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Probability Encoding of Hydrologic Parameters for Basalt

Elicitation of Expert Opinions from a Panel of Five Consulting Hydrologists

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Prepared for Rockwell Hanford Operations,
a Prime Contractor to the U.S. Department of Energy
under Contract DE-AC06-77RL01030

Rockwell International
Rockwell Hanford Operations
Richland, Washington

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Date Manuscript Completed: November 1984

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ABSTRACT

The Columbia River basalts underlying the Hanford Site in Washington State are being considered as a possible location for a geologic repository for high-level nuclear waste. To investigate the feasibility of a repository at this site, the hydrologic parameters of the site must be evaluated. Among hydrologic parameters of particular interest are the effective porosity of the Cohassett basalt flow top and flow interior and the vertical-to-horizontal hydraulic conductivity, or anisotropy ratio, of the Cohassett basalt flow interior. The Cohassett basalt flow is the prime candidate horizon for repository studies.

Site-specific data for these hydrologic parameters are currently inadequate for the purpose of preliminary assessment of candidate repository performance. To obtain credible, auditable, and independently derived estimates of the specified hydrologic parameters, a panel of five nationally recognized hydrologists was assembled. Their expert judgments were quantified during two rounds of Delphi process by means of a probability encoding method developed to estimate the probability distributions of the selected hydrologic variables.

The results indicate significant differences of expert opinion for cumulative probabilities of less than 10% and greater than 90%, but relatively close agreement in the middle ranges of values. The principal causes of the diversity of opinion are believed to be the lack of site-specific data and the absence of a single, widely accepted, conceptual or theoretical basis for analyzing these variables.

typically 80% of the cumulative probability range (between 10% and 90%) all five experts agreed to within two to three orders of magnitude for probability distributions of effective porosity values and to within one to two orders of magnitude for probability distributions of anisotropy ratios. Outside of this range, however, disagreement on values for these two parameters widens to four to five orders of magnitude. Comments by the panelists indicate that the lack of consensus directly reflects the diversity of generic information bases and conceptual models available to them. In spite of this diversity of opinion, however, many significant points of agreement emerged.

Values for four of the five panelists' probability distributions are within one order of magnitude of each other over 80% of the probability range (between 10% and 90%). Panel agreement improves considerably if the estimated values at the extremes of the probability distributions for these two parameters are excluded. When such "tails" of the distributions are excluded, panelists often agree to well within one order of magnitude; for the anisotropy ratio, panel agreement is within a factor of two. Cumulative probability distributions of the panel are in better agreement for the anisotropy ratio than for effective porosity. For effective porosity, the agreement among panelists improves significantly at the maximum value end of the distribution; whereas, for the anisotropy ratio, the reverse is true.

Agreement of the experts is especially noteworthy in view of the fact that the quantity and type of hydrologic field data currently available for the site are inadequate to significantly reduce parameter uncertainty. Consequently, the experts had to rely extensively on broad theoretical considerations and their considerable professional experience. The primary disagreements are at the distribution outliers; this result is expected given the complex nature of the variables and the scarcity of the site-specific data.

EXECUTIVE SUMMARY

BACKGROUND

The Office of Civilian Radioactive Waste Management (OCRWM) Program was created by the U.S. Government for the purpose of investigating the feasibility of storing nuclear wastes in deep geologic formations. The Basalt Waste Isolation Project (BWIP) is one of several major research and development projects conducted under the direction of the OCRWM Program. Rockwell Hanford Operations (Rockwell) is the prime contractor to the U.S. Department of Energy (DOE) for investigating the feasibility of siting a nuclear waste repository in the basalts underlying the Hanford Site.

To establish feasibility, the performance of such a repository is required to comply with the applicable licensing regulations and guidelines. The main criterion for assessing performance of a nuclear waste repository in geologic formations is the isolation of the radionuclides from the accessible environment for 10,000 yr. The primary mechanism for potential transport of the nuclear waste to the accessible environment is groundwater flow. The groundwater flow paths, in turn, are influenced principally by several hydrologic factors including specific values of effective porosity and the ratio of a flow interior's vertical-to-horizontal hydraulic conductivity, or anisotropy ratio.

Site-specific data on hydrologic properties of host-rock basalts at the Hanford Site currently are insufficient for refined assessment of repository performance. However, Rockwell requires the best estimates available for these parameters for use in preliminary performance assessment studies. To obtain preliminary estimates of these parameters, independent of any internal influence or control, Rockwell chose the Delphi method of eliciting expert opinion. The SRI International (SRI, formerly Stanford Research Institute) probability encoding method was chosen to obtain the experts' probability distributions of these hydrologic parameters in a quantitative, numerical format suitable for use in stochastic modeling of groundwater flow.

PURPOSE OF THE STUDY

The purpose of this study was to obtain unbiased expert opinion on (1) the effective porosity of the Cohassett basalt flow top and flow interior, and (2) the anisotropy ratio of the Cohassett basalt flow interior of the Hanford Site at a megascale (on the order of 100 to 1,000 m) and a macroscale (on the order of 1 to 10 m).

APPROACH

A combination of two decision analysis methodologies was used for this project. These were the Delphi method and the SRI probability encoding method. The Delphi method is a technique widely accepted by the scientific community for eliciting expert opinion on complex issues with multidisciplinary implications. Probability encoding is a process by which uncertainty can be auditably quantified for factors that are important to decision making.

The Delphi method relies on the iterative administration of a carefully prepared questionnaire to persons acknowledged to be experts on the issues of concern. In view of the objectives of this study, a panel of five nationally recognized hydrologists was assembled. Panelists were selected by Analytic & Computational Research, Inc. (ACRi), based on a set of strict qualification criteria. The panel members were highly experienced in estimation of values of hydrologic variables for fractured rock. They were also required to have considerable familiarity with issues related to assessing performance of a nuclear waste repository. The panelists were selected on the basis of a formal, previously conducted, reputational survey.

Two rounds of the Delphi process were administered to the expert panel through carefully prepared questionnaires. The questionnaires adhered strictly to established guidelines of the Delphi methodology and complied with the format and structural requirements of the SRI probability encoding process. Round 1 of the Delphi method was implemented by two interviewers from Applied Decision Analysis who are experienced in the SRI probability encoding method. This round consisted of individual personal interviews lasting 6 to 8 h. Round 2 was administered by mail. Throughout the study, individual panelists were not aware of the identity of other panelists. Background material, which provided information on the objectives of the study and the site-specific values of hydrologic parameters, was made available to the panelists before Round 1 and Round 2.

RESULTS AND CONCLUSIONS

Encoding of expert judgments on probability distributions for values of six hydrologic parameters was accomplished even though existing field data adequate for refined assessment of the six parameters are not yet available. Consequently, the experts interviewed found it necessary to rely extensively on their own concepts of basalt hydrologic properties.

Estimates by the experts indicate a diversity of opinion about the likely values of average effective porosity and the anisotropy ratio. The differences of opinion are appreciably more pronounced at the extreme limits, rather than in the middle, of the range of values. Pairs of experts are often in agreement, but no universal consensus exists. For

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1.0 INTRODUCTION

1.1 BACKGROUND

The Office of Civilian Radioactive Waste Management (OCRWM) Program was created by the U.S. Government in the mid-1970s for the purpose of investigating the feasibility of storing nuclear wastes in deep geologic formations. Currently, the OCRWM Program is focusing on the identification and characterization of candidate sites for a repository. The Nuclear Waste Policy Act of 1982 (U.S. Congress 1983) provides a legislative directive and schedule for site characterization, repository design, licensing by regulatory agencies, construction, and operation of nuclear waste repositories in geologic media.

The Basalt Waste Isolation Project (BWIP) operated by Rockwell Hanford Operations (Rockwell) is one of several major research and development projects conducted under the direction of the OCRWM Program. Rockwell is currently a prime contractor to the U.S. Department of Energy (DOE) for operation of the Hanford Site in south-central Washington State. As such, Rockwell is responsible for investigating the feasibility of siting a repository for terminal disposal of nuclear waste in the basalts underlying the Hanford Site.

To establish feasibility, the performance of such a repository must comply with the applicable licensing regulations and guidelines established by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency (EPA). The currently proposed guidelines for a successful license application are outlined in 10 CFR 60 (NRC 1983) and 40 CFR 191 (EPA 1984).

The main criterion for assessment of performance of a mined geologic repository for nuclear waste is isolation of the radionuclides from the accessible environment for 10,000 yr. The primary mechanism for potential transport of the nuclear waste to the accessible environment is groundwater flow. Thus, the hydrology of a site, which in turn is largely determined by the site geology, plays a critical role in assessing repository performance.

The hydrology of a site is determined by the natural recharge and discharge conditions, by the field gradients of hydraulic head, and by hydraulic conductivity, effective porosity and storativity. Hydraulic conductivity directly controls the groundwater flux. Groundwater flux is important for prediction of the rate of corrosion of the waste canisters and the rate of dissolution of the waste form. Effective porosity determines the velocity of fluid particles moving through the groundwater system; it affects the time required for the dissolved radionuclides to reach the biosphere. Effective porosity also influences the storativity of the rock matrix. However, for fractured, dense rocks such as basalt, storativity values are typically very small.

One of the important factors for assessing repository performance is the anisotropy of the hydraulic conductivity. Although hydraulic conductivity is a second-order tensor, for groundwater flow applications it is often assumed that the coordinate axes are aligned with the principal directions of the tensor. For most horizontally or near-horizontally layered rocks, these axes are oriented in horizontal and vertical directions. The direction of groundwater flow is strongly determined by the relative values of horizontal and vertical hydraulic conductivity. The ratio of these conductivities, the anisotropy ratio, thus determines the geometry and length of the primary radionuclide transport pathways to the accessible environment and, hence, the traveltime from the repository to the accessible environment.

The site-specific data on effective porosity and vertical hydraulic conductivity at the Hanford Site are currently inadequate for refined assessment of repository performance. Data from only one measurement location are available for effective porosity. Hydraulic conductivity data have been obtained primarily by means of small-scale single-borehole tests. The representativeness of measurements of vertical conductivity at a single test site (Spane et al. 1983) has not yet been determined.

1.2 PURPOSE AND SCOPE OF THE STUDY

Because reliable estimates of anisotropy ratio and effective porosity at the Hanford Site are currently not available, Rockwell, for the interim, is following a two-faceted approach to obtain preliminary estimates. Field studies are being initiated to obtain more site-specific data; however, it will be some time before these studies produce the required data. Because Rockwell currently requires defensible estimates for values of the hydrologic parameters for use in preliminary performance assessment studies (10 CFR 960, DOE 1984), the current probability encoding project was initiated to obtain independent estimates of these hydrologic parameters. The estimates derived by this means will be used pending the availability of more refined estimates from field and other pertinent studies. Subsequent iterations of the probability encoding process may be implemented when additional data become available to help implement the BWIP approach to seeking "reasonable assurance." Parameter value estimates were obtained for a megascale (on the order of 100 to 1,000 m) and a macroscale (on the order of 1 to 10 m). These scales were chosen to comply with the input requirements of the preliminary performance assessments currently being conducted by Rockwell.

To obtain estimates of these parameters, independent of any internal influence or control, Rockwell chose the Delphi method of eliciting expert opinion. This method was employed by Rockwell for preliminary identification of potential disruptions that may influence the performance of a repository at the Hanford Site (Davis et al. 1983). Furthermore, in view of the variability of the available information and the need to apply it in stochastic modeling of repository performance, Rockwell chose the probability encoding method developed at SRI International (SRI, formerly Stanford Research Institute) to obtain the probability distributions of the required hydrologic parameters.

The specific scope of work included the following:

1. Reviewing available published information to identify data pertinent to specified hydrologic parameters for the Hanford Site
2. Drafting of a Delphi questionnaire incorporating the probability encoding methodology
3. Selecting and contracting with a panel of five nationally and/or internationally recognized experts in hydrologic properties of fractured basalts and other similar rocks
4. Eliciting, by the Delphi method, the unbiased opinions of experts on values of hydrologic parameters pertaining to the Hanford Site
5. Encoding the probability distributions of the parameter values
6. Reporting and analyzing the results of the study.

1.3 PERSONNEL AND DIVISION OF RESPONSIBILITIES

To obtain expert opinion estimates of the specified hydrologic parameters by means of a Delphi process, Rockwell contracted with Analytic & Computational Research, Inc. (ACRi) of Los Angeles, California (Rockwell Subcontract SA-965, dated March 26, 1984). In turn, ACRi subcontracted with Applied Decision Analysis, Inc. (ADA) of Menlo Park, California, to apply the SRI probability encoding method to the Delphi estimation of hydrologic parameters. Analytic & Computational Research, Inc. also subcontracted with Professor Jack Nilles of the University of Southern California (through JALA Associates) for supervision and advice in implementing procedures for the Delphi methodology.

Analytic & Computational Research, Inc. was responsible for selection of the Delphi panel, development and application of the Delphi methodology, field-data compilation, quality assurance, project management, and liaison with Rockwell technical and contract representatives. Applied Decision Analysis, Inc. was responsible for development and implementation of the Delphi questionnaires, application of the SRI probability encoding method, and encoding of the expert opinion. Professor Jack Nilles reviewed the Delphi questionnaire prior to its use to ensure its compliance with accepted Delphi practice.

Dr. Akshai Runchal of ACRi was the Project Manager for the study. He was responsible for contractual and technical management and for liaison with Rockwell contract and technical project management personnel. Dr. Miley Merkhofer of ADA was the Principal Investigator for application of the SRI probability encoding method and Ms. Elizabeth Olmsted of ADA acted as the Project Investigator. Ms. Christine Detournay of ACRi was the Principal Investigator for the project and was responsible for review and synthesis of field data. Ms. Geri Segal of ACRi acted as the Quality Assurance Manager.

2.0 OUTLINE OF METHODOLOGY

2.1 METHODS AND PROCEDURES

Two distinct methodologies were used in combination with each other for this project: the Delphi method, which was originally developed by the Rand Corporation, Santa Monica, California, and the probability encoding method, which was developed by SRI International, Menlo Park, California. The Delphi method is widely accepted as an unbiased technique for eliciting expert opinion on complex issues with multidisciplinary implications. Probability encoding is a decision analysis tool by which uncertainty of important factors that bear on a decision can be quantified.

2.2 THE DELPHI METHOD

The Delphi technique (Helmer 1966; Dalkey 1972; and Linstone and Turoff 1975) is widely recognized to be a systematic, unbiased, and auditable approach to obtaining expert opinion about complex issues. The method consists of the selection of a panel composed of persons expert on the matter in question and the iterative administration of a questionnaire to each panel member. The questionnaire is usually administered by mail and/or in a personal meeting, and strict anonymity of panelists is maintained. Each administration of the questionnaire is referred to as a round or stage. After each round, the answers are collated and summarized for presentation to the panelists in the next round. Panelists are asked to use this feedback information in reconsideration of his or her earlier response.

The Round 1 questionnaire is normally accompanied by a packet of information describing the issues addressed in the questionnaire. Subsequent administrations of the questionnaire may include additional information. This process may continue until the researcher is satisfied that further iteration and feedback would not yield a closer approximation to the "true" answer or value. Measures of central tendency and dispersion are then applied to the final round distributions to express the consensus of the panel.

2.3 THE PROBABILITY ENCODING METHOD

Probability encoding is the process by which expert judgment concerning important uncertainties that bear on a decision may be quantified and analyzed. The SRI probability encoding method (von Holstein and Matheson 1979) is widely regarded as the state-of-the-art by the decision analysis community.

The probability encoding process is conducted as a joint undertaking by a subject (an "expert" in the areas relevant to the quantity being assessed) and an analyst (who serves as an interviewer). The specifics of a probability encoding session vary, depending on differences in the participants and on the characteristics of the quantity to be assessed. One factor, however, remains the same: from the subject's responses, the analyst strives to understand the modes of information processing used by the subject and to infer from this the biases that are likely to exist. The analyst then takes specific steps designed to minimize the effect of these biases on the probabilities derived.

The probability encoding process is described in detail by Merkhofer and McNamee (1982). Briefly, it consists of five separate stages.

1. Motivating. The motivating stage is designed to establish rapport and to enable the analyst to assess the potential for motivational biases.
2. Structuring. The structuring stage produces the quantitative structure necessary for the assessment.
3. Conditioning. The conditioning stage is a series of steps designed to free the subject from likely biases.
4. Encoding. The encoding stage produces a preliminary probability distribution.
5. Verifying. The verification stage validates the distribution as being an accurate description of the subject's uncertainty.

Further details of these five stages of the probability encoding method are provided in Appendix A.

Because of the inherently subjective and interactive nature of probability encoding, care must be taken in any attempt to integrate probability encoding into a Delphi exercise. Most importantly, a proven, systematic probability encoding process should be used. Because the probability encoding method is interactive, it depends on experienced analysts skillfully directing the questioning based on information and other cues provided by the subject. The method cannot be implemented as a series of written questions. When conducting applications with multiple subjects (as demanded by the Delphi method), maximum accuracy, consistency, and compatibility of results are obtained not by asking each subject identical questions, but rather by ensuring that the same analysts apply the same well-defined process with each subject.

3.0 SELECTION OF THE DELPHI PANEL

3.1 THE DELPHI PANEL

The Delphi panel consisted of five nationally known hydrologists having extensive practical experience with field-determined values of hydrologic parameters.

The names of the panelists and their institutional affiliation are listed in Table 1. Summaries of their expertise and education, and lists of major publications are given in Appendix B. Each panelist possesses a doctorate degree in the discipline of hydrology. Four of the panelists are affiliated with universities; the fifth is a private consultant, who, until recently, was affiliated with a national laboratory.

TABLE 1. The Delphi Panel.

Name	Current Position
Stanley Davis	Professor Department of Hydrology and Water Resources University of Arizona Tucson, Arizona
Paul Fenske	Professor Water Resources Center Desert Research Institute University of Nevada Reno, Nevada
Lynn Gelhar	Professor Civil Engineering Massachusetts Institute of Technology Cambridge, Massachusetts
Shlomo Neuman	Professor Department of Hydrology and Water Resources University of Arizona Tucson, Arizona
Charles Wilson	Partner Hydrotechnique Associates Berkeley, California

NOTE: The order of listing does not necessarily correspond to the order of alphabetical labeling used on the cumulative probability distribution curves of this report.

3.2 THE SELECTION CRITERIA

The panelist selection criteria follow:

1. Professional reputation in the hydrology of fractured rocks
2. Specific knowledge of basalt hydrology
3. Familiarity with the geographic area of the Hanford Site
4. Knowledge of issues and problems in disposal of nuclear waste
5. No apparent conflicts of interest
6. Availability during the period of the study
7. Constraints imposed by budgetary considerations.

National or international reputation within the discipline of interest is the criterion most frequently applied in selection of Delphi panelists. Harman and Press (1975) note that "someone is an expert in his field if others in his field consider him to be an expert." This fundamental tenet has become established as the foremost guide to selection of Delphi panelists. The selection criteria of issue-specific and site-specific knowledge (criteria 2 through 4, above) are also well established in Delphi practice (e.g., Harman and Press 1975). In the present study of highly specific issues relating to estimation of hydrologic parameters of a specific site, it was considered essential to include those experts who have had significant experience with the groundwater hydrology of fractured rocks, particularly basalts (including those of the Hanford Site).

A potential for conflict of interest was considered to exist if a prospective panelist considered it to exist or if the panelist was currently under active contract to one of the regulatory, supervisory, or advisory agencies that monitor the BWIP project. These agencies include the NRC, EPA, DOE, U.S. Geological Survey (USGS), and the review agencies for the State of Washington. Current or past contractual obligations of panelists to the BWIP for other contracts were not considered to be conflicts of interest.

Because the study had to be completed within a specified time, the timely availability of an expert was also a selection criteria. Furthermore, the study had to be conducted within a specified budget; therefore, experts residing outside the continental United States were not considered.

3.3 THE SELECTION PROCESS

The Delphi panelist survey and selection were made independent of any involvement by Rockwell. Rockwell was neither contacted to elicit recommendations of prospective panel members nor were Rockwell personnel asked their opinion of prospective panel members identified by ACRi. However, for the purpose of helping to identify potential conflicts of interest, the names of the candidate panelists were provided to Rockwell.

For the purpose of selecting a panel of nationally known hydrologists, ACRi started with a list of hydrologists with known national reputations who were identified by a previous reputational survey (Davis et al. 1983). This reputational survey relied on recommendations of professional societies and associations to systematically identify experts in five disciplines relevant to nuclear waste disposal. One of these five disciplines was hydrology. The selection process implemented by the current study started with this list of well known hydrologists. The next step in the selection process was to explain the nature and purpose of the present study to these hydrologists and to ask their opinion of their expertise for the study. They were then asked to supply the names of other hydrologists who, in their opinion, had expertise and reputation relevant to the study. This process was followed until nearly 30 panelists were identified in this manner. The experts were then asked about their availability for the study, the potential for any conflict of interest, and their assessment of the level of expertise of other candidates. This process was continued until a group of five experts (see Table 1) was impaneled that met all the criteria stated in Section 3.2.

4.0 IMPLEMENTATION OF THE DELPHI AND PROBABILITY ENCODING METHODS

4.1 DEVELOPMENT OF THE BACKGROUND INFORMATION

As part of the Delphi process, a package of background information was provided to each of the panelists. For Round 1 of the Delphi process, the panelists were provided with two documents.

- The first information package (Appendix C) consisted of general information on the BWIP and summarized the purpose and scope of the study within the overall objectives of the BWIP. The second information package (Appendix D) reviewed available data pertaining to the specified hydrologic parameters of selected basalt flows beneath the Hanford Site.

- The second package also summarized the effective porosity, transmissivity, and hydraulic conductivity data from about 40 boreholes in and around the Hanford Site.

This site-specific information was supplemented by other published estimates (Appendix D). Statistics of the transmissivity and hydraulic conductivity data, based on information contained in the BWIP Site Characterization Report (DOE-RL 1982), were also contained in this data package. The background information was provided to the panelists at least 1 wk in advance of the Round 1 interviews.

In addition to the background information, a Delphi questionnaire was prepared to help implement the SRI probability encoding method during the Round 1 interviews. Because individual interviews were conducted for each panelist without other panelists being present, it was considered important that a uniform format for the interviews be formalized in accordance with established Delphi practice. This questionnaire was not provided to the panelists; rather, it was used by the interviewers to guide the encoding process. The questionnaire contained the definitions of the various parameters to be encoded and outlined the five stages of the probability encoding method in a step-by-step manner. The questionnaire was prepared and refined during a preliminary encoding session involving ACRi, ADA, and Rockwell personnel, and was reviewed by Professor Jack Nilles.

The Round 2 information provided to the panelists consisted primarily of the encoded probability distributions obtained during Round 1 of the study. These probability distributions were accompanied by certain other information that was considered relevant for the panelists in reviewing the Round 1 results. At the request of one of the panelists, one additional item of information was also provided to the panelists during Round 2. It consisted of the covariance correlation structure of hydraulic conductivity for some of the field measurements (Appendix E).

