and three-dimensional arrays of caverns, can be simulated by the principle of superposition. This method uses a specified coordinate and sums all temperature effects from adjacent sources.

The use of negative images facilitates the calculation of temperatures of shallow-buried wastes (wastes buried at depths less than 30 m [100 ft]). To satisfy the boundary condition that the temperature rise at the surface be zero, a negative (heat absorbing) source is imagined to be present at the same height above the surface that the radioactive source is in the subsurface. The sum of these two temperature effects at a given radius is used to calculate the maximum temperature.

A computer program DIBUW (Direct Buried Underground Wastes) has been developed to use the previously described methods of superposition and negative images to estimate transient temperatures. Input for the program includes: (1) the coordinates of the caverns, (2) the coordinates of a point at which the temperature calculation is desired, (3) the initial heat generation rates, (4) the half lives of the sources in each cavern, (5) the depth below grade at which the caverns are located, (6) the thermal conductivity, and (7) the thermal diffusivity of the basalt surrounding the caverns. A large number of fission products

in each cavern and a large number of caverns, not necessarily parallel or in the same plane, can be accommodated. At the present time, the program does not include the effects of filling caverns at different intervals or end effects due to short heat sources.

RESULTS

Effect of Cavern Radius

Figures 1 and 2 show the effect of cavern radius on the maximum cavern temperature. The data for these plots were obtained from a single line source heat generation calculation. The rate of heat generation used was $54 \text{ cal/((sec)(meter of length))}$ [$235 \text{ BTU/((hr)(ft of length))}$] with thermal conductivity values of 0.207, 0.413, and 0.620 $\text{cal/((sec)(m}^2\text{)(}^\circ\text{C/m)}$ [$.5, 1.0, \text{ and } 1.5 \text{ BTU/((hr)(ft}^2\text{)(}^\circ\text{F/(t))}$]. These graphs demonstrate that as the radius of the cavern is increased, the maximum temperature that the cavern reaches decreased. Because these results were obtained from calculations for a line source, and equal heat generation per length was assumed, the change in radius represents storing the same relative amount of heat producing radionuclide wastes in different size containers.

Effect of Cavern Spacing and Altering the Number of Caverns

Using the DIBUW program and assuming a volumetric heat capacity of $320 \text{ kcal/((m}^3\text{)(}^\circ\text{C))}$ [$20 \text{ BTU/((ft}^3\text{)(}^\circ\text{F))}$], the data for figures 3, 4, 5, and 6 have been compiled. These graphs quantitatively describe the effects of changing the cavern spacing and altering the number of adjacent caverns on the maximum temperature of the central cavern. The depth below grade was assumed to be 30 meters (100 ft). This depth

FIGURE 3
 RISE IN CAVERN TEMPERATURE VERSUS NUMBER OF
 CAVERNS (CAVERN DIAMETER - 2 FEET [.6 METERS])

FIGURE 4
 RISE IN CAVERN TEMPERATURE VERSUS NUMBER OF
 CAVERNS (CAVERN DIAMETER - 3 FEET [.9 METERS])

FIGURE 5
RISE IN CAVERN TEMPERATURE VERSUS NUMBER OF
CAVERNS (CAVERN DIAMETER - 4 FEET [1.2 METERS])

FIGURE 6
RISE IN CAVERN TEMPERATURE VERSUS CAVERN SPACING

can be considered an infinite distance below grade, since greater depths will not change the results of the calculations significantly (because the contribution to the maximum temperature of the negative image above the surface becomes negligible). A line-source heat generation rate of $64.3 \text{ cal/((sec)(meter of length))}$ [$280 \text{ BTU/((hr)(ft of length))}$], was used for the calculations corresponding to the placing of 1 kw sources at 3 m (10 ft) intervals along the caverns. The heat generation sources were single decaying isotopes with half-lives of 30 years. Thermal conductivities of 0.145 and $0.269 \text{ cal/((sec)(m)(}^\circ\text{C))}$ [0.35 and $0.65 \text{ BTU/((hr)(ft)(}^\circ\text{F))}$] were assumed. These figures were based on all the caverns being filled at the same time.

The increase in temperature at the wall of the central cavern with increasing numbers of neighboring caverns is shown in Figures 3, 4, and 5, for 0.6, 0.9, and 1.2 m diameter [2, 3, and 4-ft diameter] caverns, respectively. As the cavern spacing decreases, the maximum temperature increases.

Figure 6 was derived from Figures 3, 4, and 5, and the effect of cavern spacing on maximum temperature is shown. Caverns were considered only within a 30 m (100 ft) radius of the central cavern. The maximum temperature rise occurs at the wall of the central cavern. With a 3.8 m (12.5 ft) spacing, 17 parallel caverns fit within the 30 m radius with 8 caverns on either side of the central cavern. With a 7.6 m (25 ft) spacing, 9 caverns are possible, and with 15 m (50 ft) spacing, 5 caverns are possible. Adding more caverns outside the 30 m (100 ft) distance limit would increase the maximum temperature that occurs at the central cavern by less than 10 percent. The effect of

cavern spacing is small at spacings greater than 15 m (50 ft). Increasing the spacing from 15 m (50 ft) to infinity decreases the maximum temperature rise by about 25 percent.

Thermal Resonance

Filling all the caverns at once will not result in the worst heating condition. For example, if two caverns with a 1.2 m (4 ft) diameter are placed 7.6 m (25 ft) apart in soil with a thermal conductivity of $0.145 \text{ cal}/(\text{sec})(\text{m})(^\circ\text{C})$ [$0.35 \text{ BTU}/(\text{hr})(\text{ft})(^\circ\text{F})$], a thermal wave proceeds from each source. If the caverns are filled with a 30-Year half-life material at an initial heat generation rate of $64.3 \text{ cal}/(\text{sec})(\text{meter of length})$ [$280 \text{ BTU}/(\text{hr})(\text{ft of length})$] at the same instance, the temperature at the wall of one cavern on a line between their centers will receive two thermal waves. The first wave to reach the wall is from the closest cavern. It peaks at 180°C (356°F) and 10.5 years. The second wave from the other cavern peaks at 48.3°C (119°F) and 20.5 years. The maximum temperature, which is the sum of the two waves, does not occur at the time of either individual maximum temperature. It reaches a value of 243°C (470°F) at 13 years.

If the far cavern is filled 10 years before the cavern whose wall is being considered, the peaks of the two thermal waves arrive simultaneously at this wall, and a maximum temperature rise of 251°C (483°F) is reached 10.5 years after the closest cavern is filled and 20.5 years after the far cavern is filled. Thermal waves from neighboring caverns on both sides could reinforce this effect by adding their own contributions if they were at appropriate spacings and filling times. The importance of the effect has not been investigated for practical spacings and fill intervals;

however, the condition should be avoided if possible. An optimum filling schedule and spacing may possibly include nonuniform spacing and unequal filling intervals. A schedule must be developed that prevents the filling of adjacent caverns at the wrong intervals.

Properties of Material Surrounding the Waste

The effect of thermal conductivity of the basalt layer on cavern temperature is shown in Figure 7. The data for Figure 7 were obtained from the calculation methods for a line underground source, using a heat generation rate of $54.0 \text{ cal}/(\text{sec})(\text{m of length})$ [$235 \text{ BTU}/(\text{hr})(\text{ft of length})$], a cavern radius of 3 m (10 ft), and a product half-life of 30 years. This plot shows that increasing the thermal conductivity causes a large reduction in the maximum cavern temperature. Since the thermal conductivity of the basalt layer is approximately $0.29 \text{ cal}/(\text{sec})(\text{m})(^\circ\text{C})$ [$0.7 \text{ BTU}/(\text{hr})(\text{ft})(^\circ\text{F})$], the actual curve would be between curves A and B under the given conditions.