4.2 SELECTION AND DEFINITION OF THE VARIABLES TO BE ENCODED

As explained in Section 1.2, the purpose of the study was to obtain expert opinion on two hydrologic parameters currently of most concern to preliminary assessment of repository performance: (1) the average effective porosity of the preferred candidate horizon flow top and flow interior and (2) the anisotropy ratio of hydraulic conductivity of the preferred candidate horizon flow interior beneath the Hanford Site at a megascale (on the order of 100 to 1,000 m) and a macroscale (on the order of 1 to 10 m). Specifically, the following six variables were encoded:

1. Average effective porosity of the Cohassett basalt flow top at megascale
2. Average effective porosity of the Cohassett basalt flow top at macroscale
3. Average effective porosity of the Cohassett basalt flow interior at megascale
4. Average effective porosity of the Cohassett basalt flow interior at macroscale
5. Anisotropy ratio of the Cohassett basalt flow interior at megascale
6. Anisotropy ratio of the Cohassett basalt flow interior at macroscale.

To avoid potential ambiguities in terminology, the six variables to be encoded were explicitly defined for the purpose of this study (Table 2). All the variables were defined with reference to the Cohassett basalt of the Columbia River Basalt Group within the reference repository location of the Hanford Site because this flow is presently considered to be the preferred candidate horizon (Long and WCC 1983).

4.3 IMPLEMENTATION OF ROUND 1

4.3.1 Overview of the Process

Round 1 of the Delphi process consisted of individual interviews with the five experts. During each interview, the SRI probability encoding process was applied to obtain a probability distribution for values of each of the six hydrologic variables. Two ADA analysts were present for each interview. Each encoding session lasted 6 to 8 h.

To promote consistency of the encoding process and to improve the efficiency of the encoding interviews, a Delphi questionnaire was prepared (see Section 4.1) that guided the interview sessions. The questionnaire structured the encoding sessions into the five stages of the SRI probability encoding process. Each of these stages was repeated for each variable. The subsections below discuss activities undertaken to implement the encoding process.

4.3.2 Motivating

Before beginning the actual encoding process, the reasons for conducting the exercise were explained to each panelist. A brief overview of the process was presented, and the importance of estimating hydrologic parameters at a potential nuclear waste repository site was discussed. It was explained that the estimates should be considered to be descriptions of uncertainty about specified parameters, rather than as inputs needed for assessing repository performance. To explore possible motivational biases, the subject was asked to describe his expertise and experience with the Hanford Site.

Next, common probability assessment biases were explained to each expert. The explanation was provided because understanding the source of bias sometimes helps subjects to prevent or reduce their occurrence. Three types of biases were described: incompleteness, lack of moderation, and anchoring (Appendix A). Incompleteness refers to the phenomenon of central bias (that is, the probability distributions selected are often too narrow, so that the actual values fall outside of their 1% and 99% confidence intervals). Lack of moderation refers to a tendency to discount general information when specific information is available. Studies show that subjects often assign a very high probability to an event that is fresh in their minds, even if previous information suggests that the

TABLE 2. Definitions of Variables To Be Encoded.

Variable	Definition
Effective porosity	The in situ volume proportion of rock that contributes to solute transport if a hydraulic gradient is applied across the volume. The volume size is specified as megascale or macroscale as defined below.
Average effective porosity	The average is defined so that an accurate gross experiment performed on this entire volume would yield this value.
Anisotropic ratio	The vertical conductivity divided by horizontal conductivity (K_v/K_h), where conductivity is defined as the flow in square meters per second that comes out of a volume cross section (specified at a megascale or macroscale) for a unit hydraulic gradient that is applied under in situ conditions.
Flow top	The vesicular and/or brecciated upper portion of a basalt flow.
Flow interior	The relatively dense portion of the basalt flow that has a characteristic cooling joint pattern and typically contains no vesicularity.
Megascale	The volumes mentioned above are specified to be 100 to 1,000 m per side and the depth is such that the volume lies entirely within the flow top or flow interior (as specified).
Macroscale	The volumes mentioned above are specified to be 1 to 10 m per side and the depth is such that the volume lies entirely within the flow top or flow interior (as specified).

NOTE: All definitions are applied to the Cohassett basalt flow beneath the Hanford Site.

event may be unusual. Anchoring refers to the tendency of individuals to make all estimates by adjusting an initial value. Typically, the adjustments are insufficient to encompass the subject's actual range of uncertainty. Although these biases are usually addressed during the conditioning stage of a probability encoding interview, they were discussed in the motivating stage in this application to avoid having to repeat the discussion for each of the six variables and to help ensure consistency in the five interviews.

4.3.3 Structuring

The structuring stage involved defining the variable of concern and exploring how the expert thinks about the variable. The definition of each variable was discussed with the experts. Each panelist was shown a standardized definition of the specified variable (see Table 2) and was given the opportunity to change any definition that seemed ambiguous; no major changes were suggested by any of the experts.

To explore how the subject thought about the variable, the following issues were explored:

- Factors that may influence the variable
- The usefulness of decomposing or breaking down the variable into its components
- Any assumptions that the subject makes in thinking about the variable
- The scale at which the variable is measured.

The results of the structuring phase indicated that the variables affecting the value of effective porosity were adequately defined and structured for probability encoding, but that the variables affecting the anisotropy ratio were not optimally structured. Three of the subjects indicated that they would find it more convenient to assess more elemental quantities from which anisotropy ratios could be derived (e.g., vertical and horizontal conductivity). Due to lack of time and the concern that the use of different methods with different subjects would complicate comparisons, the anisotropy ratios were not restructured into elemental components. Probability encoding theory suggests that restructuring might have resulted in less error and reduced variance (Morgan et al. 1979, p. 15).

4.3.4 Conditioning

The conditioning stage focused on helping the expert bring all of his relevant knowledge into his immediate thought process. This stage helps to counteract biases identified in the motivating phase. Conditioning included the following discussions:

- Possible references to which the expert compares the Hanford Site basalts
- General background information about the variable
- Site-specific information known to the expert
- Extreme high and low values, and their possible explanations.

4.3.5 Encoding

In this stage, the uncertainty about the variable was quantified. The probability wheel technique, the interval technique, or direct assessment was used, depending on the expert's relative familiarity and preference with the different approaches. All three approaches to encoding are well established and are routinely used by decision analysts. Further details of these approaches are given in Appendix A. After values sufficient to sketch a reasonably smooth cumulative probability distribution curve were elicited, inconsistencies or discontinuities were checked and the distribution was reassessed, if necessary.

4.3.6 Verifying

In this final stage, the probability distribution obtained during the encoding stage was shown to the expert. The implications of the shape of the curve (such as a bimodal shape or a log-normal distribution) were discussed. Spot checks of consistency were accomplished by dividing the range of values estimated into equally likely intervals and asking the expert if any of the intervals seemed more likely to contain the actual value. Problems or inconsistencies were corrected by repeating the appropriate previous encoding stages. An example of one such consistency check was to ask panelists whether the expected value for the macroscale of a variable ought to be equal to that for the megascale. Most of the experts believed that the expected values for the two scales ought to be equal or nearly equal, but some advanced arguments for why the expected values at the macroscale may differ from those at the megascale.

The encoding session was concluded when each expert viewed the curves as providing an accurate representation of his professional judgment of the level of his uncertainty, based on the information available at the time of assessment. Participants commented that the encoding process helped them clarify their own thinking.

4.4 IMPLEMENTATION OF ROUND 2

The second Delphi round enhanced the probability encoding process by allowing each expert to modify his original estimates after considering the Round 1 results and rationales given by the other participants. Each expert was sent a "workbook" consisting of observations from Round 1 about the likely median and extreme values of the variables, graphs displaying the cumulative probability distributions encoded for each variable in Round 1, and questions designed to elicit revised estimates of the variables being encoded. To maintain anonymity of the experts from one another, as required by the Delphi method, the Round 1 probability distributions in this workbook were identified by a letter code for each of the five experts, rather than by their names.

The experts were asked to use the interval technique to answer the Round 2 questions. This technique was considered to be the most convenient to employ in the absence of personal interviews. However, studies have shown that the interval method has a tendency to produce central bias. Consequently, the content and format of the workbook were designed to counteract this bias. The experts were asked to first consider extreme high and low values to minimize this tendency to produce central bias. The questions also asked each expert to provide his estimate of the median value before making any modification to his curve. The extreme and the median values could then be compared with initial estimates to help determine the expert's revised opinion.

Finally, for each variable, the experts were asked to verify their belief in the probability curve depicting their judgment. They were shown how to divide the distribution of estimated values into three equal portions and then asked to consider whether or not each portion was equally likely to contain the true value. The participants were familiar with this verification method because it was used repeatedly in Round 1. If the uncertain variable was judged not equally likely to be within any of the three areas, then the subject was asked to adjust and recheck the curve until it was verified. In addition, a short written description of the expert's reasons for his choice of the final probability distribution was requested. The expert's justification of his choice provided a final check on the curve.

5.0 RESULTS AND DISCUSSION

5.1 EFFECTIVE POROSITY FOR COHASSETT BASALT FLOW TOP

5.1.1 Megascale

The experts' cumulative probability distributions of the Cohassett basalt flow top average effective porosity at the megascale are presented in Figure 1. The estimates of the five experts are identified by a letter code, from "A" through "E." (The alphabetical order of the letter code does not correspond to the order of listing in Table 1.) These estimates range from just over 10^{-7} to 3 x 10^{-1}. Some salient characteristics of these distributions are summarized in Table 3. According to different experts, the estimated median value (value for which it was judged that there is a 50% chance of a lower value and a 50% chance of a higher value) ranges from 10^{-4} to 3.5 x 10^{-2}. Four of these five estimates are within a single order of magnitude of each other (from 2.9 x 10^{-3} to 3.5 x 10^{-2}). The experts are more in agreement at the high end of the estimated value range than at the low end. All of the highest values deemed possible by the experts are clustered just above 10^{-1}. The lowest values, however, range over more than four orders of magnitude, from 10^{-7} to 2 x 10^{-3}. Experts C and D (see Fig. 1, curves C and D) exhibit a very high degree of agreement on this variable and Experts B and E (see Fig. 1, curves B and E) agree to within one order of magnitude of the value.

5.1.2 Macroscale

The macroscale results for the Cohassett basalt flow top average effective porosity are presented in Figure 2. These probability distributions show a trend similar to that for the megascale. However, the highest estimated values are approximately one order of magnitude higher and the lowest values are one order of magnitude lower than the comparable values for the megascale (see Fig. 1). The median values range from 10^{-4} to 2.5 x 10^{-2} (see Table 3) and are not appreciably different from comparable values for the megascale. The estimates at the upper end of the range again are clustered, with the highest estimates approaching the maximum theoretical value of one. The lower end of the range spans more than five orders of magnitude, from just over 10^{-8} to 10^{-3}. Three of the five experts estimated the lowest probable values to be between 10^{-7} and 10^{-8}. As was the case for the megascale, the probability distribution values selected by Experts C and D (see Fig. 2, curves C and D) agree very closely with each other, whereas Experts B and E (see Fig. 2, curves B and E) estimate values that are within an order of magnitude of each other. The value estimates by Expert A (see Fig. 2, curve A) are distinct from the other four and generally are lower than the lowest estimates of the other panelists by about one order of magnitude.

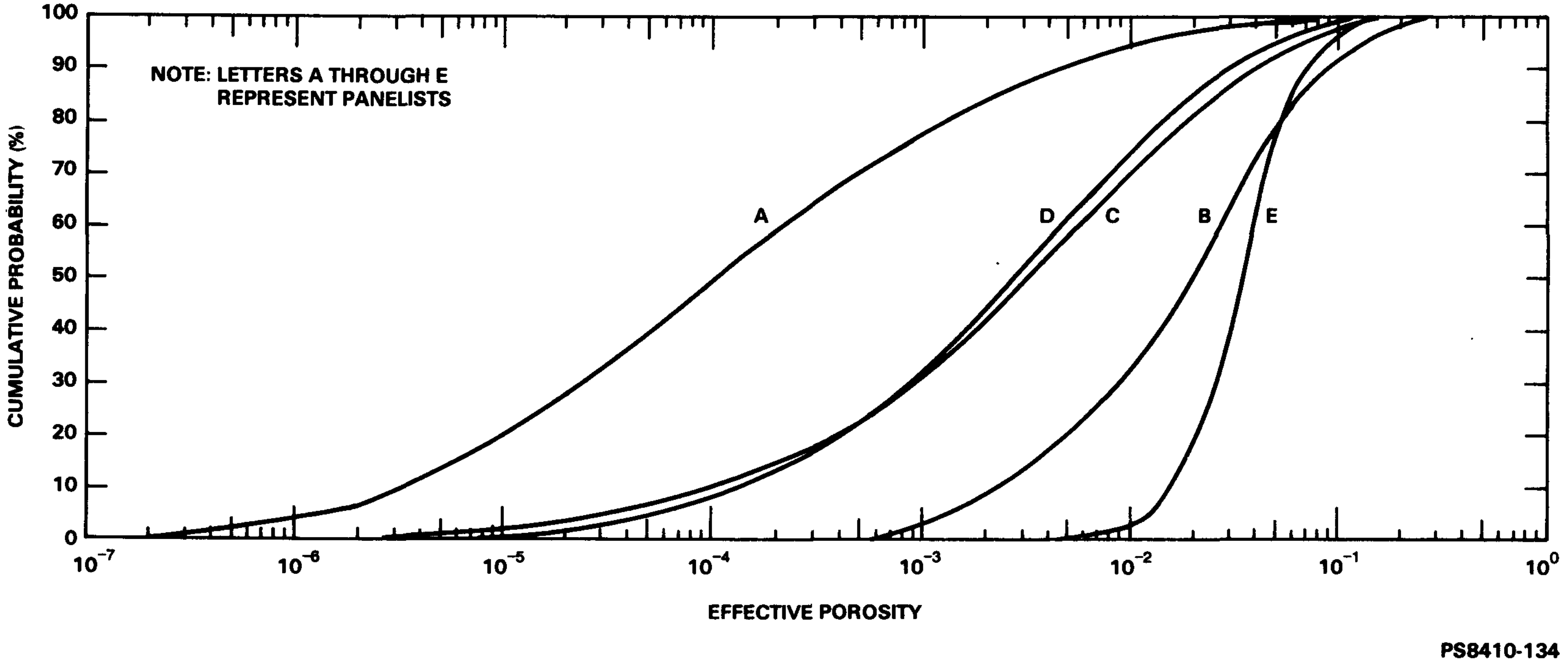

FIGURE 1. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Megascale.

TABLE 3. Characteristics of the Cumulative Probability Distributions of Values of the Cohassett Basalt Flow Top Average Effective Porosity.

Probability and Scale	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)					
10%	3.0×10^{-6}	2.5×10^{-3}	1.0×10^{-4}	1.2×10^{-4}	1.6×10^{-2}
Median	1.0×10^{-4}	2.0×10^{-2}	2.9×10^{-3}	3.1×10^{-3}	3.5×10^{-2}
90%	4.0×10^{-3}	9.0×10^{-2}	4.0×10^{-2}	3.0×10^{-2}	7.0×10^{-2}
Macroscale (1-10 m)					
10%	3.3×10^{-7}	1.0×10^{-3}	1.0×10^{-5}	4.5×10^{-5}	6.0×10^{-3}
Median	1.0×10^{-4}	1.9×10^{-2}	9.5×10^{-4}	1.8×10^{-3}	2.5×10^{-2}
90%	5.0×10^{-2}	1.2×10^{-1}	3.7×10^{-2}	3.0×10^{-2}	8.5×10^{-2}

5.1.3 Comments by Experts

For these two variables (average effective porosity of the Cohassett basalt flow top at a megascale and a macroscale) the comments made by the hydrologic experts indicate the following:

- Short-term in situ tracer tests and laboratory tests on recovered core may underestimate interconnected porosity; hence, estimates were made that were higher than that indicated by available site-specific field data.
- Some panelists believe that Experts B and E overemphasized the porous nature of the flow top.
- Expert A's median value may be anchored to the measured value of 10^{-4} reported for the McCoy Canyon flow (Appendix D). Other experts believe that this particular measurement is unrepresentatively low.
- Values initially estimated for effective porosity might subsequently be lowered to reflect the possibility that fracture porosity is sufficiently dominant to mask the effects of matrix porosity.

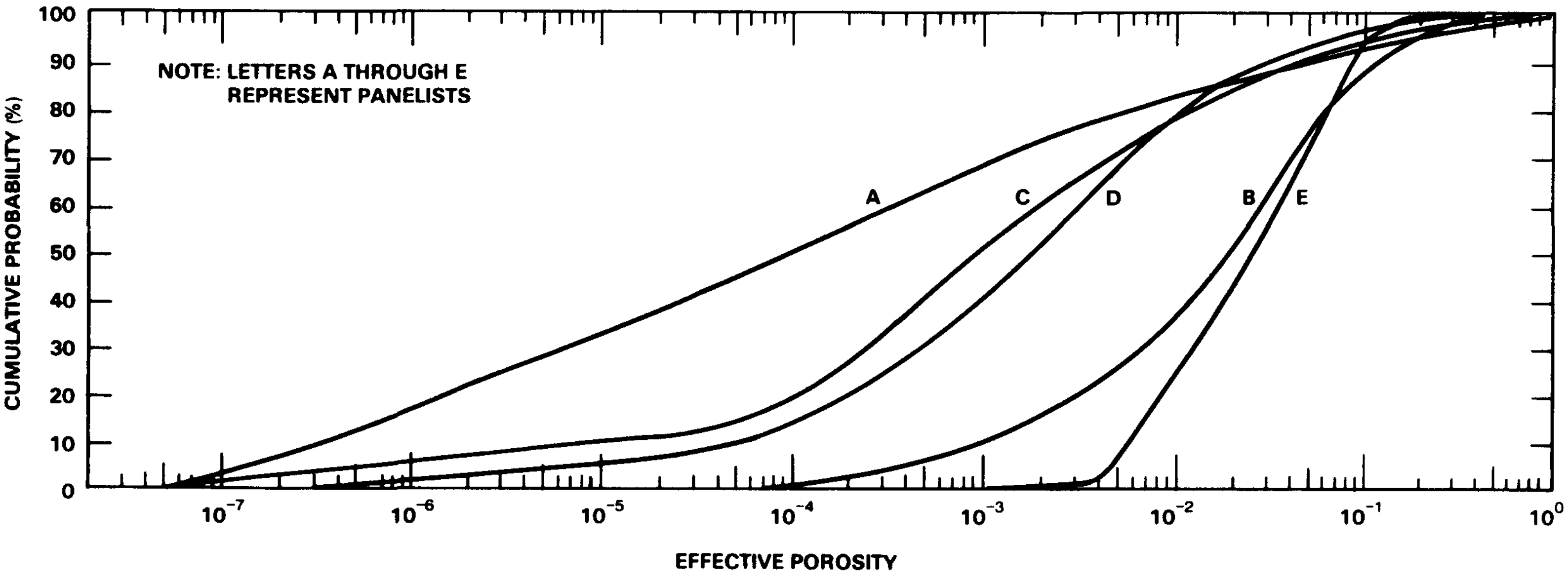

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FIGURE 2. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Macroscale.

5.2 EFFECTIVE POROSITY FOR COHASSETT BASALT FLOW INTERIOR

5.2.1 Megascale

The cumulative probability distribution curves of expert estimates for the average effective porosity of the Cohassett basalt flow interior at the megascale are displayed in Figure 3. The estimated effective porosity values for the flow interior, in general, tend to be lower than the analogous flow top values. This disparity is more pronounced near the upper end of the range of distributions than near the lower end. The highest estimated values are slightly greater than 10^{-2}; the lowest estimated values approach 10^{-8}. These curves exhibit five distinct distributions. However, as was the case for the estimated effective porosity values for the flow top, some general agreements are apparent. The estimates of four of the five experts are in two distinct groupings. The groupings are represented by curves C and D, and the upper end of curves B and E in Figure 3. The estimates of the fifth expert (see Fig. 3, curve A) again remain the lowest--often by one order of magnitude or more. As shown in Table 4, the estimated median values span a range from 10^{-5} to 2×10^{-3}. The highest estimates are clustered around a value of 10^{-2} for four of the experts, but Expert A estimates a value that is almost two orders of magnitude lower at 3×10^{-4}. The low end of the estimated values span just over one order of magnitude for four of the experts (10^{-7} to 10^{-6}), but one of the experts estimated a substantially higher value of 10^{-4}. The lowest value estimated by Expert A is almost as high as the highest value deemed possible by Expert E.

5.2.2 Macroscale

The estimates of average effective porosity for the Cohassett basalt flow at a macroscale are shown in Figure 4. The uncertainty at this scale is relatively greater than that at the megascale, although Experts C and D are in complete agreement. Again, Experts B and E estimated values that are mostly within one order of magnitude of each other (see Fig. 4, curves B and E). As was the case for the estimated effective porosity values for the flow top, the estimated macroscale effective porosities span a range in which the higher values are one order of magnitude higher and the lower values are one order of magnitude lower than the corresponding estimates at the megascale. The highest values approach 10^{-1} and the lowest value is lower than 10^{-8}. However, the median of the estimated values (see Table 4) has not shifted appreciably from the median value at the megascale. These estimates range from 10^{-5} to 2.5×10^{-3} and are almost identical to those for the megascale.