To determine and justify the ranges of physical properties used in the various calculations, tests have been run on some actual samples. Analyses of representative physical properties of the basalt rock for two samples from Well ARH-DDH-1 have been made.^[2] Samples 1005 and 1084 were utilized, corresponding to depths of 306 and 330 m (1005 and 1084 ft), respectively. The density, heat capacity, and thermal diffusivity were found by direct experimental measurements on the samples. The thermal conductivity was calculated from the temperature corrected density and the least squares line for heat capacity and thermal diffusivity.

A complete listing of the thermal properties from a least squares fit is given in Table I.

The values are in a temperature range of 37.8 to 316°C (100 to 600°F). A least squares fit of the data gives the following equations for heat capacity; C_p , and thermal diffusivity, α :

FIGURE 7

RISE IN CAVERN TEMPERATURE VERSUS TIME
 FOR VARIOUS THERMAL CONDUCTIVITIES

TABLE I

THERMAL PROPERTIES OF BASALT AS A FUNCTION OF TEMPERATURE

Sample 1005 Depth = 306 m (1005 ft)

Temperature, T		Density, ρ		Heat Capacity, C_p	
$^{\circ}\text{F}$	$^{\circ}\text{C}$	lb/ft ³	kg/m ³	Btu/(lb)($^{\circ}\text{F}$)	cal/(g)($^{\circ}\text{C}$)
100	37.8	183.6	2941	0.174	0.174
200	93.3	183.8	2944	0.186	0.186
300	149	184.0	2947	0.198	0.198
400	204	184.1	2949	0.210	0.210
500	260	184.3	2952	0.222	0.222
600	316	184.5	2955	0.234	0.234

Temperature, T		Thermal Diffusivity, α		Thermal Conductivity, k	
$^{\circ}\text{F}$	$^{\circ}\text{C}$	ft ² /hr	cm ² /sec	Btu/(hr)(ft)($^{\circ}\text{F}$)	cal/(sec)(m)($^{\circ}\text{C}$)
100	37.8	0.0206	0.00532	0.657	0.272
200	93.3	0.0201	0.00519	0.687	0.284
300	149	0.0196	0.00506	0.714	0.295
400	204	0.0191	0.00493	0.739	0.305
500	260	0.0186	0.00480	0.762	0.315
600	316	0.0181	0.00467	0.783	0.324

Sample 1084 Depth = 330 m (1084 ft)

Temperature, T		Density, ρ		Heat Capacity, C_p	
$^{\circ}\text{F}$	$^{\circ}\text{C}$	lb/ft ³	kg/m ³	Btu/(lb)($^{\circ}\text{F}$)	cal/(g)($^{\circ}\text{C}$)
100	37.8	166.1	2661	0.176	0.176
200	93.3	166.2	2662	0.187	0.187
300	149	166.4	2665	0.197	0.197
400	204	166.5	2667	0.207	0.207
500	260	166.7	2670	0.217	0.217
600	316	166.8	2672	0.227	0.227

Temperature, T		Thermal Diffusivity, α		Thermal Conductivity, k	
$^{\circ}\text{F}$	$^{\circ}\text{C}$	ft ² /hr	cm ² /sec	Btu/(hr)(ft)($^{\circ}\text{F}$)	cal/(sec)(m)($^{\circ}\text{C}$)
100	37.8	0.0200	0.00516	0.587	0.243
200	93.3	0.0195	0.00503	0.603	0.249
300	149	0.0189	0.00488	0.617	0.255
400	204	0.0183	0.00472	0.629	0.260
500	260	0.0177	0.00457	0.639	0.264
600	316	0.0171	0.00441	0.647	0.267

Sample 1005

$$C_p = 0.1659 + 0.0002171t^{\circ}\text{C cal}/(\text{g})(^{\circ}\text{C})$$

$$\alpha \times 10^5 = 539.77 - 0.2278t^{\circ}\text{C cm}^2/\text{sec}$$

Sample 1084

$$C_p = 0.1696 + 0.0001822t^{\circ}\text{C cal}/(\text{g})(^{\circ}\text{C})$$

$$\alpha \times 10^5 = 527.62 - 0.2752t^{\circ}\text{C cm}^2/\text{sec}$$

The thermal coefficient of volumetric expansion of basalt, estimated to be $1.6 \pm 0.4 \times 10^{-5}$ per $^{\circ}\text{C}$ ($9 \pm 2 \times 10^{-6}$ per $^{\circ}\text{F}$), was used to make the temperature correction for density. From these correlations, the thermal conductivity of the basalt at any reasonable temperature can be estimated. These temperature correlations are necessary for calculations of the maximum storage cavern temperature when a wide variety of cavern conditions and temperatures are considered.^[3]

Heat Generation Rates

Heat generation in stored radionuclide wastes is a key factor affecting the maximum temperature rise. The actual spectrum and intensity of the radioactivity in a waste depends on the type of fuel and on its reactor exposure history. The self-heating range 1.85 to 18.5 ca/(sec)(m³) [0.1 to 1.0 BTU/(hr)(gal)] is characteristic of long-cooled salt cake wastes that contain only cesium-137 and strontium-90 as heat generators.^[4] Should the aqueous waste be solidified to a monolithic solid having a composition similar to that of the basalt layer, a volume change would result that would change the preceding values in the heat generated per volume over a given time.

The results of the estimated wall temperatures in a cavern with radius 3 m (10 ft) located in a large volume of basalt with a thermal conductivity of $0.413 \text{ cal}/(\text{sec})(\text{m})(^\circ\text{C})$ [$1.0 \text{ BTU}/(\text{hr})(\text{ft})(^\circ\text{F})$] are shown in Table II.

The maximum wall temperatures reached for each case and the time to reach them are given for a constant inventory of ^{90}Sr and ^{137}Cs , but with decreasing amounts of short-lived isotopes present. Figure 8 shows the effect of various heat-generation rates on the maximum temperature. The precise initial heat generation rate of the different radionuclides is shown in Table III.

Secondary Considerations

When the data for the maximum waste temperature calculations were used, the radioactive wastes were considered to be surrounded by an infinite medium of basalt (or solid material) with constant temperature and thermal properties. The subsurface has a geothermal gradient (change in temperature per change in depth) that is positive with increasing depth. Differences in the heat transfer coefficient for successive layers of basalt and intercalated sediments will result in different thermal properties and will influence heat transfer rates to some degree. Further, since the interbeds between basalt layers may consist of water saturated sediments, the presence of water may lead to convective heat transfer. Therefore, the actual maximum cavern temperature will differ from the values obtained for an infinite line source surrounded by an infinite medium.

Figure 9 shows the temperature of the subsurface as a function of depth for the DC-1 drill hole. This plot shows

TABLE II
HEAT GENERATION RATE

Case	Btu/(hr) (gal)	cal/(sec) (m ³)	Ratio of Total to 90Sr + 137Cs	Time to Reach Maximum Temperature, yr
1	0.665	12	6.2	1.0
2	0.270	5	2.5	2.5
3	0.158	3	1.5	8.0
4	0.109	2	1.0	15.0

Case	Maximum Temperature		Temperature at 90 Days		Temperature at 15 Years	
	°F	°C	°F	°C	°F	°C
1	276	136	214	101	210	98.9
2	220	104	170	76.7	208	97.8
3	208	97.8	158	70.0	207	97.2
4	206	96.7	152	66.7	206	96.7

FIGURE 8

CAVERN WALL TEMPERATURE AS A
FUNCTION OF TIME AFTER BURIAL

TABLE III
INITIAL HEAT GENERATION RATE

FISSION PRODUCT	Case 1		Case 2	
	Btu/(hr) (gal)	cal/(sec) (m ³)	Btu/(hr) (gal)	cal/(sec) (m ³)
⁹⁰ Sr	0.060	1.110	0.060	1.110
¹⁰⁶ Ru	0.091	1.660	0.033	0.610
¹³⁴ Cs	0.004	0.074	0.003	0.056
¹³⁷ Cs	0.047	0.869	0.047	0.869
¹⁴⁴ Ce	0.455	8.410	0.121	2.240
¹⁴⁷ Pm	0.008	0.148	0.006	0.111
TOTAL	0.665	12.271	0.270	4.990

FISSION PRODUCT	Case 3		Case 4	
	Btu/(hr) (gal)	cal/(sec) (m ³)	Btu/(hr) (gal)	cal/(sec) (m ³)
⁹⁰ Sr	0.060	1.110	0.060	1.110
¹⁰⁶ Ru	0.012	0.222	0	0
¹³⁴ Cs	0.002	0.037	0	0
¹³⁷ Cs	0.047	0.869	0.047	0.869
¹⁴⁴ Ce	0.033	0.610	0	0
¹⁴⁷ Pm	0.004	0.074	0.001	0.019
TOTAL	0.158	2.922	0.108	1.998

FIGURE 9

SUBSURFACE TEMPERATURE AS A FUNCTION OF DEPTH
IN DC-1 DRILL HOLE (GEOTHERMAL GRADIENT)

(See FIGURE 3, CHAPTER II FOR DRILL HOLE LOCATION)

data reported from approximately 100 to 1500 m (330 to 4920 ft), and the geothermal gradient is not constant.

Water occurs in fractured zones in basalts. If the heat released from the radionuclide waste causes a temperature rise in this water, thermal expansion will occur, and stresses might result that could affect the stability of the jointed basalts. If the water vaporized, a pressure increase would occur, perhaps altering the flow pattern. These factors must be considered in the design of the storage system.

RECOMMENDATIONS

The preceding plots and discussion show the results of changing the important variables that affect the maximum waste storage temperature. Before waste storage can proceed on a large scale basis, the effects of varying storage conditions will have to be fully investigated. Two dimensional waste canister arrays may be efficient with respect to mining cost, and this geometry should be evaluated in future analyses. More advanced calculations in which all the important variables are considered at once to find optimum storage conditions may be necessary. Future calculations should take into account that the surrounding basalt layers are not infinite media with constant thermal properties and temperatures. Pilot plant operations, where the wastes can be monitored and easily retrieved, will be needed.

REFERENCES

1. R. L. Bradshaw, J. J. Perona, J. O. Blomeke, W. J. Boegly, Jr., Evaluation of Ultimate Disposal Methods for Liquid and Solid Radioactive Wastes VI. Disposal of Solid Wastes in Salt Formations, ORNL-3358, Oak Ridge National Laboratory, May 1968.
2. J. E. Nafe and C. L. Drake, "Physical Properties of Rocks of Basaltic Composition," Basalts, The Polder-vaart Treatise on Rocks of Basaltic Composition, edited by H. H. Hess and A. Poldervaart, Interscience Publishers, Volume 2, pp. 483-502 (1968).
3. F. Birch, J. T. Schairer, and H. C. Spicer, Handbook of Physical Constants: Geological Society of America Special Paper 36, p. 37, 1942.
4. F. P. Roberts, G. H. Jenks, and C. D. Bogg, Radiation Effects in Solidified High-Level Wastes - Part I, Stored Energy, BNWL-1944, January 1976, Battelle Pacific Northwest Laboratories.

CHAPTER VII

GEOCHEMICAL CONSIDERATIONS

SUMMARY

Early concern over the possibility of deleterious chemical interactions between a solidified radioactive waste and a basalt storage cavern resulted in the initiation of several studies by Atlantic Richfield Hanford Company (ARHCO) on the subjects of waste-form solubility, chemical stability, and compatibility between the waste and the host rock. These studies have drawn attention to the need to understand further the compatibility of the waste form with the host rock and the consequences of chemical reactions between them.

INTRODUCTION

The safety of any method by which nuclear waste is stored underground would depend, in part, upon the following parameters: (1) low solubility of the waste form, (2) the rate of transport of radionuclides if the waste should dissolve, (3) the chemical stability of the waste form, (4) chemical reactions between the waste and the host rock.

Initial studies of waste-rock interactions at Hanford were concerned with the potential for radionuclides to move to the biosphere from a storage cavern deep in basalt. In support of this concern, ARHCO initiated studies to evaluate the solubility of waste forms, develop models to describe radionuclide transport in solids, and develop methods for predicting the stability of waste products in geological environments. Accomplishments in these fields are summarized in this chapter.

SOLUBILITY

To contain radioactive wastes safely, they must be stored as leach-resistant solids because the integrity of the geologic barriers that would isolate the wastes from the biosphere cannot be assured for the time required for the radioactivity to decay to innocuous levels. Thus it is necessary to be able to predict the long-term potential for release of radionuclides from the solidified waste form, subject to all of the storage conditions that can be foreseen. The maximum amount of activity that could be released under the worst possible storage condition, (e.g., flooding of the storage cavern), as well as the amount expected to be released under normal conditions should then be compared with acceptable environmental tolerances.

Research by ARHCO has resulted in the development of a set of comprehensive models that describe the leaching mechanisms of solids that contain radioactive waste. These models are based on mass transport and reaction theory. The equations developed to fit and extrapolate leach data have the form:^[1]

$$f(t) = 1 - Z_2 e^{-k_2 t} - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \left[\left(Z_1 + Z_2 \right) e^{-\tau_n t} + Z_2 \frac{\tau_n e^{-\tau_n t} - k_2 e^{-k_2 t}}{k_2 - \tau_n} \right], \quad (1)$$

where:

f = fraction leached

Z_1 = fraction of ions initially mobile,

Z_2 = fraction of ions initially present in the solid,

k_2 = first-order release rate constant, (time⁻¹),

$$\tau_n = \frac{n^2 \pi D}{R^2}, (\text{time}^{-1}),$$

D = diffusivity, (length²/time),

R = sphere radius, (length),

n = index of infinite series summation,

t = time.

This equation can be evaluated precisely except when the infinite series is slow in converging at small time values.

The fraction leached equation can be interpreted as to mechanism by splitting it into the following three parts:

$$f = f_d + f_r + f_i \quad (2)$$

The term f_d is the contribution of pure diffusion to the fraction leached, and is defined by

$$f_d = Z_1 \left[1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{\left(\frac{-n^2 \pi^2 D t}{R^2} \right)} \right]. \quad (3)$$

The term f_r is for first-order release and predominates if release is the rate controlling step and if Z_1 is small.

$$f_r = \left(Z_2 \right) \left(1 - e^{-k_2 t} \right). \quad (4)$$

The interaction between the release and diffusion is given by f_i .

$$f_i = \frac{6 Z_2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \left(\frac{\tau_n e^{-\tau_n t} - k_2 e^{-k_2 t}}{\tau_n - k_2} - e^{-\tau_n t} \right). \quad (5)$$

In an attempt to partially verify the models developed, leach data from pollucite, (a naturally occurring cesium-aluminosilicate zeolite), were fitted to the equations with excellent results.^[1] However, the models require extended experimental verification before they can be used

to predict the long-term resistance to solution of the radioactive waste-containing solid form.

The solubility rates and mechanisms for glasses are of particular interest since glasses are the leading contenders for the final waste form. Unfortunately, the chemistry of glass-water reactions is quite complex and seems to vary with changes in the experimental leach procedure. If reliable predictions of leach data are to be employed, an attempt must be made to devise a general mechanism that can be used to describe the seemingly diverse leach data that are in the literature. An ARHCO study^[2] based on mechanisms proposed in the literature, has resulted in an attempt to collect these partial mechanisms into the following unified theory to explain much of the existing leach data.

The mechanism of glass-water interaction is based upon the concept of the glass structure as consisting of basic SiO_4 tetrahedral units that are linked at their vertices by bridging oxygens to form a connected three-dimensional network. Solution of a glass involves the processes of absorption, ion exchange, and diffusion, followed by the chemical processes of lattice attack and ionic reaction in the aqueous phase. Release of an alkali ion to the aqueous phase by diffusion can be considered in two separate steps; one involves the process by which an alkali ion bonded to the nonbridging oxygen is released, and the other involves the migration of this "free" cation through the lattice. It is suggested that both steps always take place, but that the actual mechanism of each depends upon the experimental conditions employed.