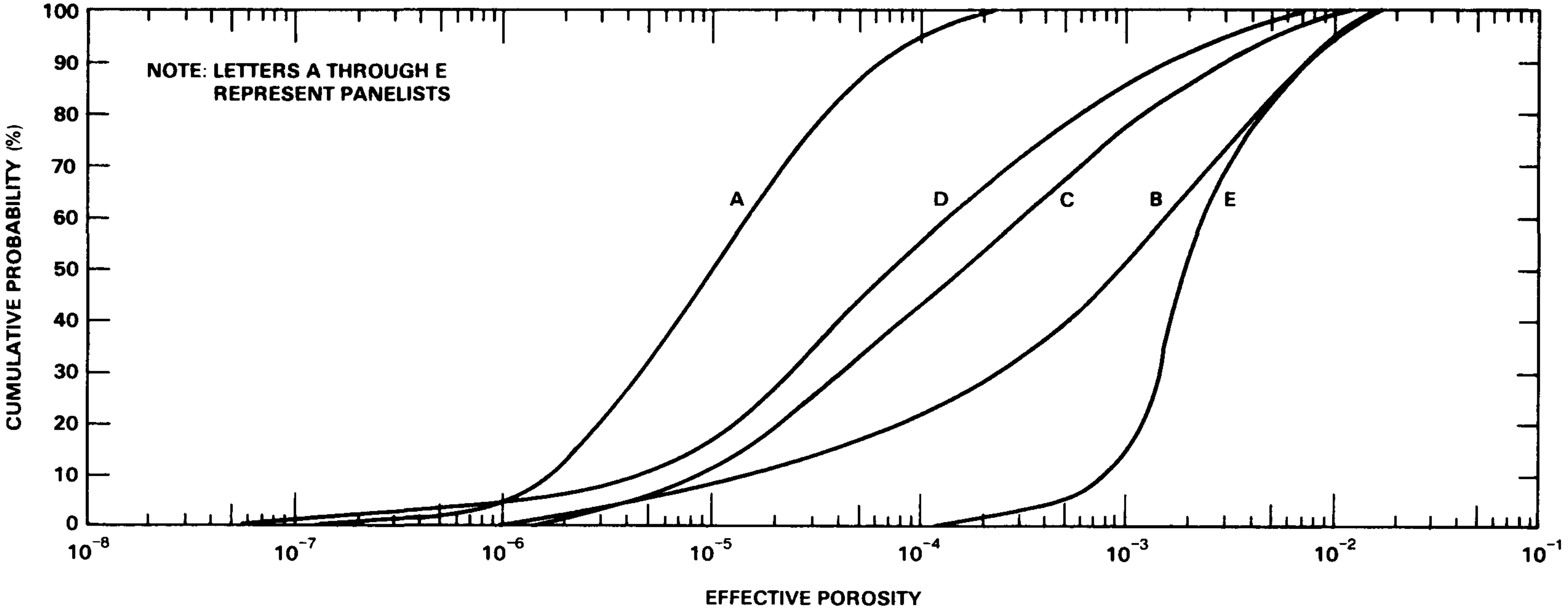

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FIGURE 3. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Megascale.

TABLE 4. Characteristics of the Cumulative Probability Distributions of Estimated Values for the Cohassett Basalt Flow Interior Average Effective Porosity.

Probability and Scale	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)					
10%	1.6×10^{-6}	1.4×10^{-5}	8.5×10^{-6}	4.5×10^{-6}	8.0×10^{-4}
Median	1.0×10^{-5}	9.0×10^{-4}	1.6×10^{-4}	7.2×10^{-5}	1.9×10^{-3}
90%	6.5×10^{-5}	7.5×10^{-3}	3.0×10^{-3}	1.6×10^{-3}	7.6×10^{-3}
Macroscale (1-10 m)					
10%	2.1×10^{-7}	1.1×10^{-5}	3.0×10^{-6}	3.0×10^{-6}	1.6×10^{-4}
Median	9.0×10^{-6}	1.0×10^{-3}	1.0×10^{-4}	1.0×10^{-4}	2.5×10^{-3}
90%	5.0×10^{-4}	1.3×10^{-2}	4.0×10^{-3}	4.0×10^{-3}	1.5×10^{-2}

5.2.3 Comments by Experts

For these two variables, comments by the experts indicate the following.

- Most estimates of effective porosity for the Cohassett basalt flow interior were made by adjusting estimates of flow top effective porosity.

- Effective porosity for the flow interior is expected to be lower than effective porosity for the flow top.

- Some experts believe that small volumes of the flow interior could have almost zero porosity. Other experts state that values less than 10^{-6} are physically impossible.

- One expert commented that short-term dynamic field tests do not measure effective porosity resulting from very small interconnected pores; therefore, such tests may underestimate actual values.

- To some experts, the apparent rationale for some of the curves that differed from their own was incomprehensible.

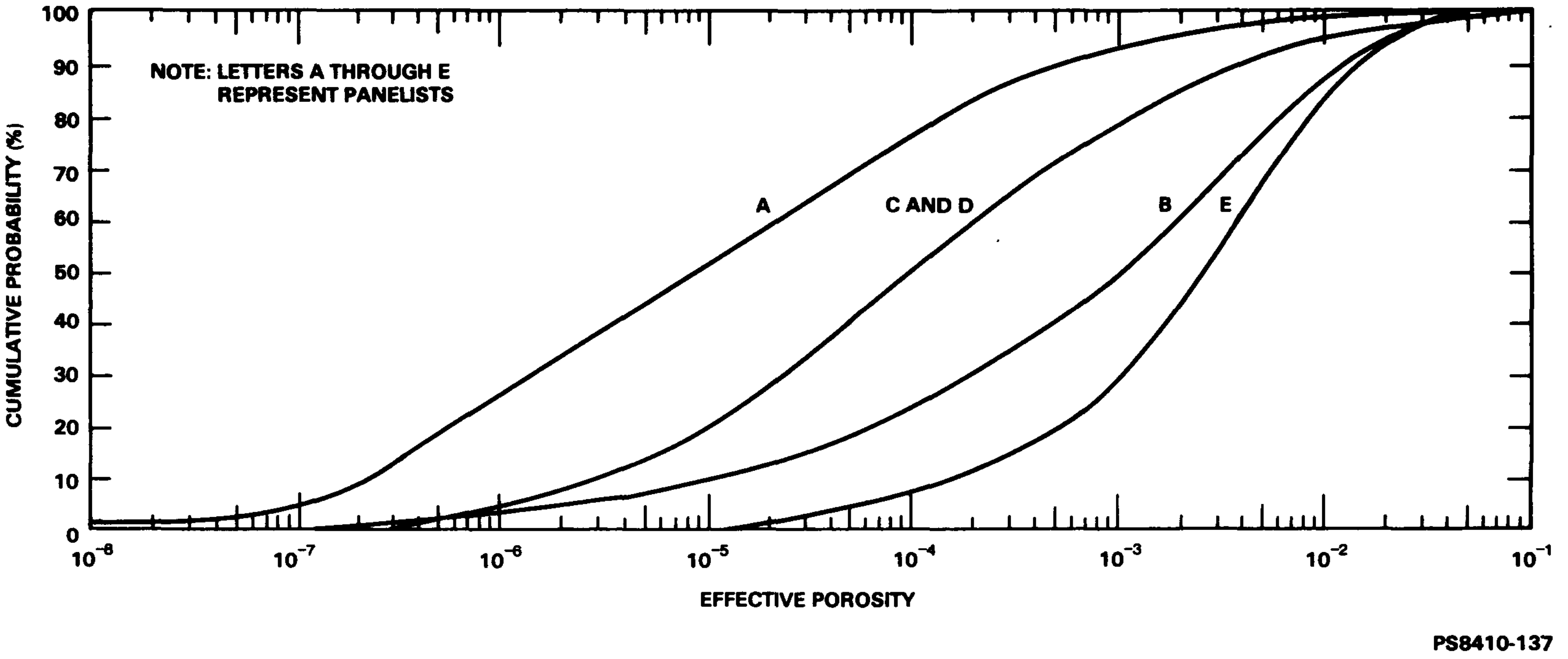

FIGURE 4. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Macroscale.

5.3 ANISOTROPY OF HYDRAULIC CONDUCTIVITY FOR THE COHASSETT BASALT FLOW INTERIOR

5.3.1 Megascale

The expert estimates of the anisotropy ratio of hydraulic conductivity for the Cohassett basalt flow interior at the megascale are shown in Figure 5. There is considerable agreement on a median value (Table 5); all five estimates are within one order of magnitude of each other and two are identical (a value of 10). By comparison, the median values for estimated effective porosity (see Table 4) often differed by two to three orders of magnitude. Furthermore, values for four of the five probability distributions are generally within one order of magnitude of each other (see Fig. 5, curves A, B, C, and E). The lowest estimates of these distributions approach 10^{-1} and the highest estimates approach 10^{3}. Expert D, however, expressed much greater uncertainty (see Fig. 5, curve D). Although the median value of his estimate is well within the range estimated by the other experts, his values for the upper and lower ends of the range differ from the other estimates by more than one order of magnitude. His highest estimated value is 10^{4}; his lowest value is 10^{-2}. Thus, the cumulative probability distribution of values selected by this expert spans six orders of magnitude. In contrast, all values of the other distributions span from two to four orders of magnitude.

5.3.2 Macroscale

Estimates for the Cohassett basalt flow interior anisotropy ratio at the macroscale are shown in Figure 6. These estimates again depict a very high degree of agreement on the median value (see Table 5). All of the median values are between approximately 5 and 20, and three of the experts estimated a value of 10. Four of the five experts chose distributions that, in general, differ by less than one order of magnitude. In fact, these cumulative probability distributions are much closer (within a factor of 4 to 5) to each other than are those at the megascale. In this case, however, values at the lower end of the range of estimates of Expert C (see Fig. 6, curve C) differ significantly from those of the other experts. His estimates, below the approximately 7% cumulative probability point, differ sharply from those of the other panelists. His lowest estimated value is less than 10^{-5}. The lowest value estimated by three of the other experts is approximately 10^{-1}. Estimates of four panelists at the high end of the distribution range are clustered around 10^{3}. As was the case for the megascale, the distribution of values estimated by the Expert D (see Fig. 6, curve D) differs from the distributions of the other experts at both the high and the low ends of the cumulative probability distribution range. Estimates at the upper end of the range in this case reach 10^{6}. Estimates at the lower end of the range reach 5×10^{-3}.

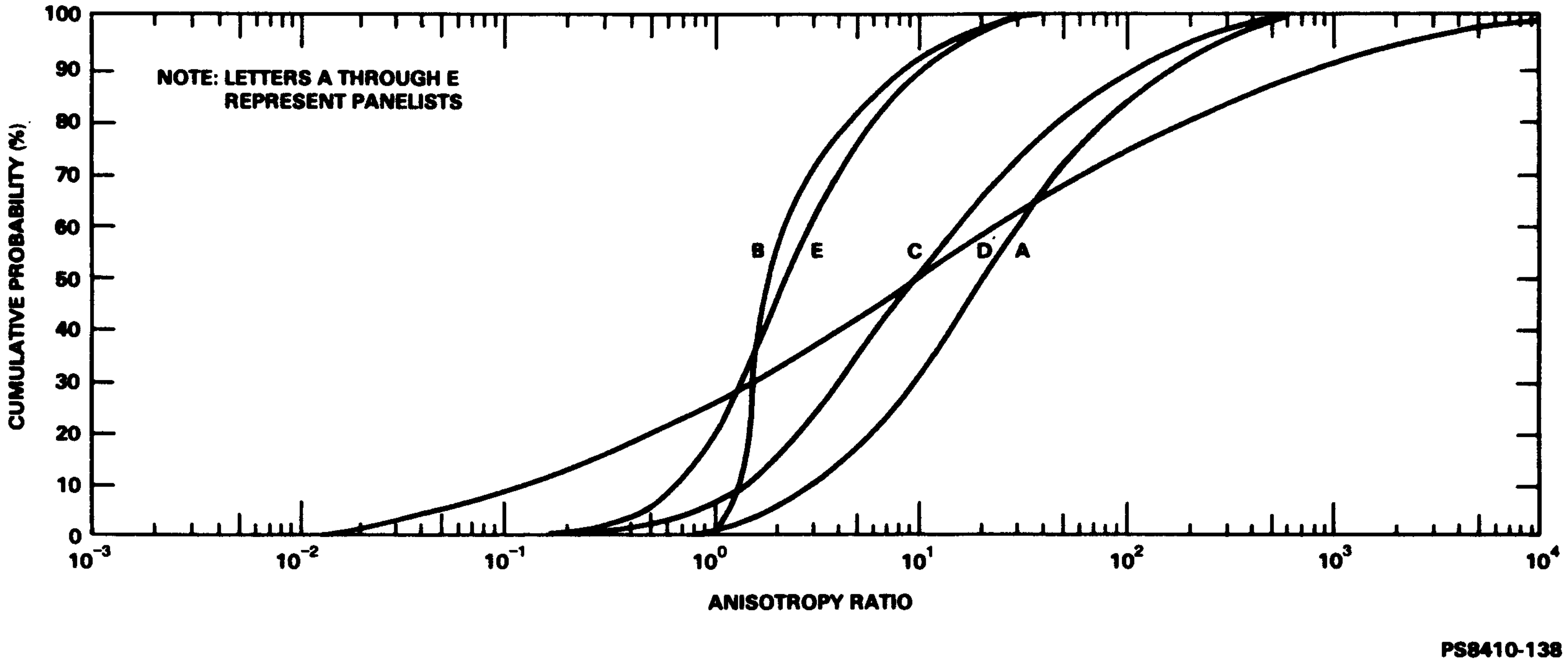

FIGURE 5. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Anisotropy Ratio at Megascale.

TABLE 5. Characteristics of the Cumulative Probability Distributions of Estimated Values for Cohassett Basalt Flow Interior Anisotropy Ratio.

Probability and Scale	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)					
10%	3	1.3	0.15	0.13	0.65
Median	20	1.8	10	10	2.3
90%	170	9	120	850	10
Macroscale (1-10 m)					
10%	1	1.4	1.1	0.20	1.0
Median	20	10	10	10	5.3
90%	300	130	110	2,000	50

5.3.3 Comments by Experts

For these estimates of anisotropy ratio of the Cohassett basalt flow interior, comments by the experts indicate the following.

- Lack of data makes it extremely difficult to confidently estimate the anisotropy ratio.
- One expert stated that because there are less data on anisotropy ratio than on effective porosity, it seems strange that some experts have smaller uncertainty ranges for the anisotropy ratio.
- The vertical cooling joints in flood basalts are unlikely to be as permeable as commonly imagined. The prominent columnar joints seen in outcrops may suggest more vertical permeability than actually exists because they transmit very little water.
- Very tortuous fractures might cause very low horizontal hydraulic conductivity, or horizontal jointing might cause very large horizontal hydraulic conductivities.
- One expert stated that vertical and horizontal hydraulic conductivity must be approximately equal for any given fracture; therefore, the probability distributions should be clustered around a value of 1.
- Another expert stated that one order of magnitude difference should be expected between vertical and horizontal hydraulic conductivity, and that vertical conductivity could be greatly increased by a vertical fault.

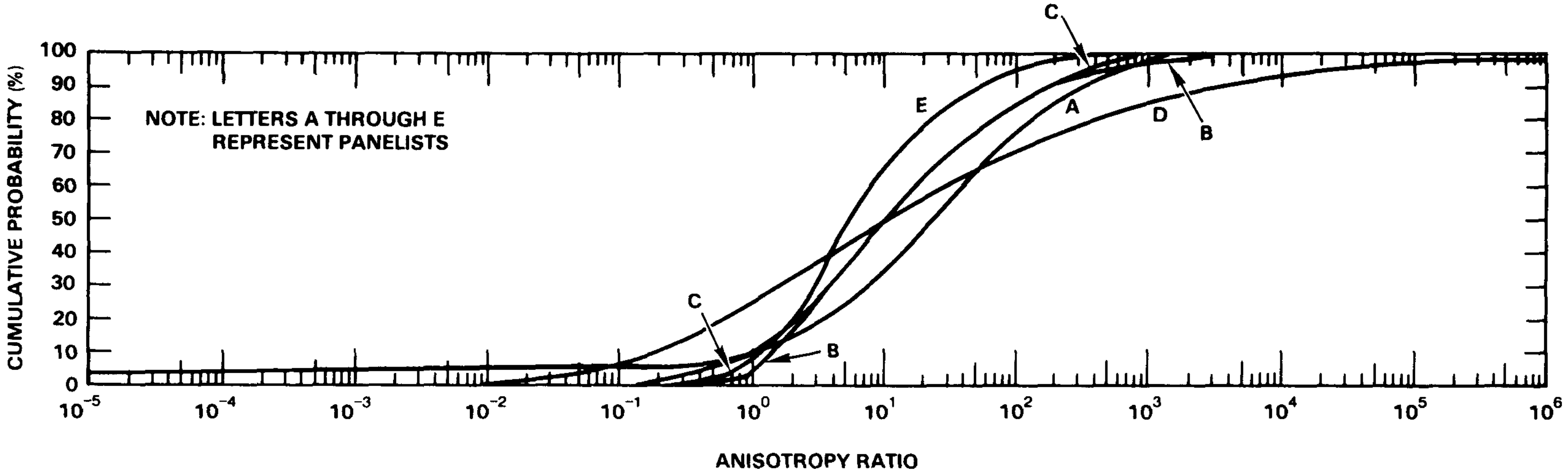

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FIGURE 6. Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Anisotropy Ratio at Macroscale.

5.4 DISCUSSION

The results described in the previous sections indicate that the five panelists tend to have diverse opinions about the likely values of average effective porosity and anisotropy ratios. For most of the variables, pairs of experts often agree but there was no general consensus among all five experts. Comments by the panelists during both rounds of opinion elicitation indicate that the lack of consensus directly reflects diversity in the general information bases and conceptual models of the experts.

However, in spite of this diversity of opinion there is significant agreement. Some important points of agreement are evident from the estimated median, 10%, and 90% values of the cumulative probability distributions for the six encoded variables (see Tables 3 through 5). Probability distributions of values estimated by four of the five panelists are generally within one order of magnitude of each other over 80% (between 10% and 90%) of the cumulative probability range.

For the effective porosity variables, all panelists except Expert A agree on the estimated value at 90% cumulative probability to well within one order of magnitude. The experts agree to almost exactly one order of magnitude at the median point, and to approximately two orders of magnitude at the 10% value. If the two bounding distribution curves (see Fig. 2 through 4, curves A and E) are excluded from consideration, the agreement improves to within one order of magnitude for the cumulative probability distribution range from 10% to 90%.

For the anisotropy ratio, the experts are in better agreement. The 10% and the median point values of the cumulative probability distribution curve generally differ by a factor of less than four for all panelists except Expert D. The values estimated at the 90% confidence level differ by approximately one order of magnitude. If the two bounding distribution curves (see Fig. 1 through 4, curves A and E) are excluded, the agreement improves significantly. With the exception of the estimated values at 90% cumulative probability for the megascale, three of the five experts agree to within a factor of two.

For the effective porosity variables, agreement among the panelists improves significantly at the upper end of the distribution. For the anisotropy ratio, the reverse is true. For the effective porosity variables, all five experts agree to within approximately one order of magnitude at the 90% probability value. At the 10% value, the agreement is only to within three to four orders of magnitude. For the anisotropy ratio, the agreement at the 10% value is slightly greater than one order of magnitude, but decreases to almost two orders of magnitude at 90% cumulative probability.

The degree of agreement (at least between four out of the five experts for 80% of the entire cumulative probability distribution range) is noteworthy for purposes of decision analysis in view of the fact that the amount of pertinent published field data currently available for the site are very small. For the most part the experts had to rely on theoretical considerations, measurements of transmissivity in other Hanford Site basalt flows, and their broad professional experience. The principal disagreements are at the extremes of the distribution ranges. This type of disagreement is to be expected given the nature of the variables and the scarcity of the site-specific data.

5.5 SYNTHESIS OF RESULTS

The experts clearly used different concepts, hypotheses, and theories to arrive at their estimates for the variables. One difference observed is that some experts based their judgments primarily on theories and conceptual models; others relied primarily on field data for rocks similar to the candidate flow and direct, but diverse, field experience. Furthermore, those experts who referred to conceptual models of groundwater flow often thought in terms of different models. Hence, the opportunity for information exchange among these experts is great. Without direct information exchange, however, closer consensus cannot be expected. Consensus would require each expert to better understand the reasoning and information sources of the other experts by means of a workshop or seminar. Such an information exchange is planned for future iterations of probability encoding, when a more extensive data base is available.

Some professional differences of opinion are likely to exist even after such a meeting, but the initial diversity of opinion is likely to be reduced. Furthermore, a carefully structured discussion among the experts is likely to identify more precisely where agreements and disagreements exist. In this context, key areas for additional data collection also would be identified by discussing the types of tests needed to promote narrowing of differences.

If consensus is not required, aggregation of probability distributions is sometimes used to resolve expert differences. Although much research has been conducted in this area during the past 15 yr, no methodology has been found that is both practical and technically correct for all situations. Researchers have proposed several approaches, but the approach chosen depends on the acceptability of relatively complicated assumptions whose appropriateness must be judged on a case-by-case basis.

One approach, which is applicable if the probability distribution curves approximate some named distribution (such as a log-normal distribution), is to compute the weighted average of values of the parameters that best describes the individual distributions. (For example, the mean and variance of the aggregated curve would be the weighted averages of the means and variances of the individual curves.)

Another approach to aggregating expert judgments is averaging. For example, the probability distributions elicited from individual experts might be averaged on a point-by-point basis. For illustration, Figures 7 through 12 show the results of such averaging for the six hydrologic variables, assuming equal weighting for each expert.

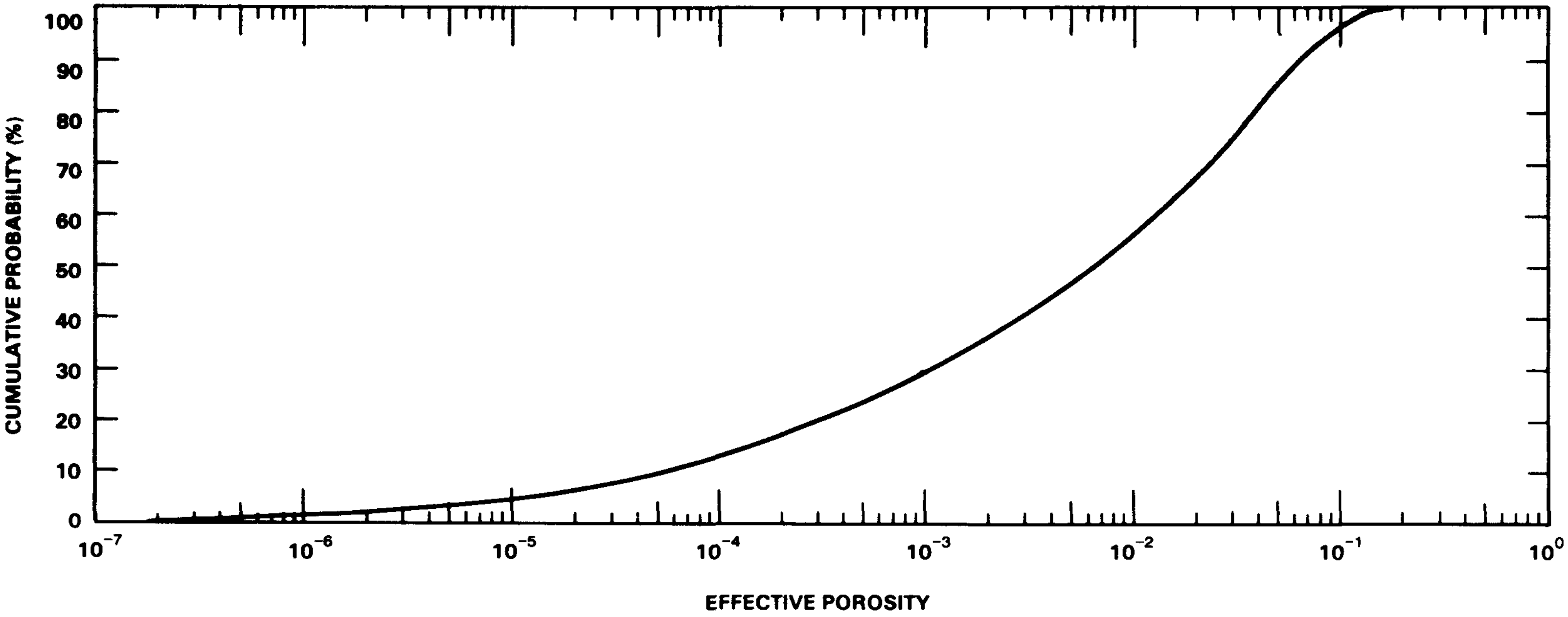

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FIGURE 7. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Megascale.