An example of one specific experimental condition is the investigation of self-diffusion of alkali ions in silicate glasses by measurement of electrical conductivity. The release mechanism in this case requires the bonded metal ion to attain sufficient vibrational energy, which, when oriented along the bond direction, is able to break the metal ion-nonbridging oxygen bond. Since there is an energy distribution for the alkali ions at any specific temperature, there will be a certain number of the metal ions available for migration through the glass lattice. In addition, since the alkali ions are coordinated with various numbers of bridging and nonbridging oxygens, a range of binding energies should exist for these ions. Thus, it is reasonable to consider some alkali ions to be more easily released than others.

Finally, the importance of determining leach rates under actual storage conditions must be mentioned. The extrapolation of leach data obtained under laboratory conditions is likely to be inadequate or misleading if the final conditions of storage vary markedly from the laboratory experiment.

STABILITY

A solid phase is defined as "stable" when it is in chemical equilibrium with its environment. Under this condition, no net changes, (e.g., dissolution, change of state, etc.) of the solid take place. Statistically, however, in a balanced way, some ions of the solid phase exchange with ions in the fluid phase of the solid's environment. The solubilities of ceramics, silicate glasses, and silicate minerals, are very low. If such materials are stored in a chemically stable environment, the radionuclides they contain will be virtually immobilized.

The radionuclide-containing waste form must be in equilibrium with the environment of its final storage site, or be capable of achieving equilibrium without permitting long-lived radionuclides to become mobile. Decisions regarding the optimum waste form will be more logically developed if methods are available to predict their long-term stability with a high degree of confidence based on thermodynamic and geological arguments.^[3] Although the selection of subsurface sites is implied, they are not the only choice and considerations of chemical stability are equally applicable to surface storage.

WASTE FORM

Research on waste forms has produced glasses and synthetic silicate minerals. Aqueous experiments ranged from room temperature to hydrothermal processes and included the use of gels and reactions with clays.^[4-6] The high temperature processes ranged from making glasses^[7-9] to developing a thermite process that produced crystalline aluminosilicates in a glassy matrix.^[10]

As more is learned about the ability of silicate structures to immobilize radioactive elements, the concept of converting high-level liquid radioactive wastes into rock-like silicates has become increasingly promising.^[11] Except for a few gaseous radionuclides (e.g., tritium, krypton, iodine, and xenon), fission products form metallic ions, which in turn can be processed into silicates of low solubility.

The three radionuclides that are given major attention when considering the need for long-term storage are ^{137}Cs , ^{90}Sr , and ^{239}Pu . Both strontium and plutonium form the

poorly soluble silicates, Sr_2SiO_4 and PuSiO_4 . Plutonium silicate is a structural analog of zircon, ZrSiO_4 , and has extremely low solubility. Strontium also forms a number of aluminosilicates, one of which is a strontium feldspar. Both the strontium silicate and the strontium aluminosilicates have very low solubilities and all are stable at elevated temperatures. In addition, the silicate and aluminosilicate forms are essentially inert and unreactive with most geologic materials, except for hydrothermal solutions and subsurface waters of low pH. Cesium is highly soluble and volatile in most of its chemical forms; however, pollucite is stable in neutral or basic environments. The conventional method of forming synthetic pollucite involves hydrothermal techniques at elevated temperatures and pressures. In experiments at Hanford, pollucite has been synthesized at atmospheric pressure and 90°C .^[11]

The selection of the most suitable environmental site for the final storage of a radioactive waste depends in part on the characteristics of the waste. If the waste is in the form of an aqueous solution, a salt cake or a calcine, it should be stored where it is isolated from natural water percolation because of its high solubility. Such wastes have been kept in storage tanks on an interim storage basis. If the waste has been separated and concentrated as cesium chloride, the steel container for the waste must be protected from corrosion because of the high solubility of cesium chloride. If, however, the waste is converted to a highly insoluble solid by appropriate chemical treatment, the resulting solid will be resistant to leaching under all foreseeable conditions, and in addition, will be safe to transport and store. Placing such solidified wastes in excavated caverns in a

geologic formation possesses the advantage of allowing retrieval of the waste, if necessary. At the same time, the waste will be safe from natural as well as man-made hazards. In the event of destruction of the chamber by earthquake or following corrosion of the waste canister, the solidified waste must be chemically compatible with the host rock and of low solubility so as to be slow to release radionuclides to the groundwater in the event of flooding of the storage chamber.

WASTE COMPATIBILITY

Radioactive wastes are transported, or stored for interim periods, by the use of containers of high integrity. The permissible time for such storage is some fraction of the anticipated lifetime of the container. Assessing the compatibility between radioactive wastes and a host rock involves the determination of the reactions, products, and product concentrations that result from contact between radioactive waste and the host rock as a function of time and ambient physical and chemical conditions. In the absence of, or eventual failure of a container, immobilization of the waste becomes increasingly important. Silicification of the waste provides one method of immobilizing the radionuclides. Also, a hydrothermal process^[4] may be used to convert radioactive waste to analogs of silicate minerals. Another process^[4] could be conversion of wastes to silicate materials in a non-aqueous pyrochemical process. These stable materials of low solubility could possibly be stored safely in deep underground caverns in rock (e.g., basalt, in which the water has a high pH and is saturated with alumina and silica).

RECOMMENDATIONS

The understanding thus far developed represents a preliminary attempt to evaluate considerations of a geochemical nature that relate to the many problems associated with the permanent storage of solidified radioactive wastes in a basalt cavern. A major advance in the understanding of the many parametric controls over the long-term containment of these wastes requires substantial additional research and development effort. To cite just a few examples of the kinds of additional information needed before a storage facility could be safely employed, one must determine, among other factors:

- (1) The character of the solidified waste. This would involve a description of the macroscopic physical and chemical properties of the solid and in addition, a quantification of the relevant thermodynamic parameters by use of phase equilibria, solubility studies, radiolytic studies, stored energy data, etc.
- (2) The character of the host rock.
- (3) The compatibility of the two.
- (4) The consequences of chemical reactions between the waste and the rock.

Chemical reactions in a wet, as well as in a dry environment, will have to be considered to allow for the possibility of eventual flooding of an underground cavern.^[5]

The effect of radiation on each component, including the effect of stored energy on stability, solubility, and compatibility must be understood.

The need for the above information is dictated by the requirement that if the final storage of radioactive wastes is to be safely controlled by placing these wastes in deep underground caverns excavated in geologic formations, it is first necessary to understand short-term, and to be able to predict long-term, chemical compatibility between the waste materials and the host rock.

REFERENCES

1. D. E. Griffing, Progress Report on The Development of Models for the Description of Radionuclide Transport in Solids, ARH-SA-190 Rev., August 1974.
2. F. E. Diebold, Discussion of Glass-Water Interactions, ARH-2905, September 1973.
3. J. W. Shade, An Approach to the Prediction of Waste-Form Stability, ARH-ST-105, October 1974.
4. G. S. Barney and L. E. Brownell, The Fixation of Radioactive Wastes in Cancrinite for Safe, Long-Term Storage, U.S. AEC Report No. ARH-IR-195, June 1973.
5. G. S. Barney, Fixation of Radioactive Waste by Hydrothermal Reactions with Clays, U.S. AEC Report No. ARH-SA-174, January 1974.
6. G. S. Barney, Immobilization of Aqueous Radioactive Cesium Wastes by Conversion to Aluminosilicate Minerals, U.S. ERDA Report No. ARH-SA-218, May 1975.
7. H. Babad, A. L. Dressen, C. W. Hobbick, W. W. Schulz, Glass Forms for Immobilization of Hanford Wastes, ARH-SA-210, April 1975.