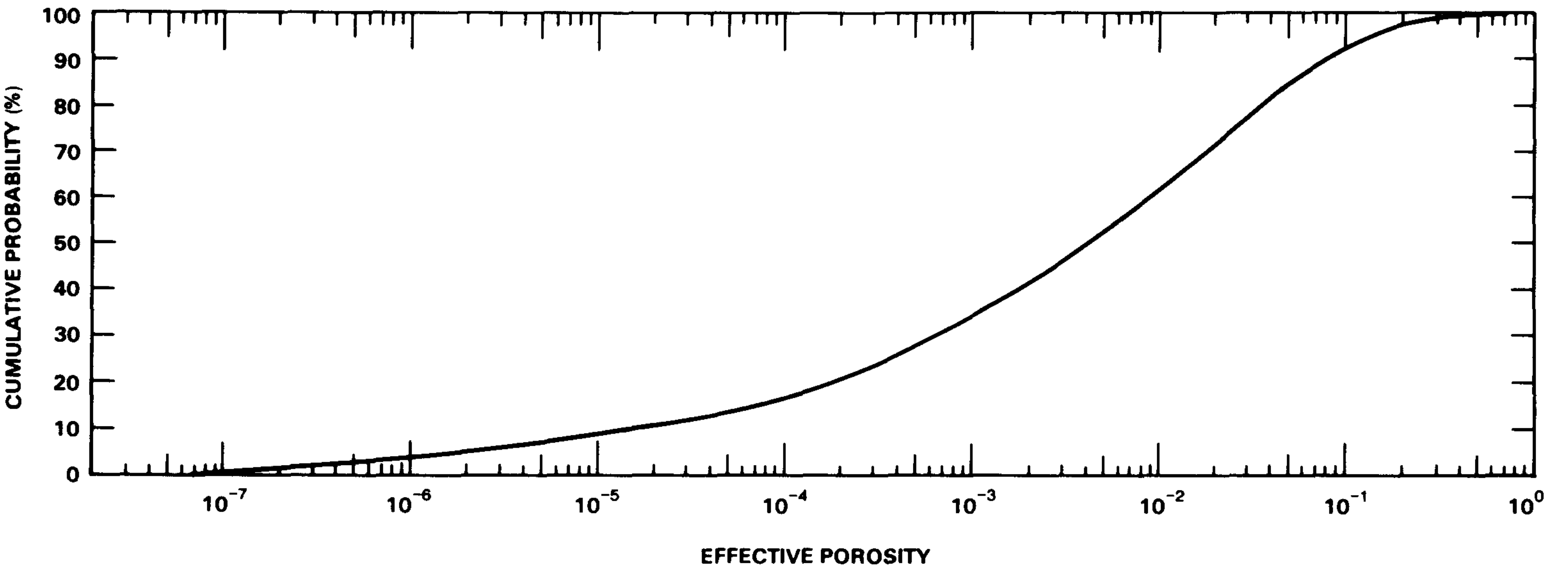

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FIGURE 8. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Macroscale.

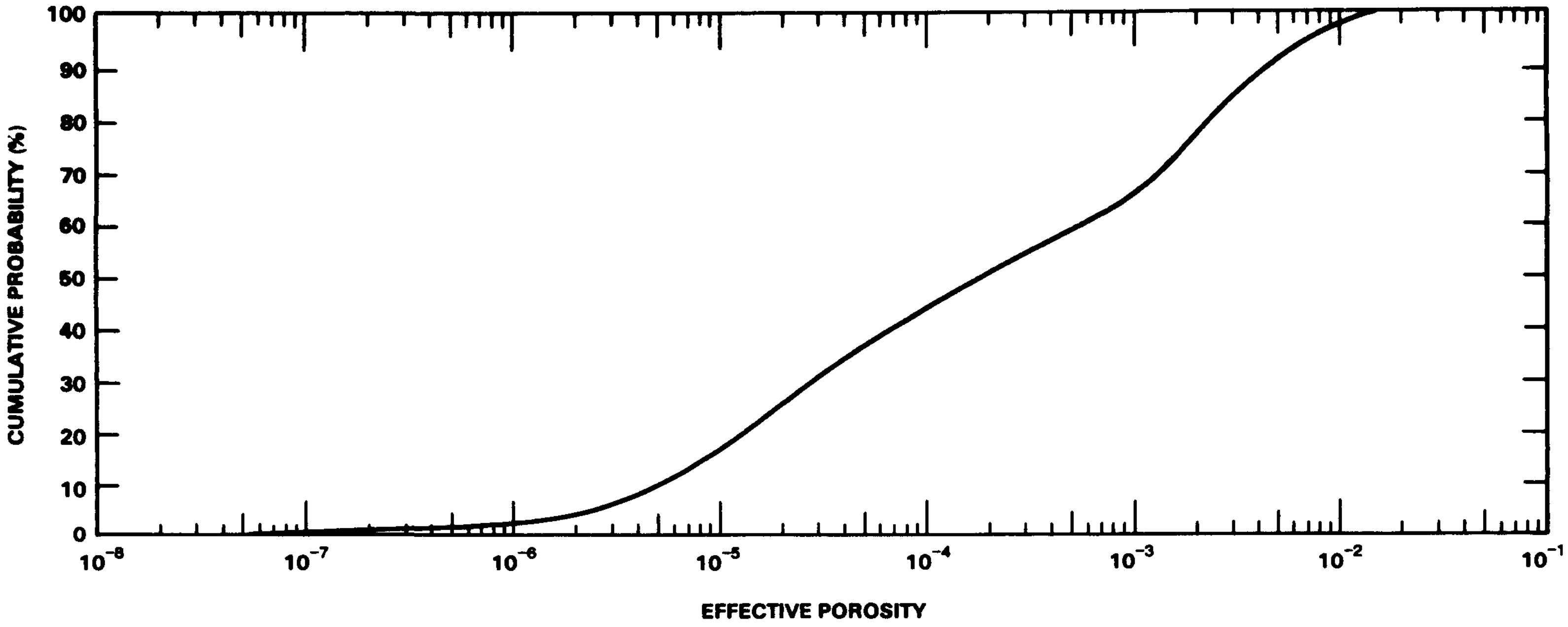

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FIGURE 9. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Megascale.

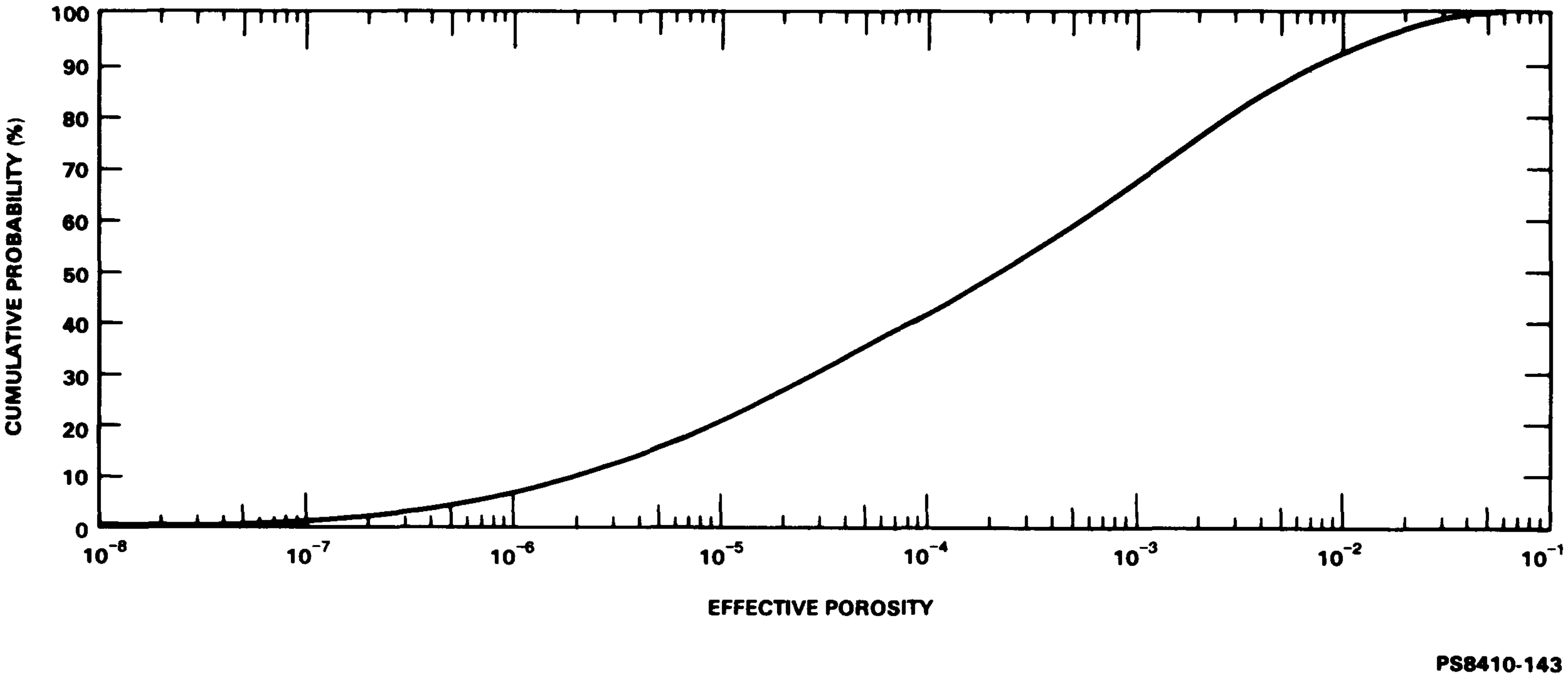

FIGURE 10. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Macroscale.

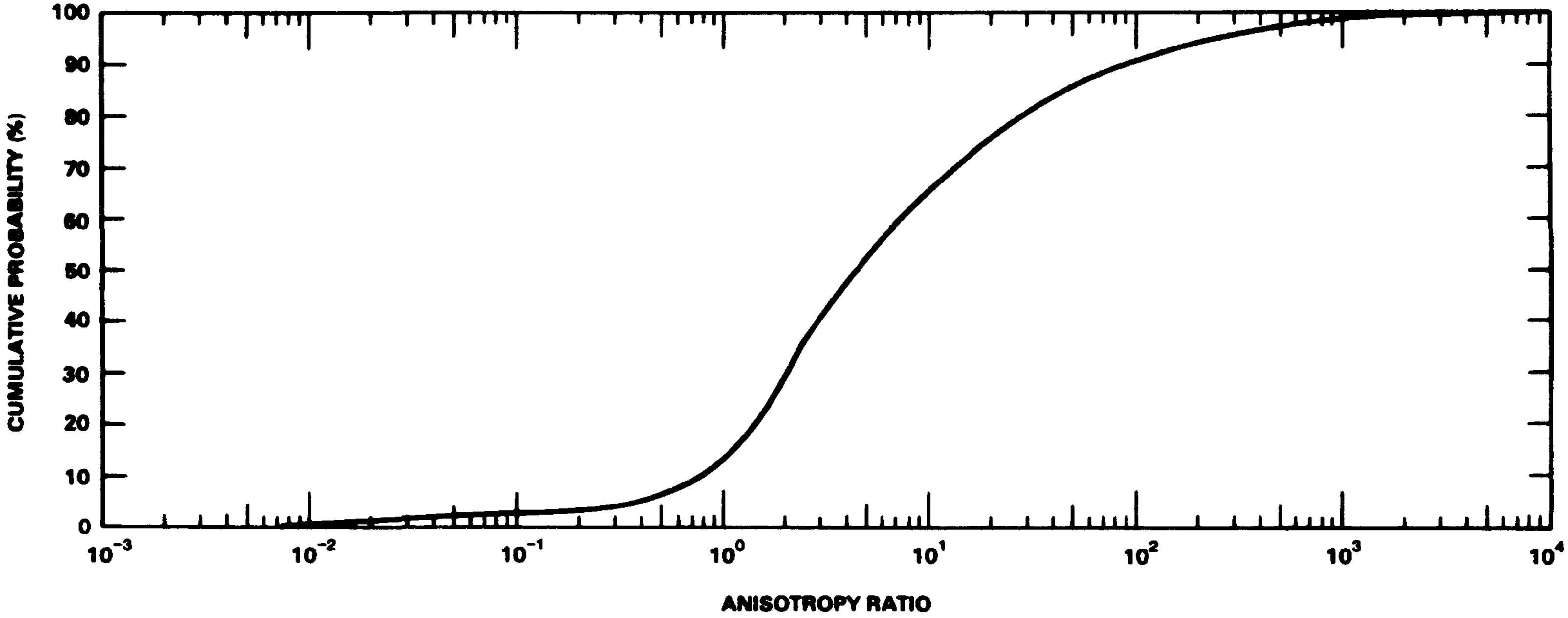

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FIGURE 11. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Anisotropy Ratio at Megascale.

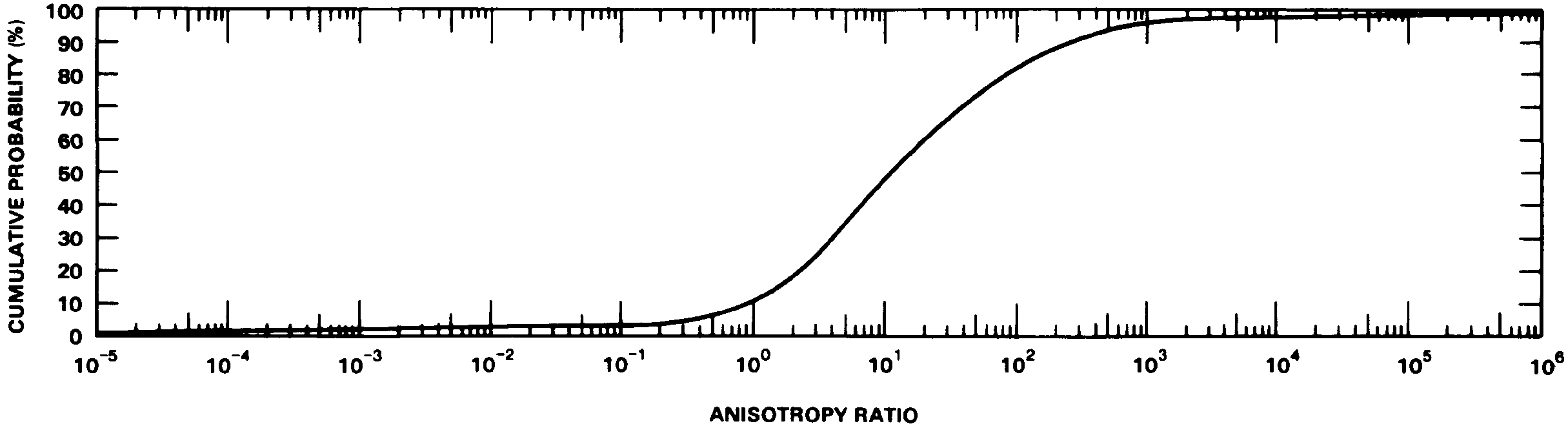

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FIGURE 12. Equally Weighted Average of Five Cumulative Probability Distributions for Estimated Values of Cohassett Basalt Flow Interior Anisotropy Ratio at Macroscale.

For averaging, two methods were considered:

1. The probability values for the five experts can be averaged for a specific value of the parameter
2. The values of a parameter for a specific cumulative probability can be averaged.

Because the present study was structured to obtain the panelists' assessments of the cumulative probability (dependent variable) of the estimated parameter values (independent variable), the first method was employed to obtain the averages. For the highly skewed distributions observed, this method is preferable in any case, because it prevents one expert's estimate from dominating the estimates of other experts. Thus, the range of values estimated by the experts is preserved by the averaging. This approach is ad hoc. The resulting distributions are averaged values and are not indicative of consensus among the panelists.

Developing a theoretically defensible method for synthesizing the probability encoding results of this project would require additional research into the nature of the information held by the individual experts and would depend on the precise purpose and interpretation of the aggregated probability distribution curves.

6.0 CONCLUSIONS

The conclusions of this study are listed below.

1. Probability encoding of expert judgments concerning the six hydrologic parameters was successfully implemented in that the experts regarded their cumulative probability distributions as accurate representations of their professional opinions.
2. Existing field data relevant to estimation of values of the six parameters are inadequate to significantly reduce parameter uncertainty. Consequently, the experts interviewed found it necessary to rely extensively on their own conceptual models and pertinent field experience to estimate the required values.
3. There is considerable difference of opinion among the experts as to the estimated values of the variables and their ranges. This difference is most pronounced at extreme values of the cumulative probability distribution range.
4. Typically, for 80% of the cumulative probability distribution range (between 10% and 90%), all five experts agree to within two to three orders of magnitude of estimated value for the effective porosity, and to within one to two orders of magnitude

for the estimated value of the anisotropy ratio. Beyond this range, however, the agreement is no better than to within four to five orders of magnitude.

5. Four of the five panelists' cumulative probability distributions are generally within one order of magnitude of each other over 80% of the cumulative probability range (between 10% and 90%). The agreement improves considerably if the probability distributions at the extremes of the range are excluded. Generally, the cumulative probability distributions estimated by the panelists are in better agreement for the anisotropy ratio than for effective porosity.

6. Agreement among panelists for estimates of effective porosity values improves significantly at the upper end of the probability distribution, whereas for estimated values of the anisotropy ratio the reverse is true.

7. The agreement among the panelists is noteworthy in view of the fact that there are few pertinent field data currently available for the site.

8. Comments by the experts indicate that there are fundamental differences in the conceptual models, information, and logic used in deriving their individual assessments. These differences probably explain much of the diversity of estimates. In the absence of convincing field data, resolution of the expert differences will require an exchange of the underlying theories, information, and logic held by the experts. A meeting of all the experts could, therefore, provide an excellent opportunity for information exchange and may lead to closer agreement among the panelists.

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APPENDIXES

The information contained in Appendixes C and D is identical to that provided to the panelists except for the correction of minor typographical and grammatical errors, none of which affected the meaning of the text.

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APPENDIX A

THE SRI INTERNATIONAL PROBABILITY ENCODING METHOD

A1.0 OVERVIEW

Probability encoding is the process by which decision analysts extract and quantify expert judgment concerning important uncertainties that bear on a decision. A milestone in the development of probability encoding methodology is the SRI Probability Encoding Manual (SRI 1979) developed by the Decision Analysis Department of SRI International (SRI, formerly Stanford Research Institute). This manual represents the results of a 5-yr development effort funded by private organizations and several government agencies, including the Office of Naval Research and the Defense Advanced Research Projects Agency. Although advancements have been made since its publication, the SRI manual remains the most comprehensive statement of the state-of-the-art in probability encoding.

The probability encoding process is conducted as a joint undertaking by a subject (an "expert" in the areas relevant to the quantity being assessed) and an analyst (who serves as an interviewer). The specifics of what goes on in a probability encoding session vary from situation to situation depending on differences in the participants and on the quantity to be assessed. One factor, however, remains the same: from the subject's responses the analyst strives to understand the modes of information processing used by the subject and to infer from this the biases that are likely to exist in the subject's responses. The analyst then takes specific steps designed to minimize the effect of these biases on the probabilities derived.

The five stages of the probability encoding process are motivating, structuring, conditioning, encoding, and verifying. The purpose of each of these stages, the types of biases that frequently occur, and the steps typically conducted within each stage are described in the subsections below.

A2.0 FIVE STAGES OF PROBABILITY ENCODING

A2.1 STAGE 1: MOTIVATING

The purpose of the motivating stage is to establish the necessary rapport with the subject and to explore whether a serious potential for motivational biases exists. Before beginning the encoding process, the analyst explains to the subject the nature of the analysis being conducted and the importance of obtaining the information that the subject can provide.

Once the subject understands the intended use of the encoding results, the encoding task is introduced. In this introduction, the analyst stresses the importance of accurately assessing uncertainty of the quantity in question. The analyst explains that the intent is to measure the subject's knowledge and best judgment concerning the quantity and not to predict the value of the quantity. This distinction may be very important if the analyst detects the possibility of "management" bias, "expert" bias, or "motivational" bias in the subject's thinking.

Management bias occurs when the subject views an uncertain variable, for example the manufacturing costs for a new product, as an objective rather than an uncertainty. This type of bias would be typified by the following sort of attitude, "Well, if that's the variable that the boss wants minimized, we'll minimize it."

Expert bias refers to a possible reaction that the subject may have to being chosen as an "expert." The subject may feel that experts are expected to not be uncertain, but to be sure of things. This bias tends to promote central bias--a tendency for the subject to underestimate uncertainty. The need for accurate estimation of the full range of uncertainty is, therefore, emphasized to the subject.

Motivational bias refers to a reward structure that might encourage the subject to bias his or her estimates high or low. The quantity is discussed to identify any asymmetries in the subject's personal benefits that might motivate the subject to bias his or her estimates.

A2.2 STAGE 2: STRUCTURING

The structuring stage has two purposes. The first purpose is to structure the uncertain quantity into one or more logically related, well-defined variables suitable for the encoding exercise. The second purpose is to explore how the subject thinks about the quantity, so that the analyst can more effectively guide discussion and properly interpret the subject's answers.

The first step in the structuring stage is to define precisely the variable for which uncertainty is to be assessed. A very useful aid for this purpose is the "clairvoyance test." Before accepting what seems to be a good definition for a variable, the analyst should consider whether a clairvoyant could give an unequivocal value to it. Often the clairvoyance test points out the inexactness of what initially appears to be a well-defined variable. For example, the price of coal in 1985 does not pass the clairvoyance test. A clairvoyant would have to know what kind of coal, its energy content, where it was sold, and so forth. Encoding uncertainty only on variables that pass the clairvoyance test ensures that vagueness in the definition does not contribute to the subject's uncertainty. If multiple subjects will be interviewed and comparability of results between subjects is desired, variable definitions should be established in advance (e.g., through trial applications using knowledgeable individuals not included within the subject group).

The second step in the structuring stage is to explore the usefulness of decomposing or breaking down the variable into more elemental variables. In some cases, the variable should be decomposed to reduce biases. For example, in research and development (R&D) resource allocation analyses, experts seem especially prone to "conjunctive" bias; that is, if a number of essentially independent successes have to occur in order that an R&D effort be successful, the probability of success of the entire sequence would seem higher than the actual probability. The appropriate approach in such circumstances is to decompose the variable, assess the probability of the enabling events individually, and then use probability calculus to compute the probability of the desired compound event.

The third step in the structuring stage is to list all the assumptions the subject is making in thinking about the variable. A useful means for identifying hidden assumptions is to ask: "What would you like to insure against?" It could be stated in other words: "If you could take out insurance on certain events that might cause your estimates to be grossly inaccurate, what are those events?" Often, this question will uncover previously unstated factors that can influence the value of the variable.

The fourth and final step in the structuring stage is to select an appropriate measurement scale. The most important rule here is to use the units that are most familiar to the subject.

A2.3 STAGE 3: CONDITIONING

The purpose of the conditioning stage is to draw out into the subject's immediate consciousness all relevant knowledge relating to the uncertain variable. Usually, the discussion will indicate that the subject is basing judgment concerning the variable on both specific information (relating to the specific quantity being assessed) and general information (relating to quantities similar to that being assessed).

The first step in the conditioning phase, therefore, is to discuss the data and background knowledge available to the subject. In this discussion, the analyst must watch for signs of bias caused by focusing only on specific information. Empirical evidence shows that subjects often tend to attach less importance to general information. For example, if the specific information is some recent data (such as the results of recent field tests), then the importance of that information might be overrated in the subject's mind. If the analyst suspects this may be the case, it is helpful to educate the subject on this effect (known as a lack of "motivation") and to use formal processing of probabilities where possible. A useful device here is to ask the subject to guess what estimate of the quantity would be given by another subject who does not have access to the specific information. This gives a prior probability for using Bayes' rule (Larson and Shubert 1979) to formally compute a posterior probability that properly weights both general and specific information.

The second major step in the conditioning stage is to counteract "anchoring" and "availability" biases. Anchoring refers to the tendency of individuals to produce estimates by starting with an initial value (suggested perhaps by the formulation of the problem) and then adjusting the initial value to yield the final answer. The adjustment is typically insufficient. Availability (or incompleteness) bias refers to the fact that if it is easy to recall instances of an event's occurrence (e.g., the event had some personal significance to the subject), then that event tends to be incorrectly assigned a higher probability. An effective approach for counteracting anchoring and availability bias is for the analyst to elicit extreme values for the variable and then ask the subject to describe scenarios that would explain these outcomes. (At this point, additional "hidden assumptions" are often uncovered.) Another useful method is to explain or demonstrate to the subject what is sometimes called the "2/50 Rule." This rule refers to the results of demonstration exercises in which subjects are asked to assign probability distributions to the answers to questions drawn from the World Almanac (e.g., the elevation of the highest mountain in Texas). If people are well calibrated, 2% of the time the actual values for such variables should fall outside the 1% and 99% confidence intervals derived from the assessed probability distributions. However, for the many experiments that have asked these kinds of questions, nearly 50% of the answers have been found to be outside the 1% and 99% confidence points.

A2.4 STAGE 4: ENCODING

The first three stages of the probability encoding process define the variable, structure it, and establish and clarify the information useful for assessing its uncertainty. Stage 4 quantifies the uncertainty.

Of the various encoding methods available, an indirect method using a probability wheel generally seems to be the most effective. The wheel is constructed so that two colors (blue and orange) can be adjusted to occupy varying amounts of area. The subject is asked whether he or she prefers a bet in which a prize is received if the spinner lands in the target color area or a bet in which the same prize is received if some event described by the uncertainty occurs. To define the event based on the uncertainty, the analyst selects a value for the variable that the subject thinks is not too extreme (but not the most likely or central value). For example, if the value happened to be the Dow Jones Industrials closing average for the end of the current year, a value of 1,200 might be chosen. The subject would be asked, "Would you rather bet that the Dow Jones average at the end of the year will be less than 1,200, or that, when I spin this wheel, the pointer lands in the blue?" The relative sizes of the blue and orange region are then adjusted and the questions repeated until a setting is found for which the subject is indifferent; in other words, the subject believes that the probability of the two events--that the Dow Jones average will be less than 1,200 and that the pointer will land in the blue region--are identical. A scale on the back of the wheel gives the probability of the event. This is plotted as one point defining a cumulative probability distribution curve.

Several important rules should be followed when using the probability wheel. The analyst must carefully avoid leading the subject to a value that the analyst thinks makes sense or is consistent. A wiser approach is, for example, to strive to confound the subject's possible attempts to mislead or impose false consistency by varying the form of the questions, and skipping back and forth from high to low values so that the subject must think carefully about each question.

In addition to the probability wheel, probabilities may be encoded using an interval technique. In the interval technique, the subject must specify values for the uncertain variable that serve as the boundaries for intervals over the range of possible values. The values are adjusted until the intervals are such that the subject thinks it equally likely for the actual value to lie in each. Typically, the median value is determined first by dividing the range of possible values into two equally likely regions. Then, values for the 25% and 75% points on the probability distribution are found by subdividing each of those regions. This process may be repeated to obtain points sufficient to permit the analyst to draw a reasonably smooth probability distribution curve. For subjects very familiar with probabilities, value and probability pairs can sometimes be elicited directly by asking the subject what the probability or odds might be for various events.

Once the analyst has elicited 5 to 10 value and probability pairs, the next step in the encoding process is to fit a cumulative distribution to the encoded points. The encoded points are plotted out of the subject's view. The analyst looks for any inconsistencies or odd discontinuities, especially shifts in the plotted points that might indicate a change in the subject's thinking. Often, the first few points encoded will appear to lie along one curve, while subsequent points lie along a different, shifted curve. Questioning the subject generally reveals that he or she thought of some new piece of information that created a shift in perspective. When this occurs, the analyst should discuss the new thought with the subject and be prepared to eliminate all of the earlier points if the perspective has been improved.

A2.5 STAGE 5: VERIFYING

The last stage of the encoding process is to test the judgments obtained in the encoding stage to see if the subject really believes in them. The encoded distribution is now shown to the subject and explained. To help investigate whether the subject feels comfortable with the results, the analyst often converts the cumulative distribution to a probability density function. Obviously, bimodal shapes or sharp extremes in the distribution should be discussed with the subject. The final step is to check whether the subject would willingly bet his or her own money according to the results. To check this, the analyst forms equally likely outcomes based on the encoded probabilities and explores whether the subject would have a difficult time choosing which to bet on. For example, the cumulative distribution can be broken into thirds and the subject asked whether he or she has any preference as to which interval the variable will fall within. If any problems are found within the verification stage, the previous steps of the encoding process must be repeated. The process is continued until the expert is confident that the curve is a good representation of his or her judgment.

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APPENDIX B

RESUMÉS OF DELPHI PANEL HYDROLOGISTS

Stanley N. Davis

Professor
Department of Hydrology and Water Resources
University of Arizona
Tucson, Arizona

Education:

Ph.D. in Geology, Yale University, 1955
M.S. in Geology, University of Kansas, 1951
B.S. in Geology with minor in Mathematics, University of Nevada, 1949

Professional Experience:

1979-present	Professor of Hydrology, University of Arizona
1975-79	Professor and Head, Department of Hydrology and Water Resources, University of Arizona
1973-75	Professor of Geology, Indiana University-Bloomington
1972-73	Associate Dean, College of Arts and Sciences, University of Missouri-Columbia
1969-72	Chairman, Department of Geology, University of Missouri-Columbia
1967-73	Professor of Geology, University of Missouri-Columbia
1966-67	Director of Hydrology Program, Stanford University
1961-67	Associate through Full Professor of Geology, Stanford University
1960-61	University of Chile (I.C.A. contract through Stanford)
1954-60	Assistant through Associate Professor of Geology, Stanford University
1953-54	Instructor of Geology, University of Rochester

Honors and Awards:

Science Award, National Water Well Association, 1980
Distinguished Alumni (Haworth Award), University of Kansas, 1975
Session Chairman, UNESCO Conference on Hydrology of Volcanic Rocks, Lanzarote, Spain, 1974
Listed in Who's Who in the World
Listed in Who's Who in America
Faculty-Alumni Award for Teaching and Service, University of Missouri, 1972
Award for Outstanding Teaching, Department of Geology, University of Missouri, 1969

Professional Activities:

American Association for the Advancement of Science
American Geophysical Union
Geological Society of America
Society of Economic Paleontologists and Mineralogists
Association of Engineering Geologists
Sigma Xi
Technical Division, National Water Well Association
American Water Resources Association
Associate Editor, Water Resources Research (American Geophysical Union), 1966-72.
Consulting Professor (honorary), "Curso de hidrologia subterranea," Barcelona, Spain. Trips to Spain in 1968, 1970, 1971, 1974.
Member of advisory team to Argentine scientists. Sponsored by United States National Academy of Science. Trips to Argentina in 1969, 1970, 1972.
Member of advisory group for Department of Interior's Earth Resources Observation Satellite under sponsorship of National Research Council, 1967-73.
Member of Committee on I.H.D. (UNESCO), 1967-70.
Lecturer for UNESCO training school in Sao Paulo, Brazil, 1969.
Important committees at the University of Missouri:
  Personnel Committee, elected member, 1969-72
  Water Resources Research Committee, past Chairman
  Honorary Degrees Committee
  Graduate School Environmental Sciences Study Committee
  Arts and Sciences College Planning Committee.
Registered Engineering Geologist, California.
Board of Directors, American Water Resources Association, 1970-75.
Penrose Conference contributor, Monterey, California, 1971.
Woods Hole Conference sponsored by the National Academy of Sciences, Science and Technology in Developing Countries, summer of 1971.
President, Missouri Association of Geologists, 1972-73.
National Committee for the International Hydrologic Program (National Academy of Sciences), 1973-76.
Chairman, Hydrogeology Division of Geological Society of America, 1974-75.
National Research Council and National Academy of Sciences. Panel on Hanford High-Level Wastes, Panel on Savannah River Wastes, Committee on Radioactive Waste Management, Panel on KBS (Swedish report), 1978-81.
Consultant to private, local, and Federal agencies, including the City of Los Angeles, Rand Corporation, Lawrence Radiation Laboratory, Kaiser Aluminum, Union Carbide Corporation, Battelle Pacific Northwest Laboratory, and U.S. Nuclear Regulatory Commission.
United Nations Development Program consultant on hydrogeologic training, New Delhi, India, 1978.
Invited speaker at various colleges and universities, including the University of California, Berkeley; S.U.N.Y., Buffalo; University of Illinois, Urbana; Memphis State University; Millsaps College; University of Southern Illinois; University of Hawaii, Honolulu; University of Madrid, Spain; Grand Valley College; University of Toledo; Texas Tech;

University of South Florida; University of Texas, Arlington; University of Buenos Aires, Argentina; University of Texas, Austin; Wright State University; Vanderbilt University; University of Washington.

Program review groups: Geology Review Group, OWI, Oak Ridge National Laboratory, 1976-79; Visiting Review Panel, Environmental Science Division, Oak Ridge National Laboratory, 1978-80; Geologic Review Group, Los Alamos National Laboratory, 1979 to present; Hydrology and Water Resources Program, Program of Excellence, University of Nebraska, 1977-79.

Member, Engineering Committee of Science Advisory Board, United States Environmental Protection Agency, 1982 to present.

Publications:

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Education:

Ph.D. in Geology, University of Colorado-Boulder, 1963
M.S. in Geology, University of Michigan-Ann Arbor, 1951
B.S. in Geological Engineering, South Dakota School of Mines and Technology, 1950

Professional Experience:

1983-present	Executive Director, Water Resources Center, Desert Research Institute
1981-83	Acting Executive Director, Water Resources Center, Desert Research Institute
1979-81	Deputy Director, Water Resources Center, Desert Research Institute, and Consultant in hydrogeology, radioactive waste management, and groundwater contamination
1971-73	Research Professor, Water Resources Center, Desert Research Institute, University of Nevada System, Reno, Nevada
1965-71	Manager, Hydrogeology section, Teledyne Isotopes, Palo Alto, California
1963-65	Assistant Professor, Department of Geology, Idaho State University, Pocatello, Idaho
1956-59	Oil field development and evaluation, Delfern Oil Company, Lubbock, Texas
1954-56	Oil Exploration, Magnolia Petroleum Company, Midland, Texas
1953-54	Oil field exploitation, Magnolia Petroleum Company, Midland, Texas
1951-53	Oil exploration, Magnolia Petroleum Company, Bismark, North Dakota

Honors and Awards:

American Men of Science
Who's Who in the West

Professional Activities:

Sigma Xi
American Geophysical Union
American Water Resources Association
American Institute of Mining Engineers
Colorado River Water User's Association
Containment Evaluation Panel, DOE, NVO, Member (1971-present)
Peer Review Panel, Radioactive Waste Management, Nevada Test Site (1979, 1980, 1981, 1982)
Technical Advisory Panel on Radioactive Waste Classification (1967)
Registered Geologist, State of California
Registered Professional Engineer, State of Texas (inactive 20 years)

Publications:

Fenske, P. R. (1984), "Unsteady Drawdown in the Presence of a Linear Discontinuity," Groundwater Hydraulics, J. S. Rosenshein and G. D. Bennett (eds.), pp. 125-145.

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Education:

Ph.D. in Civil Engineering, University of Wisconsin, August 1964.
M.S. in Civil Engineering, University of Wisconsin, June 1960.
B.S. in Civil Engineering, University of Wisconsin, January 1959.

Professional Experience:

1982-present	Professor of Civil Engineering, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts
1973-82	Associate Professor through Professor of Hydrology and Program Coordinator for Hydrology, New Mexico Institute of Mining and Technology (NMT), Socorro, New Mexico
1964-73	Assistant Professor through Associate Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts
1961-64	Research Assistant and Instructor, University of Wisconsin, Madison, Wisconsin
1960-61	Junior Engineer, Fairbanks Morse & Co., Beloit, Wisconsin
1959-60	Civil Engineer, Soil Conservation Service, USDA, Madison, Wisconsin

Honors and Awards:

Fellow, American Geophysical Union, 1983
Robert E. Horton Award, American Geophysical Union, 1982
Ford Postdoctoral Fellow, Massachusetts Institute of Technology, 1964-66
National Science Foundation Graduate Fellow, 1964
Tau Beta Pi, Chi Epsilon, Sigma Xi

Professional Activities:

American Society of Civil Engineers: Groundwater Hydrology Committee, 1972-76; Fluid Dynamics Committee, 1974-76; Task Committee on Calibration and Verification in Groundwater Modeling, 1974-77; Hydraulics Division Awards Committee, 1980-84.

American Geophysical Union: Associate Editor, Water Resources Research, 1981-present; Hydrology Section Nominations Committee, 1983; Search Committee for Water Resources Research Editor.

International Association for Hydraulic Research: Porous Media Committee, 1972-77; Organizing Committee for the conference, The Stochastic Approach to Subsurface Flow, Fontainebleau, France, 1985.

International Association of Hydrological Sciences: U.S. National Committee, 1980-present; Associate Editor, Hydrological Sciences Bulletin, 1981-present.
International Groundwater Modeling Center, Butler University, Indiana, Technical Advisory Committee, 1983-present.
State of New Mexico: Governor's Advisory Committee on WIPP (radioactive waste disposal site), 1975-80; Water Resources Research Institute Review Board, 1975-1982.
U.S. Department of Energy, Review Panel for Office of Health and Environmental Research, 1983.
Co-convener of the Geological Society of America Penrose Conference on Geostatistical Concepts and Stochastic Methods in Hydrogeology, Vancouver, B.C., 1977.
Organizer of the Socorro Workshop on Stochastic Methods in Subsurface Hydrology, Socorro, New Mexico, 1979.
Organizing Committee for the seminar Degradation, Retention, and Dispersion of Pollutants in Groundwater, International Association on Water Pollution Research and Control, Copenhagen, Denmark, 1984.

Publications:

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Gelhar, L. W. (1978), Groundwater Quality Models: Review, Calibration and Application, seminar presented at University of Karlsruhe, Germany.

Gelhar, L. W. (1978), Stochastic Analysis of Groundwater Systems: Temporal Variability, seminar presented at University of Karlsruhe, Karlsruhe, Germany.

Gelhar, L. W. (1978), Stochastic Analysis of Macrodispersion in Aquifers, seminar presented at Water Research Centre, Medmenham, England.

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Gelhar, L. W. (1978), Four lectures presented at Conference Sur L'Analyses Stochastic des Ecoulements en Milieu Poreux et la Macrodispersion, Fontainebleau, France.

Bakr, A. A., L. W. Gelhar, A. L. Gutjahr, and J. R. MacMillan (1978), "Stochastic Analysis of Spatial Variability in Subsurface Flow, Part I, Comparison of One- and Three-Dimensional Flows," Water Resources Research, 14(2).

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Mizell, S. A., L. W. Gelhar, and A. L. Gutjahr (1980), *Stochastic Analysis of Variability in Two-Dimensional Groundwater Flow with Implications for Observation Well Network Design*, Hydrology Research Report H-6, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Gelhar, L. W. (1979), *Calibration of Lumped Parameter Groundwater Models: Application to the Mesilla Valley, New Mexico*, seminar presented at University of Arizona, Tucson, Arizona.

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O. E. Meinzer Award, U.S. Geological Society of America, for distinguished contribution to hydrogeology during the past 5 yr, 1976.
Certificate of Appreciation, a team award for cooperation and technical capabilities brought to bear in the successful completion of a major research effort, granted by the U.S. Department of Agriculture, 1975.
Robert E. Horton Award, American Geophysical Union, for the best hydrology paper to appear in *Water Resources Research*, 1969.
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APPENDIX C

GENERAL INFORMATION ON BASALT WASTE ISOLATION PROJECT PROVIDED TO THE PANEL OF EXPERTS

C1.0 BACKGROUND

The National Waste Terminal Storage (NWTS)* Program was initiated by the United States Government in the mid-1970s for the purpose of investigating the feasibility of storing nuclear wastes in deep geologic formations. Initially, several rock types, such as bedded salt, domal salt, granite, tuff, and basalt, were studied on a non-site-specific basis to evaluate their general suitability for a nuclear waste repository. Currently, the NWTS Program is focusing on the identification and characterization of candidate sites for a repository. The Nuclear Waste Policy Act of 1982 (U.S. Congress 1983) provides a legislative directive and schedule for site characterization, repository design, licensing by regulatory agencies, construction, and operation of nuclear waste repositories in geologic media.

The Basalt Waste Isolation Project (BWIP) is one of several major research and development projects conducted under the direction of the NWTS Program. Rockwell Hanford Operations (Rockwell) is the prime contractor to the U.S. Department of Energy (DOE) for operation of the Hanford Site in south-central Washington State (Fig. C-1). As such, Rockwell is currently responsible for investigating the feasibility of siting a repository for terminal disposal of nuclear waste in the basalts underlying the Hanford Site.

Field investigations completed to date at the Hanford Site have focused on the geologic and hydrologic characterization of the Columbia River Basalt Group, a thick accumulation of tholeiitic plateau basalts. The accumulations of basalt are notable for their thickness, locally in excess of 1,000 m. Individual basalt flows are commonly as thick as 70 m and are laterally continuous over many miles (Myers et al. 1979). Although the basaltic rock is characteristically jointed and fractured, field measurements (Gephart et al. 1979; DOE 1982) commonly show that the deep basalt strata may possess very low permeabilities (e.g, 10^{-12} m/s). The permeabilities of the dense basalt flows at depth appear to be restricted because of the relatively large lithostatic pressure and infilling of fractures by secondary minerals (Spane 1982).

During the past 38 yr, the Hanford Site has been dedicated to nuclear waste management (ERDA 1975; National Academy of Sciences 1978). The Hanford Site occupies a land area of 1,500 km^2 (see Fig. C-1). The candidate repository site is within the Hanford Site (see Fig. C-1). Studies of the candidate site have identified four horizons that may be suitable as a repository host rock. These candidate basalt flows are the Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum (Fig. C-2), and are at depths in excess of about 900 m in the candidate site area. These horizons were identified

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*Now known as the Office of Civilian Radioactive Waste Management.

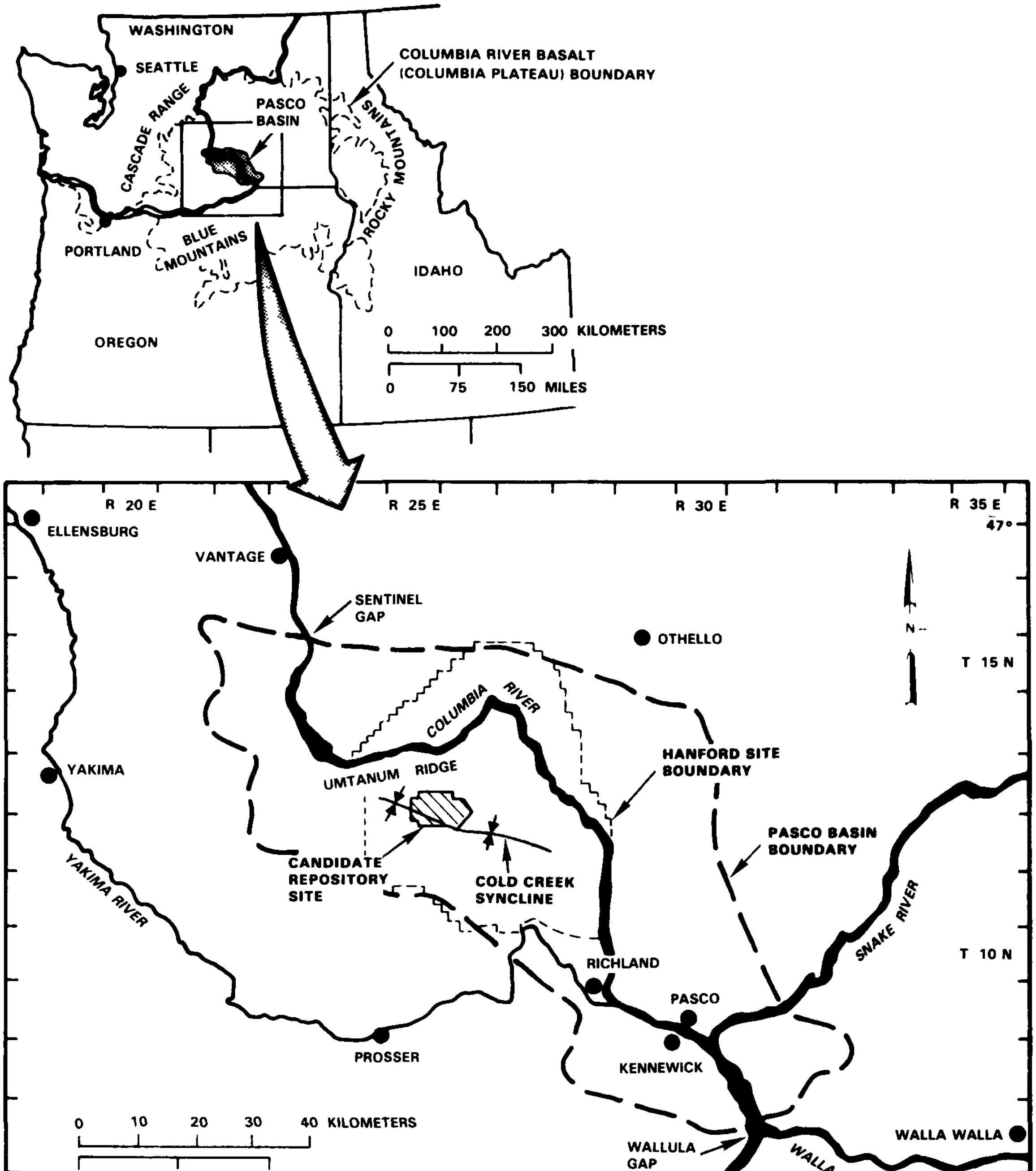

FIGURE C-1. Location of the Columbia Plateau, Pasco Basin, Hanford Site, and the Candidate Repository Site.