8. The Endothermic Process - Application to Immobilization of Hanford In-Tank Solidified Waste, ARH-2800, July 1973.
9. C. W. Hobbick, M. J. Kupfer, J. W. Mendel, W. W. Schulz, Glass Forms for Alpha Waste Management, ARH-SA-239, July 1975.
10. R. E. Isaacson and L. E. Brownell, Continuous Process for Immobilization Radionuclides Including Cesium and Ruthenium Fission Products, ARH-SA-222, April 1975.
11. L. E. Brownell and R. E. Isaacson, Ultimate Storage of Radioactive Wastes in Terrestrial Environments, ARH-SA-126, August 1972.

(This page intentionally blank)

CHAPTER VIII
TECTONIC STUDIES

SUMMARY

The Pasco Basin region has had a history of moderate earthquake activity that can be expected to continue indefinitely. Some historic earthquakes have had intensities of greater than VI MM (Modified Mercalli Scale) at their epicenters, but none of these have actually occurred on the Hanford Reservation. Consequently, the intensity produced by them at Hanford has been less than VI MM, (probably IV for most).

Microearthquake activity has been monitored in the Hanford region since 1969. Microearthquakes are numerous and relatively continuous. They are concentrated in time and space into microearthquake clusters. The epicenter locations of the microearthquakes form diffuse bands rather than sharply defined linear trends (which would be expected with active faults). The mere occurrence of the historic earthquakes and microearthquakes indicates that the crust in the Hanford region is being tectonically deformed, but no evidence suggests that this deformation is concentrated along a major, regional fault, hidden or otherwise. Similarly, trilateration and triangulation surveys have not revealed significant horizontal strain accumulation. Leveling surveys have indicated a continuation of folding in the region, apparently in an episodic fashion.

Studies of known faults in the Hanford Reservation region are largely incomplete, and results are inconclusive.

HISTORIC EARTHQUAKES IN THE PACIFIC NORTHWEST

The United States Coast and Geodetic Survey has compiled a Seismic Risk Map (Figure 1) using the historic records of earthquakes occurring in the United States since 1840. This map is updated annually and gives an approximation of the expected long-term earthquake hazards for different regions of the United States. The Seismic Risk Map shows the eastern half of Washington state to be within what is designated as a Zone 2 area indicating a potential for moderate damage from earthquakes. The nearest Zone 3 areas - which have a potential for major damage from earthquakes - are: (1) western and northwestern Washington (around and within Puget Sound), (2) southwestern Montana, eastern Idaho, northwest Wyoming, western Utah, and (3) northern Nevada, northern California. The Puget Sound area is the nearest Zone 3 area to the Hanford Reservation.

A visual examination of the epicenter locations for earthquakes of intensity VI MM or greater, occurring in Washington State between 1842 and 1974 (Figure 2)^[1] indicates that the Hanford Reservation is more than 150 kilometers from the seismically active Puget Sound region. Nevertheless, within 150 kilometers of Hanford are the epicenters of the 1936 Milton-Freewater (near Walla Walla, Washington) earthquake (VII MM), the 1918 Corfu earthquake (V-VI MM), the 1893 Umatilla earthquake (VII ? MM), and some earthquakes near Chelan, Washington (IV-V MM). These earthquakes, plus four others that occurred in the Puget Sound area, are described in Table I in order of decreasing intensity produced by them at Hanford.^[2] A comparison of Table I and Figure 2 indicates that no historic earthquake occurring within 150 kilometers of the Hanford Reservation has had

FIGURE 1
UNITED STATES SEISMIC RISK MAP

FIGURE 2
EARTHQUAKE EPICENTER LOCATIONS, WASHINGTON AND NEARBY

TABLE I

DESCRIPTIONS OF SELECTED LARGE EARTHQUAKES
IN THE PACIFIC NORTHWEST AND THEIR ESTIMATED INTENSITY
AT HANFORD

(This Table is a summary of written descriptions
in Reference 2)

<u>Earthquake Location</u> <u>(Latitude, Longitude)</u>	<u>Date</u>	<u>Magnitude</u> <u>Intensity (MM)</u> <u>(at Epicenter)</u>	<u>Intensity (MM)</u> <u>(at Hanford)</u>	<u>Comments</u>
Milton-Freewater (46.0 118.3)	7/15/36	$\frac{5-3/4}{VII}$	IV	Estimated duration 10-30 seconds. Important because of proximity to Blue Mountains and Olympic-Wallowa lineament.
N. W. Washington (near Canadian Border)	12/14/1872	<u>unknown</u>	IV	- - - -
Corfu (46.7 119.5)	11/01/18	$\frac{\text{unknown}}{V-VI}$	V-VI	Epicenter location uncertain. Important because of proximity to Saddle Mountains structure and Hanford.
Near Seattle (47.4 122.3)	4/29/65	$\frac{6-1/2}{VII-VIII}$	IV	Hanford is in the I-VI intensity zone on the NOAA Isoseismal Map for this earthquake.
Puget Sound (47.1 122.7)	4/13/49	$\frac{7}{VIII}$	I-IV	Largest earthquake recorded instrumentally within 200 miles of Hanford.
East of Seattle (47.4 121.7)	4/29/45	$\frac{5-1/2}{VII}$	I-IV	- - - -
Puget Sound (47.3 122.7)	2/14/46	$\frac{5-3/4}{VII}$	I-IV	Not felt in Richland.
Near Seattle (47.2 123.0)	11/12/39	$\frac{4-3/4}{VII}$	I-IV	- - - -
Near Chelan	4/23/43	$\frac{\text{unknown}}{VI}$	I-IV	- - - -
Chelan (47.7 120.0)	8/05/59	$\frac{\text{unknown}}{VI}$	I-IV	Not felt in Richland.
Near Chelan (47.8 120.1)	12/30/1876	$\frac{\text{unknown}}{V}$	I-III	- - - -
Umatilla (46.0 119.0)	3/15/1893	$\frac{\text{unknown}}{VII?}$	?	Wall of a stone building tumbled. Intensity at Hanford unknown.

a magnitude greater than 5-3/4 or intensity at the epicenter greater than VII MM, and none have produced an intensity on the Hanford Reservation greater than IV MM, except possibly the Corfu earthquake. In addition, none of the larger magnitude earthquakes (up to 7.0) in the Puget Sound region has produced an intensity greater than IV on the Hanford Reservation.

Thus, the Hanford Reservation and nearby area can be described as having had a moderate level of earthquake activity in the historic past. This level of activity can be expected to persist indefinitely.

Using past levels of earthquake activity to predict future levels is a common technique for assessing the earthquake hazard for a given area. But recent studies in the People's Republic of China have indicated that perhaps some caution should be exercised when doing this, particularly if the time interval for the prediction is on the order of hundreds of years or more.^[3]

The earthquake record in China extends nearly 3,000 years B.P. This record indicates that China has experienced several major earthquakes and that these major earthquakes have occurred in various earthquake-prone regions. Some of these regions have had vastly different earthquake histories both before and after the occurrence of a great earthquake. For example, some great earthquakes have occurred in regions where the rate of seismicity has been at an approximately constant level, both before and after the occurrence of the major earthquake. Other major earthquakes, however, have occurred in regions where the rate of seismicity shows distinct secular variations: several hundreds of years of high to moderate activity followed by tens to hundreds of years

FIGURE 3
EARTHQUAKE EPICENTERS, MAJOR ANTICLINES, AND FAULTS;
HANFORD RESERVATION REGION

of relative quiescence terminated by the major earthquake. Still other regions show secular variations wherein the major earthquakes were both preceded and followed by periods of low activity or even quiescence. Secular variations in earthquake activity such as these are not unique to China but appear to be typical of those regions where historical records extend over a sufficiently long interval. This is true, for instance, in the Middle East.^[3] The implication of such secular variations in earthquake activity are obvious. The earthquake record in the entire Pacific Northwest is less than 150 years. Consequently, any attempt to predict future earthquake activity in the Hanford region based on this meager record should be done with extreme caution and prudence.

EARTHQUAKES AND GEOLOGIC STRUCTURES IN THE HANFORD REGION

Macroearthquakes

A visual examination of the spatial association between earthquakes having intensity IV and larger (on the Modified Mercalli Scale of I through XII), and geologic structures in the Hanford Reservation region indicates no obvious or unambiguous linear pattern of epicenters associated with any of the known faults (Figure 3). However, the group of eight earthquakes near Walla Walla, Washington, form a southwest-northeast trending pattern parallel to the southwest-northeast trending Blue Mountains structure. The largest of these earthquakes near Walla Walla, the 1936 Milton-Freewater earthquake, caused intensity IV MM ground motion at Hanford (Table I) and has been interpreted as being associated with the Olympic-Wallawa lineament^[4] (the Rattlesnake-Wallula

lineament on Figure 3 is a segment of the Olympic-Wallowa lineament). In addition, Jones and Deacon^[5] proposed that the 1918 Corfu earthquake was related to movement on the Saddle Mountains fault, but this proposal is now considered doubtful (evidence for this is discussed below under "Geologic Structures and Evidence for Faults").

Microearthquakes

In March of 1969, a network of seven high-sensitivity seismometers was established in the Hanford area by the National Center for Earthquake Research of the United States Geological Survey to determine the location and magnitude of microearthquakes and thereby detect patterns of seismic activity that may exist. The network has been subsequently enlarged, and currently consists of 29 seismograph stations (Figure 4). The University of Washington Geophysics Program assumed responsibility for operation of the network in July of 1975. Preliminary results from the microseismic network are in two open-file reports by the U. S. Geological Survey^[6,7] and in three quarterly reports and one annual report by the University of Washington.^[8-11] In addition, a third open-file report is being prepared by the U. S. Geological Survey that will evaluate and interpret all data collected from 1969 to 1976 when the U. S. Geological Survey was responsible for the operation of the microseismic network.

Preliminary results to date indicate that more than 90 percent of the microearthquakes occurring in the Hanford region are shallow, originating at depths of less than 10 kilometers, and that less than 10 percent are deeper, originating at depths of more than 10 kilometers (Figure 5).

FIGURE 4

SEISMOGRAPH STATIONS - MICROSEISMIC NETWORK

MAGNITUDE (RICHTER SCALE)	FOCAL DEPTH	
	LESS THAN 10 KILOMETERS	GREATER THAN 10
3.0-3.3	○	■
1.0-2.5	○	■
0.1-0.5	○	■

V7606-9.7

FIGURE 5

MICROEARTHQUAKE EPICENTERS,
HANFORD RESERVATION REGION

Furthermore, the shallow microearthquakes are not randomly distributed but show a clustering pattern. The individual clusters of microearthquakes are spatially arranged in a somewhat diffuse, linear pattern trending roughly east-west, approximately parallel to the Saddle Mountains structures (compare Figure 3 and Figure 5). Detailed studies of several of the microearthquake clusters made with a portable seismic network installed when the clusters began to form indicate that, although the basalt was fracturing, " . . . large, scale, through-going fault zones are unlikely."^[12] The deep microearthquakes are confined to depths of between 10 and 27 kilometers, and form a somewhat diffuse, north-south trending band (Figure 5). The spatial arrangement of the deep earthquakes within the band does not appear to delineate a major fault.

Thus, the occurrence of the microearthquakes does indicate that the crust beneath the Hanford Reservation is currently being deformed by faulting, but the spatial pattern of the epicenters reveals no obvious evidence of a major, currently active fault.

Geologic Structures and Evidence for Faults

Geologic mapping of surficial deposits, geophysical investigations, drilling of shallow hydrologic and engineering bore holes, and excavations of shallow trenches and exploratory pits have not revealed features interpreted as recent faults on or at shallow depths beneath the Hanford Reservation.^[2,13,14] Likewise, as mentioned above, studies of macro- and microseismic activity have not revealed evidence for major, currently active subsurface faults. Consequently, most attempts at detecting recent faults have been directed toward evaluating geologic structures in the

Pasco Basin and surrounding region within an approximately 100 kilometer radius of the Hanford Reservation.

The Pasco Basin is surrounded on three sides by anticlinal ridges. To the north are the Saddle Mountains, to the west is Manashtash Ridge - Hanson Creek and Umtanum Ridge, and to the south is Rattlesnake Mountain. These anticlinal ridges, and others throughout the region, possess several features in common: they trend east or southeast; they are transversely asymmetrical with one limb having a gentle dip and the other a steep dip; and the crest of the anticline is typically broad and open, but may be locally complicated by en echelon folding or minor flexures. Several of the ridges have faults - or what have been interpreted as faults - associated with them. Largely because of the presence of these faults, the ridges have been mapped and studied in varying detail, mostly since 1966, to determine if the faults actually exist; and if they do, to determine if any remain active.

The geological field studies described below illustrate what is apparently at least one reason for sharply divergent geological interpretations of the Pasco Basin. Investigators who did only reconnaissance studies have often concluded that the alignment of breccia zones and certain topographic features indicate the presence of laterally extensive faulting.^[5,13,15,16] Investigators who did detailed field studies, or who have had extensive geological field experience, often concluded that the same breccia zones are either nontectonic (e.g., flow breccias), or if tectonic, formed essentially contemporaneously with folding and in response to the same lateral forces producing the folds; and that the topographic features can be explained

by differential erosion during Pleistocene flooding. [2,6,17,19]

Saddle Mountains

One of the earliest and most important geological studies was that of Jones and Deacon. [5] Its importance lies not in its accuracy, but in the questions it raised concerning recent faulting. Mollard, in Jones and Deacon [5] studied aerial photographs and reported several "fault systems" in the Hanford region. Among these were fault systems in the Saddle Mountains, on Gable Mountain-Gable Butte, and along the Rattlesnake Mountain-Wallula Gap lineament, a segment of the Olympic-Wallowa lineament. [4] According to Jones and Deacon, the Saddle Mountains fault (Figure 3) shows evidence of recent tectonic activity, including fresh scars, depressions, and grabens which were probably associated with the Corfu earthquake of 1918. In addition, they stated that the Gable Mountain-Gable Butte fault system contains cross faults that may be part of a larger fault system which, in turn, is " . . . a potential locus for future fault movement due to earthquakes . . ." and the Rattlesnake Mountain-Wallula fault system shows evidence of recent tectonic activity including the Milton-Freewater earthquake of 1936.

Because of the implications of these conclusions for establishing seismic design criteria for Hanford facilities, the Atomic Energy Commission requested an additional study to verify or refute the findings of Jones and Deacon. This additional study was conducted by Bingham, et.al., [6] of the U. S. Geological Survey. It was based not on aerial photographs, but on detailed field studies that included limited trenching. Bingham, et.al., [6] concluded that the depressions, scarps, and graben-like features associated with the Saddle Mountains fault were not related to the

Corfu earthquake of 1918 nor to recent tectonic activity along the fault, but were genetically associated with large landslide blocks which probably formed during Pleistocene time. Furthermore, Carbon-14 age dating of layers of wind-blown sand within the landslide deposit indicated that " . . . the Saddle Mountains faulting can be dated clearly only as older than Pinedale age (12,000 to 25,000 years ago)." Results of other geological field work^[2] and an aerial reconnaissance survey^[18] in the Saddle Mountains is consistent with the Bingham, et.al.,^[6] interpretation.

Gable Mountain - Gable Butte

The Gable Mountain-Gable Butte area is completely within the Hanford Reservation. Jones and Deacon^[5] mapped a fault on both Gable Mountain and Gable Butte, and Bingham did discover a fault on Gable Mountain, but not on Gable Butte.^[6] The Gable Mountain fault has been exposed by exploratory trenching. The geometry of the fault suggests that the fault is contemporaneous with folding. Carbon-14 age dating of wood fragments^[6] taken from undisturbed sediments overlying the fault indicates no movement on the fault in more than 40,000 years.