PERIOD	EPOCH	GROUP	SUBGROUP	FORMATION	K-Ar AGE YEARS X 10^6	MEMBER OR SEQUENCE	GEOLOGIC MAPPING SYMBOL	SEDIMENT STRATIGRAPHY OR BASALT FLOWS	
QUATERNARY	Pleistocene/ Holocene					SURFICIAL UNITS	Ql	LOESS	
							Qd	SAND DUNES	
							Qa, Qaf	ALLUVIUM AND ALLUVIAL FANS	
							Qld	LANDSLIDES	
							Qt	TALUS	
							Qco	COLLUVIUM	
	Pleisto- cene			Hanford		TOUCHET BEDS PASCO GRAVELS	Qht Qhp		
								PLIO PLEISTOCENE UNIT	
TERTIARY	Pliocene			Ringold			Trs	UPPER RINGOLD	FANGLOMERATE
							Trc	MIDDLE RINGOLD	
							Trls	LOWER RINGOLD	
							Trg	BASAL RINGOLD	
	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	8.5	ICE HARBOR MEMBER	Ti Tig	GOOSE ISLAND FLOW	ELLENSBURG FORMATION Tel
							Tim	MARTINDALE FLOW	
							Tib	BASIN CITY FLOW	
								LEVEY INTERBED	
					10.5	ELEPHANT MOUNTAIN MEMBER	Tem Tem$_2$	UPPER ELEPHANT MOUNTAIN FLOW	
							Tem$_1$	LOWER ELEPHANT MOUNTAIN FLOW	
								RATTLESNAKE RIDGE INTERBED	
					12.0	POMONA MEMBER	Tp Tp$_2$	UPPER POMONA FLOW	
							Tp$_1$	LOWER POMONA FLOW	
								SELAH INTERBED	
						ESQUATZEL MEMBER	Te	UPPER GABLE MOUNTAIN FLOW	
							Te$_2$	GABLE MOUNTAIN INTERBED	
							Te$_1$	LOWER GABLE MOUNTAIN FLOW	
								COLD CREEK INTERBED	
						ASOTIN MEMBER	Ta	HUNTZINGER FLOW	
						WILBUR CREEK MEMBER	Tw	WAHLUKE FLOW	
						UMATILLA MEMBER	Tu Tu$_s$	SILLUSI FLOW	
							Tu$_u$	UMATILLA FLOW	
					13.6			MABTON INTERBED	
				Wanapum Basalt		PRIEST RAPIDS MEMBER	Tpr Tpr$_l$	LOLO FLOW	
							Tpr$_r$	ROSALIA FLOWS	
								QUINCY INTERBED	
						ROZA MEMBER	Tr Tr$_2$	UPPER ROZA FLOW	
							Tr$_1$	LOWER ROZA FLOW	
								SQUAW CREEK INTERBED	
						FRENCHMAN SPRINGS MEMBER	Tf Tf$_a$	APHYRIC FLOWS	
							Tf$_p$	PHYRIC FLOWS	
					15.6			VANTAGE INTERBED	
				Grande Ronde Basalt		SENTINEL BLUFFS SEQUENCE	Tsb	UNDIFFERENTIATED FLOWS	
								ROCKY COULEE FLOW	
								UNNAMED FLOW	
								COHASSETT FLOW	
								UNDIFFERENTIATED FLOWS	
								McCOY CANYON FLOW	
								INTERMEDIATE Mg FLOW	
						SCHWANA SEQUENCE	Ts	LOW Mg FLOW ABOVE UMTANUM	
								UMTANUM FLOW	
								HIGH Mg FLOWS BELOW UMTANUM	
								VERY HIGH Mg FLOW	
					16.1			↓ AT LEAST 30 LOW Mg FLOWS	

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FIGURE C-2. Stratigraphy of the Pasco Basin.

for further study based upon the relative thickness of flow entablature, lateral continuity, and hydrologic and geologic properties that may enhance radionuclide isolation.

This summary briefly describes general characteristics of the candidate repository facility and its geologic and hydrologic setting.

C2.0 GEOLOGIC CHARACTERISTICS

C2.1 STRATIGRAPHY

The lavas underlying the candidate site comprise part of the Columbia Plateau flood-basalt province (see Fig. C-1). The province has an area of approximately 200,000 km^2 and is estimated to contain on the order of 200,000 km^3 of tholeiitic basalts. Individual flows commonly are laterally extensive and may range upwards of 100 m in thickness. The Pasco Basin, in the south-central part of the Columbia Plateau (see Fig. C-1), occupies about 5,180 km^2 and contains the DOE Hanford Site. Columbia River basalts within the Pasco Basin are at least 1,460 m thick and in most of the basin are overlain by glacio-fluvial, fluvial-lacustrine, and aeolian sediments. Volcaniclastic sediments locally are interbedded between basalt flows, particularly in the upper part of the basalt section (see Fig. C-2).

The Cold Creek syncline is located in the southern and southwestern part of the Pasco Basin and contains the candidate repository site (see Fig. C-1). The syncline is a topographic and structural basin that is bounded by the Umtanum Ridge-Gable Mountain anticline to the north and by the Yakima Ridge-Rattlesnake Mountain anticline to the south. Two subtle depressions are present along the northwest-trending hinge line of the syncline: the Cold Creek Valley depression, and the Wye Barricade depression. The candidate site is located within the Cold Creek Valley depression where the Columbia River basalts are within a few degrees of horizontal.

The Columbia River Basalt Group is the youngest assemblage of tholeiitic flood basalts known. It has been dated radiometrically as ranging from 6 to 16.5 million years old (Watkins and Baksi 1974; McKee et al. 1977), but more than 99% of the basalt was erupted during a 2.5- to 3-million-year interval beginning approximately 16-million-years ago (Swanson and Wright 1978). The basalts were erupted from vents, now exposed as north-trending dikes, in the southeastern part of the Columbia Plateau. The Columbia River basalts have been subdivided into five formations, three of which are present in the Pasco Basin. The two oldest formations, the Imnaha and the Picture Gorge Basalt flows, are present at the surface only at the southeastern and southern margins, respectively, of the Columbia Plateau. The younger three formations, the Grande Ronde, Wanapum, and Saddle Mountains Basalt flows, are present within the Pasco Basin. The stratigraphic section of the Pasco Basin is shown in Figure C-2.

In the Pasco Basin, as elsewhere in the Columbia Plateau, the Grande Ronde basalts are the most voluminous and areally extensive formation of the group. Although its thickness varies as a consequence of the buried topography onto which it was erupted and subsequently eroded, its thickness is known to exceed 1,000 m in the Pasco Basin. The formation probably consists of hundreds to thousands of individual flows. Within the Cold Creek syncline, the more than 1,000 m of Grande Ronde Basalt flows consist of at least 50 flows that average from 4 to 150 m in thickness. The top of the Grande Ronde Basalt typically is distinguished by a zone of weathering or a thin bed of volcaniclastic sediment. Grande Ronde Basalt flows are exposed at the margins of the Pasco Basin in the Sentinel Gap, Wallula Gap, and Umtanum Ridge areas (see Fig. C-1).

The Grande Ronde Basalt flows conformably are overlain by basalts of the Wanapum Formation. In turn, these basalts are overlain by flows of the Saddle Mountains Basalt, the youngest formation of the Columbia River Basalt Group. The Wanapum Formation is the second-most voluminous of the formations of the Columbia River Basalt Group. Wanapum basalts define the surface of much of the Columbia Plateau. Compared to the underlying Grande Ronde flows, Wanapum basalts have a relatively high ferrous oxide (FeO) and titanium dioxide (TiO_2) content. Saddle Mountains Basalt flows, comprising less than 1% of the Columbia River Basalt Group, are characterized by the greatest chemical, petrographic, and paleomagnetic variability of any formation of the Columbia River Basalt Group. Additionally, volcaniclastic sediments of the Ellensburg Formation commonly are interbedded with Saddle Mountains Basalt flows, in contrast to their lesser abundance in the underlying basalt formations. Saddle Mountains Basalt flows contain a number of major water-bearing horizons. The Wanapum and Saddle Mountains basalts, within the Cold Creek syncline, are composed of as many as 20 flows, with a total thickness of about 700 m.

Overlying the Columbia River basalts in the Cold Creek syncline are up to 220 m of fluvial-lacustrine sediments.

C2.2 INTRAFLOW FEATURES AND STRUCTURE OF THE CANDIDATE BASALTS

Four candidate horizons have been identified after a preliminary screening study (Long and WCC 1983). These are the Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows of the Grande Ronde Basalt. The nature of internal characteristics of the candidate flows currently is known from outcrops and drill core observations (Fig. C-3). However, because the internal structures of plateau flood basalts commonly change laterally, larger scale, subsurface explorations within the candidate repository site are planned to reduce the predictive uncertainties of intraflow characteristics.

The primary internal structures of basalt flows are the fracture patterns, vesiculation, and brecciation that originate during the emplacement and cooling of each flow. These features play a significant role in determining the suitability of a flow for a nuclear waste repository. First, the degree of vesiculation and brecciation of the interior of a flow determines, in part, the type of roof support systems required in a

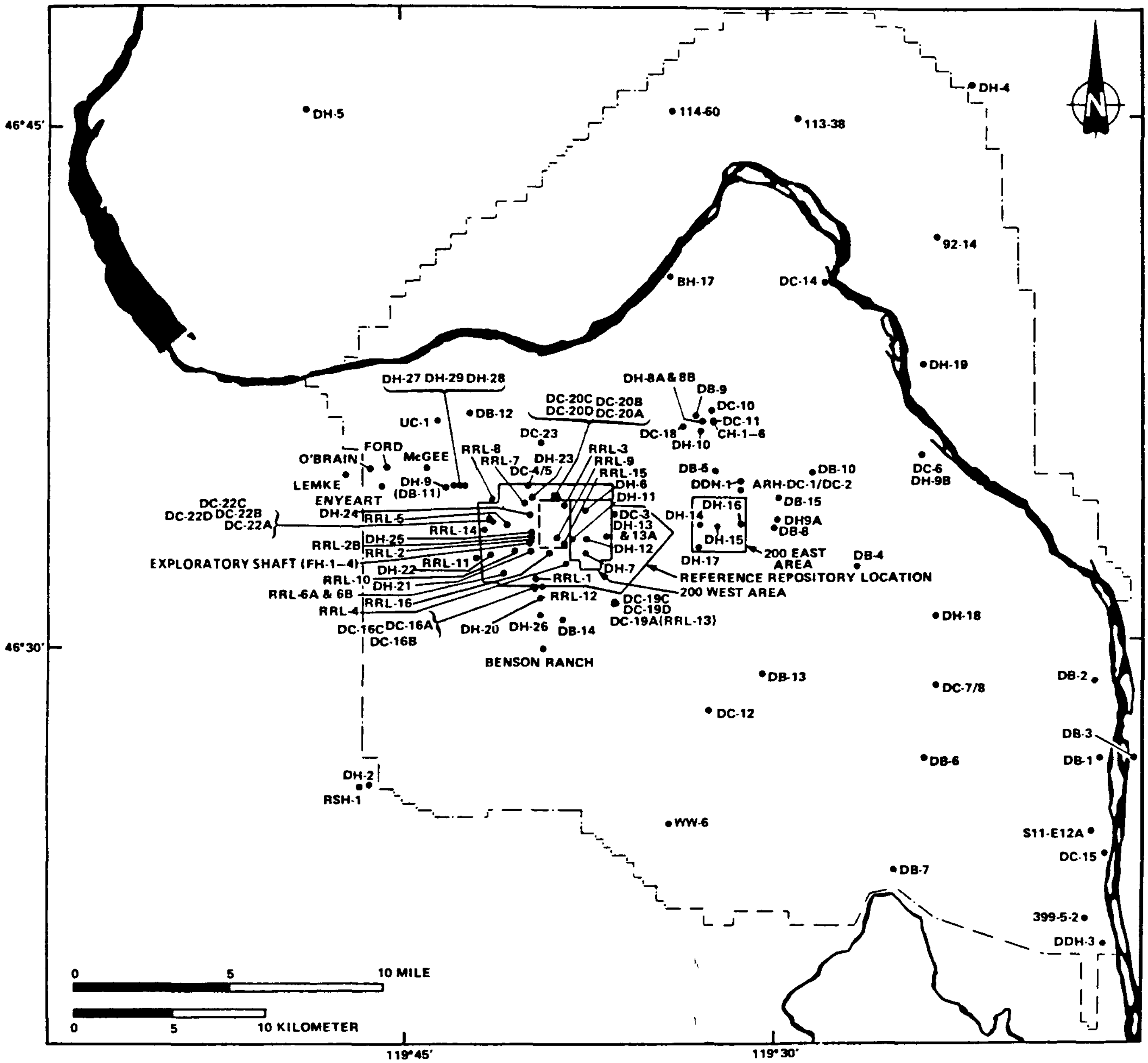

FIGURE C-3. Borehole Location Map. (Sheet 1 of 2; Hanford Site.)

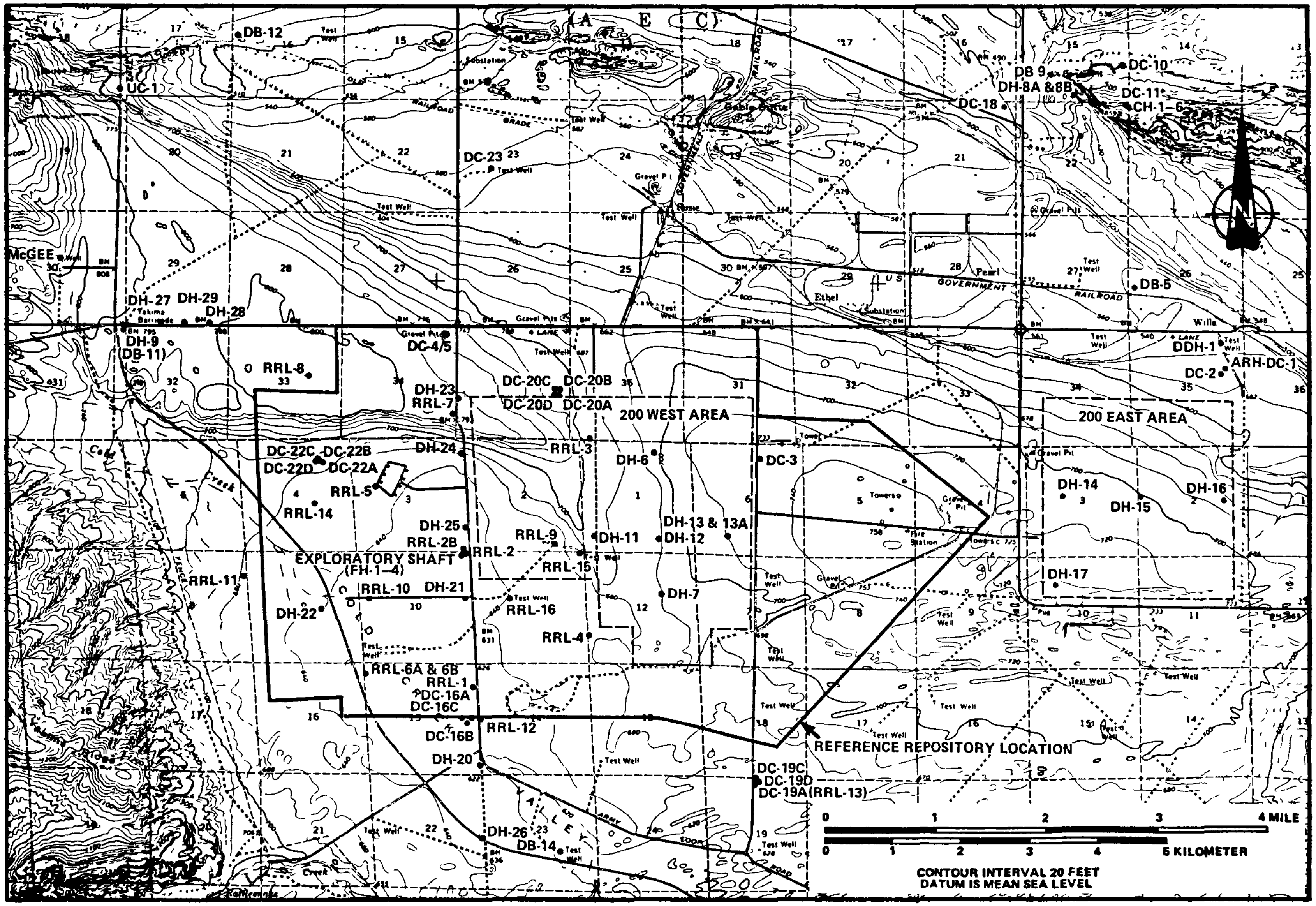

FIGURE C-3. Borehole Location Map. (Sheet 2 of 2; Detail of Reference Repository Location.)

repository. Second, the vesicularity and brecciation within the interior of a flow partly determine permeability; it is the interior of a flow that is the first barrier to radionuclide migration. The thickness of nonvesiculated and unbrecciated flow interior (hereafter referred to as dense interior) is, therefore, important in repository performance. Moreover, the extent and character of fracturing of the flow interior, including the secondary mineral infillings within the interior, as well as its thickness, influence the near-field hydrologic characteristics of the repository.

The general internal characteristics of Grande Ronde Basalt flows in the Pasco Basin have been reported previously (Long 1978; Myers/Price et al. 1979; Long and Davidson 1981). This work defined nomenclature and classification of internal structures for Columbia River Basalt Group flows. Typical intraflow structures are shown in Figure C-4.

The flow tops consist of the vesicular and/or brecciated crust of the flow. They typically grade downward into a vesicular zone that, in turn, grades into the dense interior of the flow. The dense interior in most, but not all, cases consists of two parts: a central entablature and a basal colonnade. The entablature is comprised of irregularly to regularly jointed rock with relatively small columns. The colonnade contrasts markedly with the entablature and consists of relatively well-formed columns with fewer fractures overall. The basal part of the flow is ordinarily a thin (0.5 m) zone of fractured, glassy basalt, but in some flows it may be a thick, pillowed zone that occupies as much as half the flow thickness. To date, such pillowed zones have not been encountered in Grande Ronde Basalt flows within the Pasco Basin.

The thicknesses of the four candidate flows and their intraflow structures, as currently known, are summarized in Table C-1. The individual candidate flows are discussed below.

C2.2.1 Rocky Coulee Flow

The Rocky Coulee flow lies within the upper third of the Sentinel Bluffs sequence and is interpreted to occur throughout the Pasco Basin as well as to the north in the vicinity of Vantage, Washington. The Rocky Coulee flow in the Pasco Basin is correlated with the Rocky Coulee flow of Mackin (1961) near Vantage. Within the Pasco Basin, the Rocky Coulee flow is correlated on the basis of stratigraphic position, thickness, and chromium content. The flow is thickest in the southeast and thinnest in the northeast portions of the basin. In the reference repository location, the flow maintains a relatively consistent thickness but does thin to the east. At borehole DC-3, in the eastern portion of the reference repository location, the flow is approximately 10 m thinner than in the remainder of the reference repository location. Thinning of the Rocky Coulee flow in the eastern part of the reference repository location is attributed to emplacement of the flow over a single thin flow of limited extent that overlies the Cohassett flow in this area.

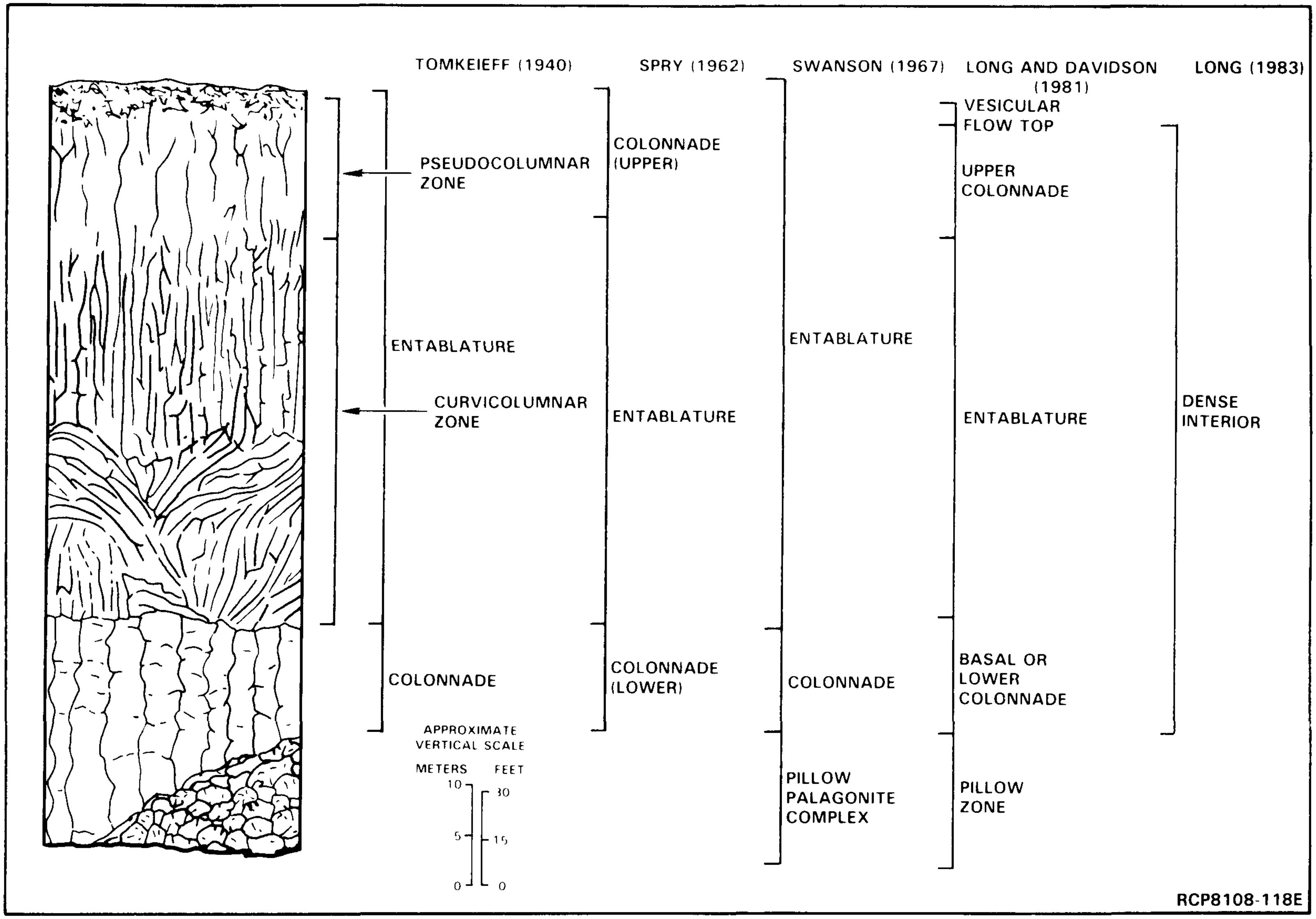

FIGURE C-4. Typical Intraflow Structures Present in Grande Ronde Basalt.