Rattlesnake Mountain - Wallula Gap

Bingham, et.al.,^[6] did only reconnaissance mapping along the Rattlesnake Mountain-Wallula Gap lineament (Figure 3). They did not resolve questions concerning the presence or absence of faulting along the lineament, but merely noted the presence of several aligned linear outcrops of breccias and strongly sheared zones that they interpreted as " . . . indicating the existence and continuity of the Rattlesnake-Wallula Gap fault." Other studies have agreed

in essence with this interpretation, but they too were mainly reconnaissance studies.^[13,15]

The most recent study, however, involved detailed surface mapping at selected localities along the lineament and reinterpreted the breccia outcrops as both flow breccia, and as breccia produced by slippage between basalt layers during folding; nonetheless, some evidence was found for small faults of limited displacement and lateral extent along the Rattlesnake-Wallula Gap lineament.^[2] The exact determination of the extent displacement and age of faulting along the Rattlesnake-Wallula Gap portion of the Olympic-Wallowa lineament remains unresolved, but the available evidence does not indicate that a continuous or sharply defined fault along which recent or historic movement has occurred. This conclusion is consistent with microearthquake monitoring that failed to reveal an alignment of earthquake epicenters with the lineament.

Wallula Gap Fault

The Wallula Gap fault is in Wallula Gap about 50 kilometers southeast of Hanford. The trace of the fault is about five kilometers south of the inferred trace of the Olympic-Wallowa lineament.^[20] The Wallula Gap fault has a proposed westward extension along the front of the Horse Heaven Anticline,^[13] but this extension has been disputed because of lack of evidence of stratigraphic offset in overlying strata.^[2] East of Wallula Gap, the fault merges with the Olympic-Wallowa lineament. Evidence for the existence of the Wallula Gap fault includes breccia outcrops and aligned topographic features.^[5,13,15] The same evidence has been questioned because of a reinterpretation of the breccias as

having formed by slippage during folding and a reinterpretation of the topographic features as having resulted from differential erosion during Pleistocene flooding.^[2,17]

Badger Coulee Alignment, Horn Rapids Alignment, and Horse Heaven Anticline

Several other structures in the Hanford region have been interpreted as having faults associated with them. Among these are the Badger Coulee Alignment and Horn Rapids Alignment.^[16] Both of these are subparallel to the Olympic-Wallowa lineament (Figure 3). Detailed mapping has revealed a lack of stratigraphic offset along the trace of the proposed faults associated with the alignments.^[2]

The Horse Heaven Anticline has been interpreted as a major, possibly active, tectonic feature that is potentially more significant as an earthquake generator than the Olympic-Wallowa lineament. Field evidence for recent faulting along the structure and the continuity of the structure itself from the Cascade Mountains to the Blue Mountains has been cited as supporting this interpretation.^[14]

Maximum Anticipated Earthquake

Inasmuch as no known or inferred recent faults have been discovered on or beneath the Hanford Reservation, displacements caused directly by fault rupture are thought to be highly unlikely. Other seismic hazards, such as landslides, differential ground setting, soil liquefaction, seiches, floods from dam or levee failure, and fires, are surface phenomena and can also be disregarded. The remaining and most important phenomenon is earthquake induced ground shaking.

Several historic earthquakes in the Pacific Northwest have produced different intensities of ground shaking on the Hanford Reservation. Table I describes several such earthquakes and lists them in order of decreasing intensity at Hanford. Ground shaking of intensity IV is the largest recorded to date at Hanford. Several authorities^[1,18,22,23] have estimated that the maximum anticipated earthquake to be expected in the Rattlesnake-Wallula area or perhaps near the Saddle Mountains could have a magnitude of 5.5 to 6.8 and produce up to MM-VIII intensity ground shaking with 25 percent gravity accelerations.^[14] The consequences of this hypothesized acceleration level on a mined cavern in the basalt must be evaluated.

A comparison of seismograms from seismometers deep within mines with seismometers on the ground surface above the same mines has revealed little difference in the intensity of shaking between the two locations.^[21]

GEODETIC SURVEYS

Tillson^[24] has analyzed geodetic data from first order benchmark (leveling) and triangulation network surveys across the Columbia Plateau made by the U. S. Coast and Geodetic Survey. Results of his analysis indicate that the Columbia Plateau as a whole is gradually basining " . . . at an average rate of 1 mm per year." Locally, however, some areas within the Plateau are basining at rates of up to 4 mm per year and some others are rising at rates of up to 3 mm per year. The leveling results indicated no " . . . contemporary vertical movement that would be associated with known or postulated fault systems . . ." The triangulation results indicated no discrepancies that might

indicate horizontal displacement, and those discrepancies in position that were found were not greater in magnitude than " . . . the magnitude inherent in the measurement system." [24] The triangulation network used in this analysis extended across both the Hanford Reservation and the Olympic-Wallowa lineament.

Following Tillson's work, a trilateration network consisting of 19 stations was established across the Hanford Reservation from the Saddle Mountains to Rattlesnake Mountain (Figure 6). The network has been surveyed four times (March and June 1972, March 1973, and May 1975) using laser geodolites having a distance measuring precision of 1 mm between stations in the network. Results of the surveys to date indicate no relative motion of any stations. [25]

Thus, the results of the trilateration survey and the leveling and triangulation survey are consistent with a contemporary-and apparently episodic-downwarping in the Pasco Basin vicinity of the Columbia Plateau at a rate of about 1 mm per year. [24,25] Many geologic processes, including regional deformation, proceed at seemingly uniform rates when observed over long intervals of time, but in reality proceed at varying rates in an episodic fashion when observed over shorter intervals of time. A continuation of folding is also indicated by the post-depositional warping of Ringold beds reported by Brown and McConiga. [26]

RECOMMENDATIONS

A program of basinwide geologic mapping should be initiated and given a high priority. The objective should be the detection and evaluation of capable faults. This program

FIGURE 6
TRILATERATION NETWORK, HANFORD REGION

should involve classical geological mapping supplemented, as necessary, by sufficient geochemical, petrographic, paleomagnetic, and mineralogical studies to insure an adequate knowledge of stratigraphic relationships. Results from geophysical studies such as gravity, aeromagnetic, and seismic surveys should be more fully utilized. Trenching and drilling may be necessary in critical areas.

The Hanford trilateration network should be maintained and surveyed periodically to monitor crustal strain in the region. If possible, the network should be enlarged to the south and east toward Walla Walla, Washington; Milton-Freewater, Oregon; and Umatilla, Oregon. This would extend the net across the Olympic-Wallowa lineament, Wallula Gap fault, the Horse Heaven Hills and other structures in the region of questionable tectonic activity.

Microearthquake monitoring using the Hanford micro-earthquake net now in operation should continue. The seemingly nebulous, diffuse, and somewhat unusual pattern of microearthquake activity now observed may become better defined with time. Continued operation of the net would also provide information relating to faulting mechanisms, regional stress patterns, and physical characteristics of the crust.

REFERENCES

1. N. H. Rasmussen, Seismology Report on Washington, Idaho, Northern Oregon and Western Montana and the Hanford Area, Douglas United Nuclear Report, DUN-1409, 1966 and personal communication, 1976.

2. Washington Public Power Supply System Project No. 1, 1300 MW Nuclear Power Plant, Preliminary Safety Analysis Report, Vol. 1 and Vol. 2.
3. F. Press, M. Bullock, R. M. Hamilton, W. F. Brace, C. Kisslinger, M. G. Bonilla, C. R. Allen, L. R. Sybes, C. B. Raleigh, L. Knopoff, R. W. Clough, and R. Hofheinz, Earthquake Research in China, Transactions, American Geophysical Union, Vol. 56, No. 11, p. 838-881, 1975.
4. E. Raise, The Olympic-Wallowa Lineament, American Journal of Science, Vol. 243-A, p. 479-485, 1945.
5. F. O. Jones and R. J. Deacon, Geology and Tectonic History of the Hanford Area and Its Relation to Geology and Tectonic History of the State of Washington and the Active Seismic Zones of Western Washington and Western Montana, DUN-1410, June 1966.
6. J. W. Bingham, C. J. Londquist and E. H. Baltz, Geologic Investigations of Faulting in the Hanford Region Washington, U. S. Geological Survey, Open-File Report, 1970.
7. A. M. Pitt, Microearthquake Activity in the Vicinity of Wooded Island, Hanford Region, Washington, U. S. Geological Survey, Open-File Report, 1971.
8. Quarterly Technical Report, No. 1 for Hanford and Central Seismic Networks, July 1, 1975 through September 30, 1975, Geophysics Program, University of Washington, Seattle, Washington, February 1, 1976.