TABLE C-1. Thicknesses of Flow Tops and Dense Interiors of Candidate Repository Horizons in Boreholes RRL-2, RRL-6, and RRL-14.

Unit	Borehole			Mean value (m)
	RRL-2 (m)	RRL-6 (m)	RRL-14 (m)	
Rocky Coulee				
Flow top	5.1	5.2	24.4	11.6
Dense interior*	46.7	46.2	30.5	41.1
Cohassett				
Flow top	5.1	9.0	10.4	8.2
Dense interior above vesicular zone	22.3	16.1	23.4	20.6
Laterally extensive vesicular zone	7.3	8.0	3.1	6.1
Dense interior below vesicular zone	45.1	43.2	35.6	41.3
McCoy Canyon				
Flow top	6.4	12.0	11.7	10.0
Dense interior*	31.4	30.5	33.2	31.7
Umtanum				
Flow top	45.1	28.5	20.9	31.5
Dense interior	25.3	41.7	39.0	35.3

*Significant discontinuous zones of vesiculation occur within the dense interiors of the Rocky Coulee and McCoy Canyon flows.

C2.2.2 Cohassett Flow

The Cohassett flow is stratigraphically near the center of the Sentinel Bluffs sequence and can be correlated throughout the entire basin. Correlations of the Cohassett flow are based primarily on stratigraphic position and thickness. The Cohassett flow is thickest in the central Pasco Basin, maintains a fairly consistent thickness in the reference repository location, and thins in the southeastern portion of the map area. The thinning of the flow in the southeast is thought to be related to the mechanics of flow emplacement rather than to thinning over a topographic high, either structural or constructional. Several lines of evidence point to this: (1) no present-day structures found in the vicinity account for this thinning; (2) the underlying basalt between the Umtanum and the base of the Cohassett is no thicker than elsewhere in the basin, thus ruling out a constructional or structural topographic high; and (3) two flows overlying the Cohassett are thicker in the southeastern portion of the map area, indicating that there was a topographic low in that area at the time of their emplacement over the Cohassett.

Within the interior of the Cohassett there is a vesicular zone that aids in the identification and correlation of the Cohassett. It is characterized by isolated vesicles, averaging from one-half to several centimeters in diameter. Brecciation typical of flow tops is not present and, in outcrops, cooling joints pass through this zone undisrupted. The vesicular zone occurs at a particular depth into the flow ($\approx 30 \pm 5$ m) and can be correlated throughout the basin except in boreholes DC-8, DC-15, and DDH-3 in the southeastern portion of the Hanford Site.

C2.2.3 McCoy Canyon Flow

The McCoy Canyon flow is the lowermost flow of the Sentinel Bluffs sequence. It is correlated within the Pasco Basin and to the north on the basis of its position relative to the magnesium horizon and on its major-element chemistry as a possible chemical subtype (Long et al. 1980). The total thickness of the flow varies from 73 m at Sentinel Gap to 25 m at borehole DDH-3. The flow is relatively thick to the northwest and west of the Pasco Basin, in an area of thickening in the underlying Umtanum flow. Apparently, a similar structural low existed in this area when both the McCoy Canyon and Umtanum flows were emplaced. This low may have resulted from continued deformation after emplacement of the Umtanum flow or perhaps the Umtanum flow incompletely filled a structural low.

To the southeast, where the McCoy Canyon flow thins, it may have covered constructional topography formed by the Umtanum flow (see the discussion on Umtanum). The flow also thins progressively to the northeast on the southwest-dipping paleoslope of Swanson and Wright (1976).

Across the reference repository location area the McCoy Canyon flow thins to approximately 11.5 m.

C2.2.4 Umtanum Flow

The Umtanum flow is the uppermost flow in the Schwana sequence throughout the Pasco Basin (except in borehole DH-4 and west of the Emerson Nipple section). It is correlated on the basis of its relatively high TiO_2 content and on its stratigraphic position relative to the magnesium horizon. In the Pasco Basin, the Umtanum flow thins to the northeast (see Fig. C-1) and is not present in surface sections to the north (Long and Landon 1981). It also thins dramatically to the west of the Emerson Nipple section, based on data from Price (1982). The Umtanum is thickest in the area of Emerson Nipple and Sentinel Gap surface sections, and in the southeast near boreholes DC-15 and DDH-3 (see Fig. C-1 and C-3). Current data suggest that a broad zone of relatively constant thickness occurs in the central Pasco Basin. Within the reference repository location the thickness is variable and possibly related to the development of the thick flow top breccia found in the Umtanum flow in portions of the reference repository location.

C3.0 REPOSITORY CHARACTERISTICS

As currently envisioned (Rockwell 1981; Kaiser Engineers et al. 1982; Deju 1982), the repository will be designed to accommodate 35,000 waste packages containing spent reactor fuel. The spent fuel is expected to be emplaced at a rate of 1,750 packages per year for a period of 20 years. Each waste package is anticipated to consist of a container filled with unreprocessed light-water reactor fuel rods, with each container enclosing spent fuel rods from either three pressurized-water reactor (PWR) assemblies or seven boiling-water reactor (BWR) assemblies. For purposes of thermal calculations, the rods are assumed to have been removed from the reactor 10 yr prior to their terminal underground emplacement.

At the time of emplacement, the thermal output from each container enclosing PWR spent fuel will be about 1.74 kW. Thermal output from each container enclosing BWR spent fuel assemblies will be about 1.33 kW. For the purpose of repository design, a conservative thermal output of 1.74 kW has been assumed for all containers.

C3.1 SHAFTS

The mined geologic repository is envisioned to be serviced by five access shafts (Fig. C-5), each with separate and distinct functions. Each shaft will be lined with steel or with iron tubbing backed by poured concrete. The waste-transport shaft currently is designed to have an inside diameter of 3.7 m. The excavated basalt transport shaft will function as the main air exhaust from the underground mining areas and will have an inside diameter of 4.3 m. The service shaft, utilized for raising and lowering personnel, equipment, and materials, and serving as the main air intake for underground mining areas, will have an inside diameter of 4.9 m. The confinement exhaust shaft will provide for air exhaust from the

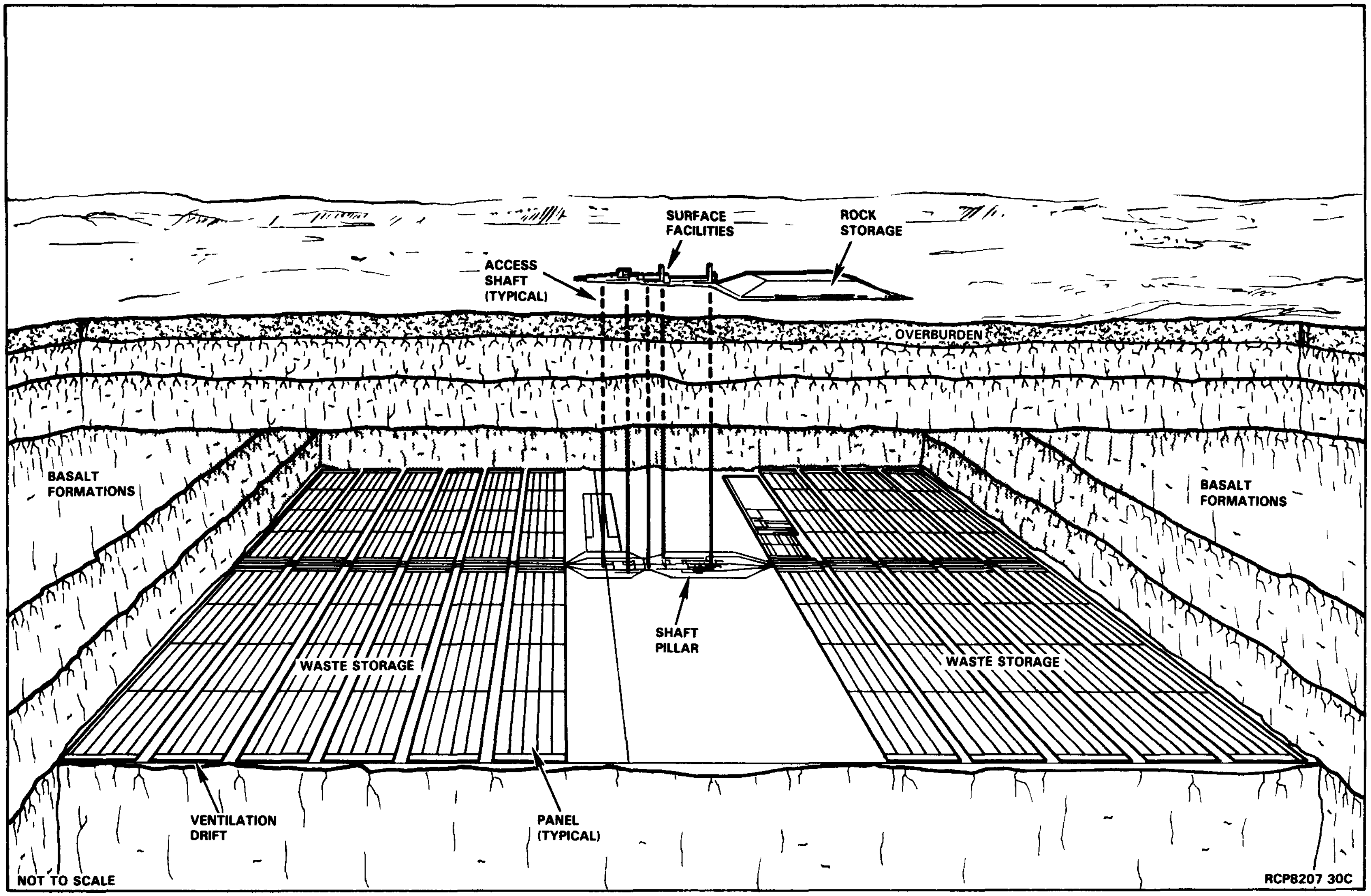

FIGURE C-5. Conceptual Nuclear Waste Repository in Basalt.

subsurface waste confinement area and will have an inside diameter of 3 m. The confinement air intake shaft, supplying fresh air to the subsurface waste storage area and providing access for chilled water pipes, will have an inside diameter of 3.35 m. Excavation diameters of all access shafts will be approximately 1 m greater than the finished (inside) diameters.

C3.2 REPOSITORY-LEVEL LAYOUT

The repository-level excavations are designed to provide (1) operational safety and (2) isolation of ventilation of areas containing emplaced waste (confinement area) from ventilation of developmental headings. The configuration of excavations in the shaft-support pillar area surrounding the five shafts is controlled by requirements for loading, unloading, storage, maintenance, service, personnel, and ventilation (see Fig. C-5). Waste emplacement panels will likely be excavated in two rows on both sides of the shaft pillar (see Fig. C-5) and will be accessed by seven main entries for developmental headings, confinement area ventilation, and haulage.

C3.3 THERMAL FLUX FROM EMPLACED WASTE

Facility heat loads resulting from thermal output of emplaced waste have been calculated based on the value of 1.74 kW per canister. The calculations neglect consideration of thermal decay with time; hence, actual thermal fluxes will be less. Within each panel, heat released from emplaced waste is anticipated to be 130 kW/hectare. Within the cluster of waste storage panels, the average heat load will be about 127 kW/hectare. Thermal output averaged over the entire repository level of the facility will be about 108 kW/hectare.

The canister emplacement hole and panel design allows fuel cladding temperatures no greater than 300 $^{\circ}$C. This temperature, in turn, is expected to result in maximum host-basalt temperatures of 200 $^{\circ}$C. Thermomechanical analyses for repository design are based upon the following reference conditions: a depth of 1,128 m from the surface, initial hydrostatic rock stress conditions, and in situ, pre-emplacement temperatures of 57 $^{\circ}$C.

C4.0 OBJECTIVES OF THE STUDY

Prediction of long-term performance measures for a repository in basalt requires the specification of several hydrologic parameters. Quantitative estimates for these parameters will eventually be refined by means of hydrologic testing conducted as part of the site characterization activities at the Hanford Site. Among the most critical of these parameters are effective porosity and vertical conductivity (or anisotropy ratio) of host-rock units. These two parameters are of key importance in the calculation of groundwater flow paths and traveltimes. Groundwater flow path and traveltime calculation form the basis for assessing repository performance.

In the absence of currently available test data on which to base refined estimates of these two critical parameters, and in consideration of a pressing need for parameters for use in initial iterations of performance assessment modeling calculations, technically based, independently derived estimates of these two hydrologic parameters must be obtained. Such values will be used as surrogates of test-based values for use in performance assessment calculations, pending the availability of more refined values.

The estimates are to be obtained by means of an opinion survey of hydrologic experts independent of Rockwell. The survey is to be conducted in a manner free from involvement or direction by Rockwell that could be construed as influencing the results.

To this end, Rockwell has chosen a Delphi method for use in this study because of its systematic, unbiased approach to obtaining technical consensus of expert opinion (Dalkey and Helmer 1963). The Delphi method of expert opinion solicitation has the advantage of being fully auditable, with well documentable traceability of the rationale employed by the impaneled experts in reaching their conclusions. Because of the statistical format required by the stochastic modeling effort, a probability encoding method is also needed. A probability encoding interviewing technique (SRI 1977) is, therefore, to be used in conjunction with the Delphi technique to ensure that the expert opinions are in a statistical format. That is, the expert opinion consensus is to be expressed in terms of the mean, standard deviation, and probability distribution function for the two hydrologic parameters, as needed for stochastic modeling of groundwater flow (Clifton et al. 1983). Because all hydraulic properties are, in general, scale-dependent, the parameter estimates for effective porosities and vertical conductivities (or anisotropy ratios) shall be developed for two scales: (1) Mega (on the order of 100 to 1,000 m) and (2) Macro (on the order of 1 to 10 m). For parameters developed at both scales of consideration, available site-specific geologic and hydrologic information for the candidate horizons and other flows shall be considered by the panelists.

The parameter estimates developed by this study will be used by Rockwell as input to the computer code MAGNUM-MC. This computer code uses a Monte Carlo sampling technique in conjunction with a two-dimensional finite-element groundwater model (Baca et al. 1983). This model considers porosity and hydraulic conductivity as stochastic parameters that can be represented by means of either normal or log-normal distributions.

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APPENDIX D

REVIEW OF THE DATA PERTAINING TO THE HYDROLOGICAL PARAMETERS OF SELECTED BASALT FLOWS BENEATH THE HANFORD SITE (PROVIDED TO THE PANELISTS)

D1.0 INTRODUCTION

Approximately 200 transmissivity and hydraulic conductivity determinations have been made by the Basalt Waste Isolation Project (BWIP) in approximately 40 boreholes in and around the Hanford Site. The location of these boreholes is indicated on the site map as shown in Figure D-1. The majority of these determinations have been made in relatively transmissive basalt flow tops and sedimentary interbeds within the basalt sequence. Most of these data are considered to be preliminary and, in many cases, only a range of values is given rather than a best estimate. Despite the lack of finality of these data, some basic statistical analyses are useful to highlight the range estimates for hydraulic parameters that exist for the basalt formations. These statistics may change as more data are added to the data base and as existing parameter estimates are refined.

This report gives a summary of the hydraulic conductivity and the porosity measurements of selected basalt flows at the Hanford Site in Washington State. The formations reviewed are the (1) Saddle Mountains Basalt, (2) the Wanapum Basalt, and (3) the Grande Ronde Basalt. These formations, in the context of the stratigraphic cross section at the reference repository location, are shown in Figure D-2. The depths shown in this figure are those from borehole RRL-2. The data from these three formations are presented in graphical form and the summary of the statistics is presented in tabular form. The current candidate horizons for nuclear waste emplacement are all located in the Grande Ronde Basalt. These horizons are the (1) Rocky Coulee, (2) Cohassett, (3) McCoy Canyon, and (4) Umtanum flows. Data for these flows, as well as for the Priest Rapids and the Frenchman Springs members of the Wanapum Basalt, are reviewed in detail and presented in tabular format.

The hydrologic parameters have been measured primarily from short-duration, single-hole tests using packer technology. They are therefore representative of macroscale (1 to 10 m) investigations. One dual borehole test (boreholes DC-7 and DC-8) yielded a bulk value of the hydraulic conductivity on a scale of at least 15 m. Most of the field tests performed are concerned with the evaluation of transmissivity and horizontal conductivity. In contrast, no reliable field data for vertical conductivity have been reported. Only one test for determination of the porosity has been reported.

This report gives, successively, a brief description of the hydrologic tests, a review of the available transmissivity and horizontal conductivity values, and estimates of vertical conductivity and porosity.

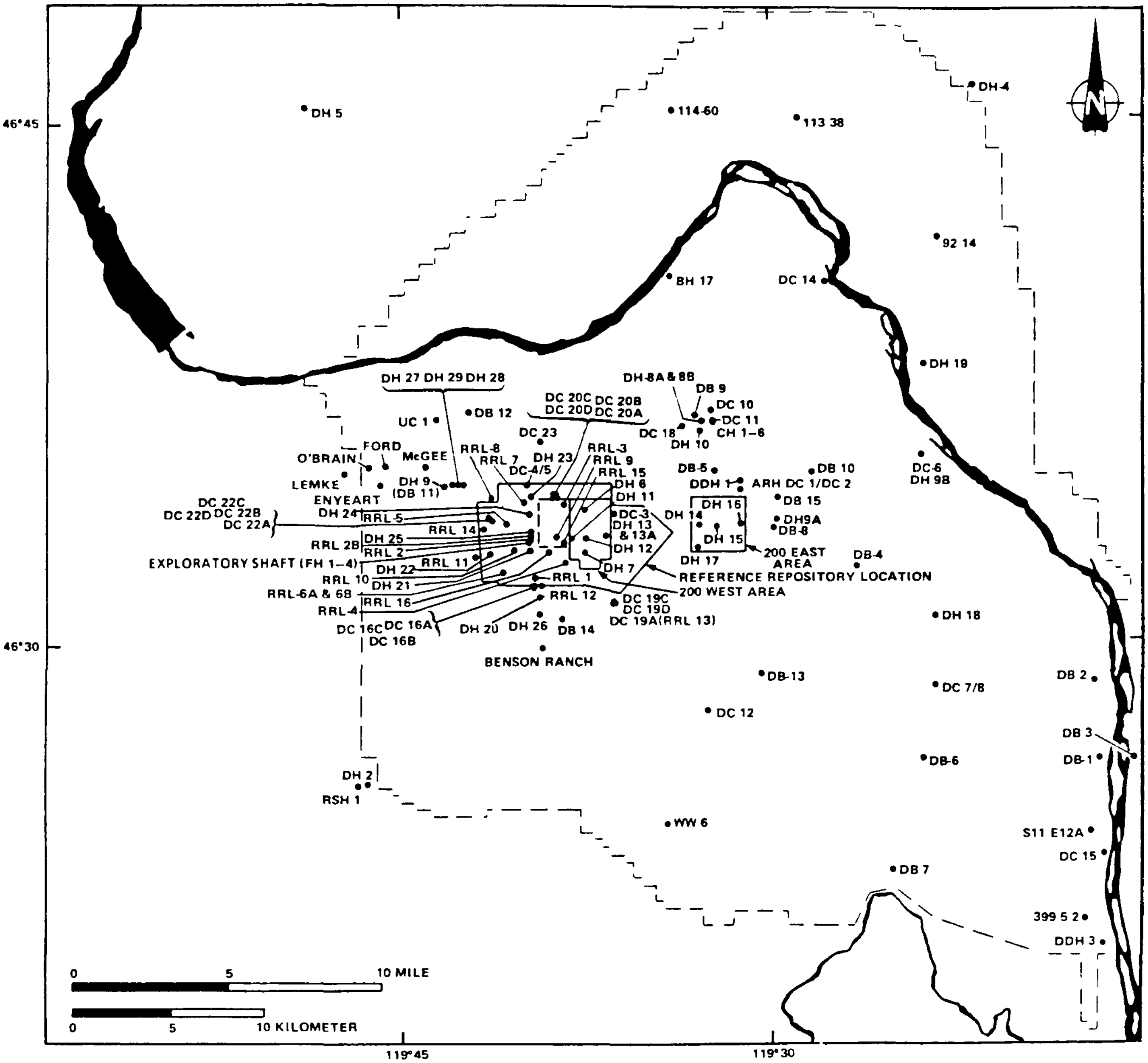

FIGURE D-1. Borehole Location Map.