9. Quarterly Technical Report, No. 2 for Hanford and Central Seismic Networks, October 1, 1975 through December 31, 1975, Geophysics Program, University of Washington, Seattle, Washington, February 1, 1976.
10. Quarterly Technical Report, No. 3 for Hanford and Central Seismic Networks, January 1, 1976 through March 31, 1976, Geophysics Program, University of Washington, Seattle, Washington, May 1, 1976.
11. S. W. Smith, Microearthquake Monitoring of the Hanford Region, Annual Progress Report, Geophysics Program, University of Washington, Seattle, Washington, March 30, 1976.
12. S. D. Malone, G. H. Rothe, and S. W. Smith, Details of Microearthquake Swarms in the Columbia Basin, Washington, University of Washington Geophysics Program, Seattle, Washington, February 4, 1975.
13. J. A. Blume and Associates, Engineers, Seismic and Geologic Siting Evaluation, Fast Flux Test Facility Near Richland, Washington, JABE-WADCO-03, August 1970.
14. Final Environmental Statement, Waste Management Operations, Richland, Washington, U. S. Energy Research and Development Administration, Vol. 2, Appendix II.3-B and II.3-C.
15. J. W. Skehan, A Continental-Oceanic Crustal Boundary in the Pacific Northwest, Prepared for Air Force Cambridge Research Laboratories, Report No. AFCRL-65-904, p. 52, 1965.
16. J. A. Blume and Associates, Engineers, Supplementary Geologic Investigations for Seismic Evaluation for

- the Fast Flux Test Facility Site Near Richland, Washington, Report No. JABE-WADCO-04, February 1971.
17. R. E. Brown, Reported Faulting in the Pasco Basin, Battelle Northwest Laboratory Report No. BNWL-SA-1704, 1968.
 18. R. H. Jahns, Geologic Factors Relating to Engineering Seismology in the Hanford Area, Washington, Douglas United Nuclear Report, DUN-3100, 1967.
 19. A. C. Waters, Geomorphology of South Central Washington, Illustrated by the Yakima East Quadrangle, Geol. Soc. of American Bull., Vol., 66, no. 6, p. 663-684, 1955.
 20. R. C. Newcomb, Tectonic Structure of the Main Part of The Columbia River Group, Washington, Oregon and Idaho, U. S. Geological Survey, Misc. Geol. Invest. Map I-587, 1970.
 21. C. F. Richter, Elementary Seismology, W. H. Freeman and Co., San Francisco, 1958.
 22. G. W. Housner, Recommended Seismic Design Criteria for Hanford Nuclear Facility - Revised, Douglas United Nuclear Report, DUN-3130, 1967.
 23. J. A. Blume and Associates, Engineers, A Summary Report, Seismic Evaluation and Development of Ground Acceleration and Response Spectra For FFTF Site, JABE-WADCO-03, 1971.
 24. D. D. Tillson, Analysis of Crustal Changes in the Columbia Plateau Area From Contemporary Leveling and Triangulation Measurement, BNWL-CC-2174, February 1970.

25. W. H. Prescott and J. C. Savage, Progress Report on Geodolite Measurements at Hanford, Washington, Informal Report, National Center for Earthquake Research, December 1973.
26. R. E. Brown and M. W. McConiga, "Some Contributions to the Stratigraphy and Indicated Deformation of the Ringold Formation, Northwest Science, Vol. 34, No. 2, 1960.

ACKNOWLEDGEMENTS

Publication of this report was made possible by a contract from the U. S. Energy Research and Development Administration through the Office of Waste Isolation, Union Carbide Nuclear Company, a contractor of the U. S. Energy Research and Development Administration. Work was under the technical direction of the Atlantic Richfield Hanford Company (ARHCO) with program management provided by the Energy Research and Development Administration, Richland Operations Office.

The document was prepared by the collected efforts of members of the Research and Engineering Division at ARHCO. The figures in the document were prepared by VITRO Engineering, a Division of Automation Industries, Inc. Extensive technical support was received from the United States Geological Survey.

The technical work was initiated in 1968 under Mr. R. E. Isaacson. Individual chapters of this document were written by Messrs. D. J. Brown, R. E. Isaacson, R. K. Ledgerwood, and T. W. Taylor and Drs. R. A. Deju, C. Klingsberg, and C. W. Myers of ARHCO. Dr. R. A. Deju was Program Manager.

As in any large effort of any disciplinary nature, many individuals and organizations whose names are not specifically mentioned, contributed to the success of this project. To them go our greatest appreciation.

DISTRIBUTION

Number of Copies

2	<u>Battelle Pacific Northwest Laboratories</u> T. W. Ambrose A. M. Platt
1	<u>Boeing Computer Sciences Richland</u> R. W. Nelson
8	<u>Consultants</u> A. C. Waters, Santa Cruz, CA (2) W. K. Summers, Socorro, NM (2) A. M. Piper, Carmel, CA (2) R. H. Jahns, Stanford U., CA (2)
6	<u>United States Geological Survey</u> G. Debuchanne (2) D. A. Swanson (2) W. Twenhofel (2)
3	<u>United States Environmental Protection Agency</u> G. L. Meyer R. Kaufman J. Sceva
2	<u>Nuclear Regulatory Commission</u> E. P. Regnier (2)
1	<u>United States Bureau of Reclamation</u> Project Geologist, Columbia Basin Project, Ephrata, WA
1	<u>United States Army Corps of Engineers</u> District Geologist, Walla Walla, WA
1	<u>United Nuclear Industries, Richland</u> R. K. Robinson

DISTRIBUTION (continued)

Number of Copies

50

Office of Waste Isolation, Union
Carbide Corporation, Nuclear Division,
Oak Ridge, TN

C. A. Zerby (50)

285

U. S. Energy Research and Development
Administration Technical Center,
Oak Ridge, TN

2

U. S. Energy Research and Development
Administration, Oak Ridge Operations
Office

22

U. S. ERDA, Richland Operations Office

J. H. Straub
L. F. Perkins
P. G. Rhoades
R. L. Hames
F. R. Standerfer
T. A. Bauman (2)
O. J. Elgert (15)

1

Washington State University, Pullman, WA
Department of Geology

1

University of Washington, Seattle, WA
Department of Geology

1

Central Washington State College,
Ellensburg, WA
Department of Geology

1

Eastern Washington State College,
Department of Geology

1

Washington Public Power Supply System,
Richland, WA

D. D. Tillson

DISTRIBUTION (continued)

Number of Copies

1	<u>State of Washington, Department of Ecology, Olympia, WA</u>
1	<u>University of Idaho, Moscow, ID</u> Department of Geology
109	<u>Atlantic Richfield Hanford Company</u> G. Burton, Jr. J. H. Warren J. Faulhaber C. W. Malody G. O. Wheeler A. T. White H. P. Shaw W. Campbell D. E. Kelley D. D. Wodrich R. W. Smith (5) R. C. Roal V. D. Schrag W. M. Harty, Sr. H. Babad R. A. Deju (65) M. W. Legatski (6) D. J. Brown (2) P. A. Eddy (2) R. E. Isaacson (2) C. Klingsberg (2) R. K. Ledgerwood (2) C. W. Myers (2) C. T. Webster (4) ARHCO Document Control (3)