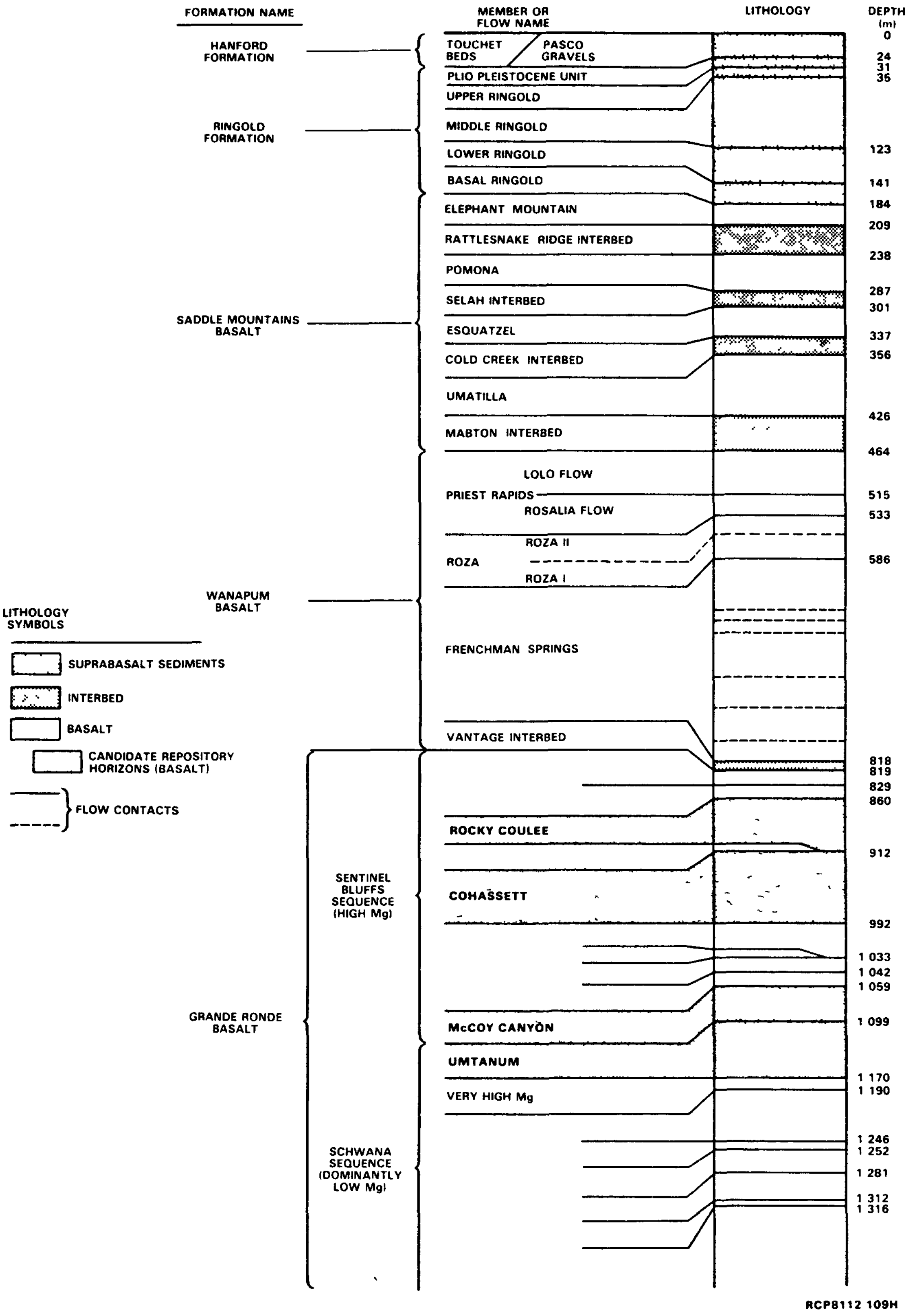

FIGURE D-2. General Stratigraphy of the Reference Repository Location, Showing Relative Positions of the Candidate Repository Horizons. Depths are from Borehole RRL-2.

D2.0 DESCRIPTION OF HYDROLOGIC TESTS

Most of the conductivity tests consist of short-duration experiments in single wells. The effective porosity is determined from a tracer test. The diameters of the tested boreholes range from 8 to 10 cm for cored holes and up to 20 cm for rotary-drilled holes. Most of the tests were performed during drilling of the boreholes.

The hydrologic properties are evaluated by injecting or withdrawing fluid in a packed interval. Single or straddle packers are used depending on whether the hydrologic test is performed during drilling or after completion of the borehole. (An inflatable packer at the top of the interval and an inflatable bridge plug at the bottom of the interval can be used instead of a straddle packer.) Four different tests were used to evaluate the conductivity of the basalt flows: constant discharge, slug injection/withdrawal, pulse, and constant-head injection tests. Which test is performed depends on the conductivity of the formation as estimated by an examination of the lithologic and geophysical logs and inspection of core samples. Pulse and constant-head injection tests are utilized in low permeability horizons; constant discharge and slug tests are reserved for high transmissivity zones. Information on the specific duration of the test is generally not available from the publications reviewed.

Several sources of data uncertainty are reported. First, there are potential problems associated with short-term monitoring of hydraulic head (NRC 1983, Appendix G). Second, the evaluations of the hydraulic conductivity tests do not take into account the effect of drilling mud, which may cause a decrease of the transmissivity (NRC 1983, Appendix I). Also, inferences about the large-scale properties must take into account the fact that no large-scale hydrologic testing has been carried out at the Hanford Site.

D3.0 TRANSMISSIVITY AND HORIZONTAL HYDRAULIC CONDUCTIVITY

D3.1 FLOW TOPS AND SEDIMENTARY INTERBEDS

D3.1.1 Transmissivity

Log-normal plots of transmissivity data from the Saddle Mountains, Wanapum, and Grande Ronde basalts are given in Figures D-3 through D-5, respectively. All these data are from the more transmissive sections of individual hydrostratigraphic units within each formation. In the Saddle Mountains Basalt, a hydrostratigraphic unit is either a basalt flow or a sedimentary interbed plus the underlying basalt flow. Except for the Vantage interbed, no extensive sedimentary interbeds exist in either the Wanapum or Grande Ronde basalts within the Hanford Site; hence, the majority of hydrostratigraphic units within these formations are single basalt flows.

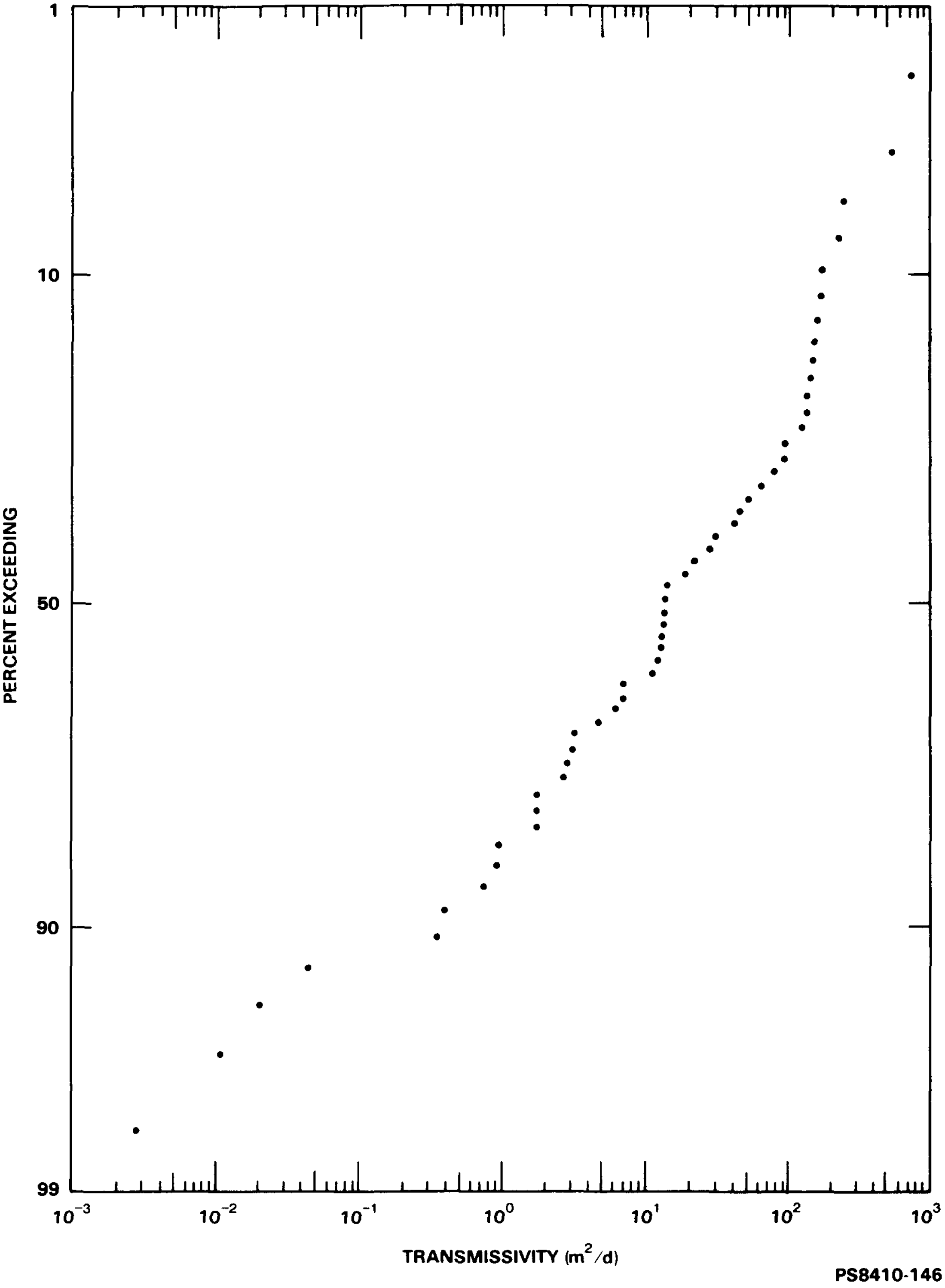

FIGURE D-3. Log-Normal Probability Plot of Transmissivity Data from Saddle Mountains Basalt Flow Tops and Interbeds.

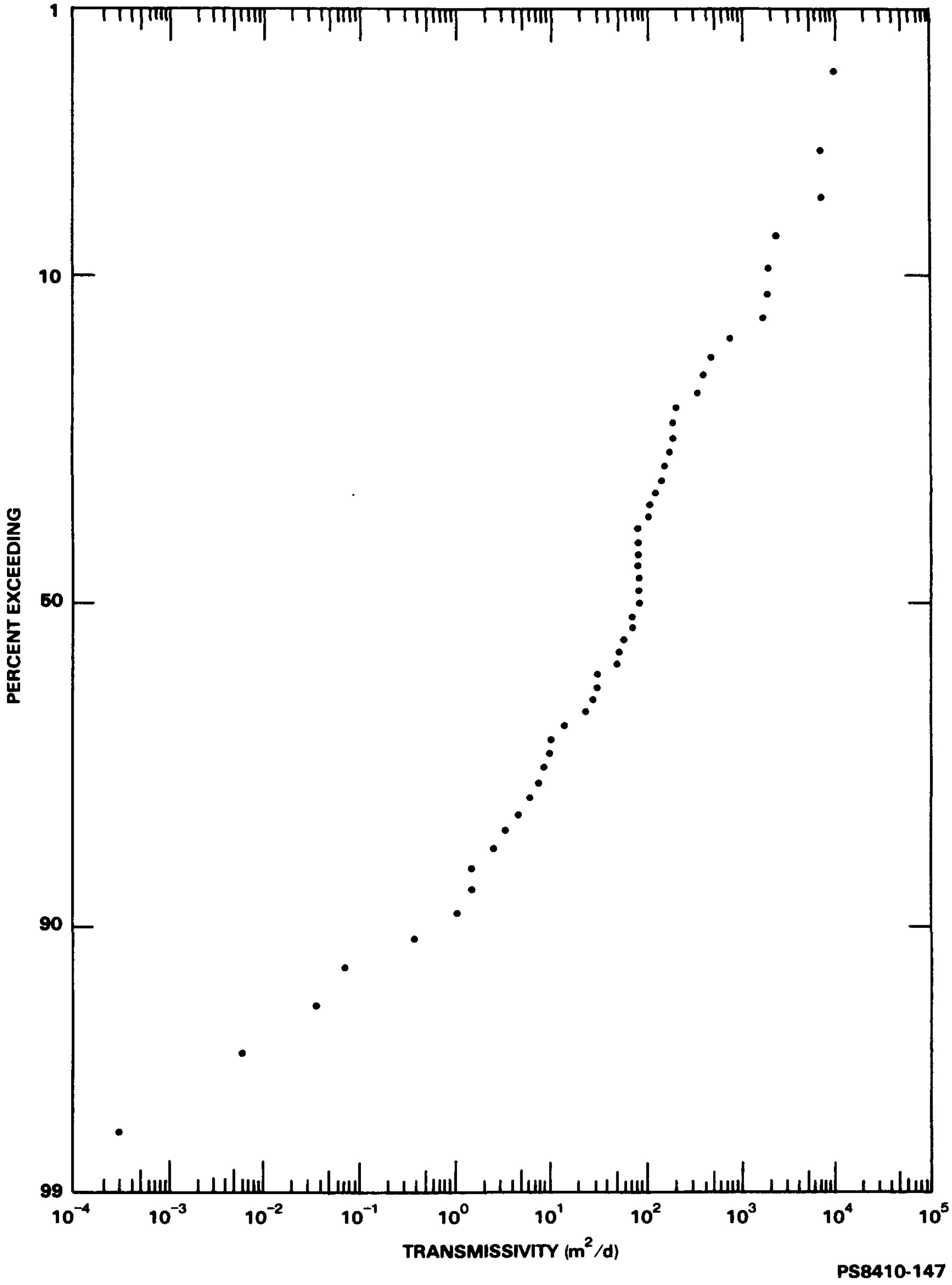

FIGURE D-4. Log-Normal Probability Plot of Transmissivity Data from Wanapum Basalt Flow Tops.

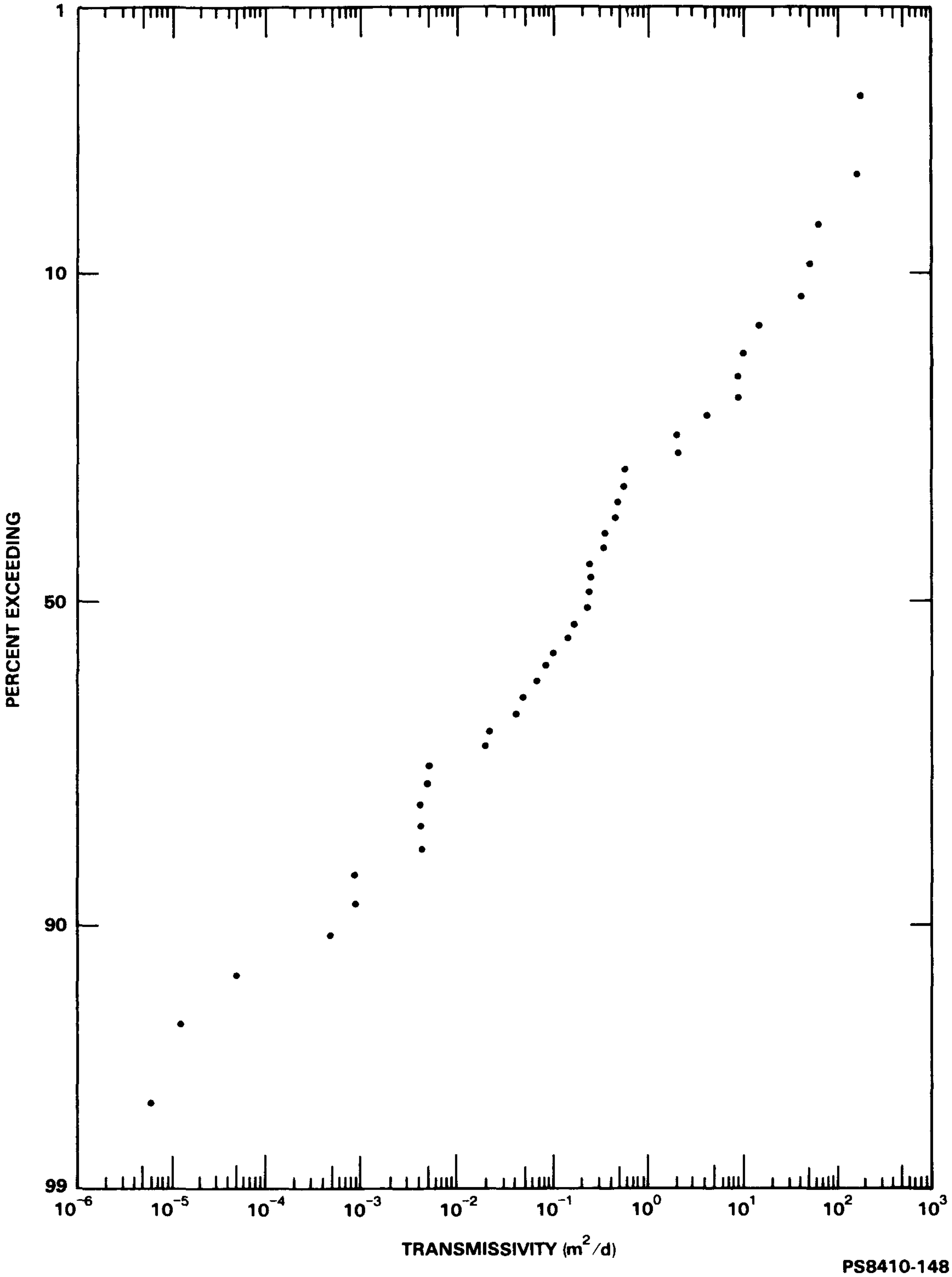

FIGURE D-5. Log-Normal Probability Plot of Transmissivity Data from Grande Ronde Basalt Flow Tops.

The near-linearity of the plots in these figures suggests that these transmissivity data are log normally distributed. This observation is consistent with published conclusions about the frequency distribution of transmissivity data. The geometric mean of transmissivity and the standard deviation of log-transmissivity are listed in Table D-1. These statistics were determined by the method of moments.

TABLE D-1. Statistics of Transmissivities for Basalt Flow Tops and Sedimentary Interbeds.

Formation	Member	Geometric mean (m^2/d)	Standard deviation (log 10)
Saddle Mountains		11.6	1.20
Wanapum		39.8	1.47
Wanapum	Priest Rapids	167.0	1.60
Wanapum	Roza and Frenchman Springs	22.6	1.36
Grande Ronde		0.153	1.83

As indicated in Table D-1, the geometric mean of transmissivities from the Grande Ronde Basalt is relatively low compared to the geometric means of transmissivities from the Wanapum and Saddle Mountains basalts. Possible explanations for this decrease with depth are (1) closure of fractures in brecciated and vesicular flow tops due to lithostatic loading, (2) increased secondary mineralization in the deeper basalts, or (3) decreased thickness of groundwater-contributing zones within basalt flow tops with depth. Also evident in this table is the increase in log-transmissivity standard deviation with depth.

The relatively high geometric mean of transmissivity from the Wanapum Basalt reflects a strong bias from the highly transmissive Priest Rapids member of this formation. Also presented in Table D-1 are the statistics for the Priest Rapids and the combined statistics for the Roza and Frenchman Springs members of the Wanapum Basalt. Although the transmissivity statistics of the Priest Rapids member are based on a relatively small sample, the contrast with the transmissivity statistics from the other Wanapum Basalt members is apparent.

In all cases, the log-transmissivity standard deviations of the basalt formations and members listed in Table D-1 are relatively large compared with those of other groundwater-bearing formations reported in the literature. For example, log-transmissivity statistics presented by Delhomme (1979) for several aquifers indicate standard deviations of less than 1 and, in many cases, less than 0.6. The large log-transmissivity standard deviations of the basalt flow tops and sedimentary interbeds tested by the BWIP are most likely reflective of the following factors:

- The nature of the processes causing permeability in basalt flow tops and possible trending of sedimentary interbed transmissivity within the domain of sampling
- The relatively small volume of host rock investigated during hydrologic testing.

The majority of the primary effective pore space that causes permeability of basalt flow tops is due to brecciation. Flow top breccias are dynamically produced as the basalt flow is being emplaced. Rapid chilling of the flow surface creates a thin crust that is repeatedly broken and reincorporated into its lower, still molten section. When this process is combined with vesiculation due to out-gassing, the result is a brecciated flow top that typically comprises 10% to 15% of the total flow thickness. In general, the brecciation of basalt flow tops results in a wide variety of clast sizes that usually range between 2 and 30 cm (Myers/Price et al. 1979). Such flow tops tend to lack the hydrologic uniformity that characterizes many sedimentary sequences. This characteristic could partially account for the relatively high variability observed in the basalt flow top transmissivities determined by the BWIP.

Part of the BWIP hydrologic testing program has been purposely designed to test laterally continuous transmissive units that are important in both regional and local hydrologic or performance assessment studies. In most cases, the thickness of the effective groundwater-contributing zones within these units is about 10 m or less and rarely exceeds 15 m. These thicknesses contrast sharply with the many tens of meters of aquifer sections tested by the groundwater production wells that are the principal sources of transmissivity data reported in the literature. It is well known that the variance of a spatially distributed quantity or regionalized variable increases as the sampling volume decreases (Journel and Huijbregts 1978). Hence, the suite of transmissivities determined by the BWIP could be expected to have a relatively high variation due to this consideration alone.

D3.1.2 Hydraulic Conductivity

Estimates of the equivalent hydraulic conductivity are obtained by dividing transmissivity by the apparent thickness of the packed interval. The apparent thickness, in turn, is determined by analysis of lithologic and geophysical logs and by examination of core samples.

Some of the statistics of the equivalent hydraulic conductivity of these basalt formations and members are listed in Table D-2. Log-normal probability plots of equivalent hydraulic conductivity are essentially similar to those for the transmissivities, suggesting that these data are also log-normally distributed. The trends observed in the transmissivity statistics are also evident in the conductivity statistics. In all cases, the log-hydraulic conductivity has a slightly higher standard deviation than the corresponding log-transmissivity. This feature is indicative of the negative correlation between hydraulic conductivity and apparent test-interval thickness.

TABLE D-2. Statistics of Hydraulic Conductivities for Basalt Flow Tops and Sedimentary Interbeds.

Formation	Member	Geometric mean (10^{-6} m/s)	Standard deviation (log 10)
Saddle Mountains		10.0	1.29
Wanapum		99.0	1.52
Wanapum	Priest Rapids	710.0	1.71
Wanapum	Roza and Frenchman Springs	48.0	1.33
Grande Ronde		0.23	1.85

A summary of the hydraulic conductivity measurements is presented in a tabular format in Tables D-3 through D-11. The abbreviations used in these tables, along with some general comments about the nature of the data, are presented in Section D6.0. The sources used to compile these tables are also listed in Section D6.0.

The data in Tables D-3 through D-11 are presented by formation and member. In these tables, the data presented for flow tops, in fact, include data for flow bottoms and interflows. The terms "interflow" and "flow top," as used here, are, therefore, hydrostratigraphically synonymous and the term "flow bottom" includes the flow top of the underlying basalt flow.

D3.2 BASALT FLOW INTERIORS

A log-normal probability plot of hydraulic conductivities from dense basalt flow interiors is shown in Figure D-6. Two of these data are from the Wanapum Basalt and the remainder are from the Grand Ronde Basalt. Because of the type of testing procedures used in their determination, these data are inferred to be horizontal hydraulic conductivities. The near linearity of the data in this figure suggests that a log-normal distribution governs hydraulic conductivities from dense basalt flow interiors. These hydraulic conductivities have a geometric mean of 1.5×10^{-3} m/s, and their logarithms have a standard deviation of 1.04. This mean conductivity is six orders of magnitude less than the geometric mean of hydraulic conductivity from Grande Ronde Basalt flow tops (see Table D-2).

TABLE D-3. Equivalent Hydraulic Conductivity for Mabton Interbed.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
MB-IB	DB-1	297.0	302.0		NA	NA	NA	1.0×10^{-4}	DOE/RL 82-3
MB-IB	DB-10	242.0	272.2	15.2	NA	NA	NA	1.8×10^{-8}	10120-83-051[b]
MB-IB	DB-10	259.0	272.0		NA	NA	NA	1.0×10^{-8}	DOE/RL 82-3
MB-IB	DB-11	216.1	315.8	43.3	NA	NA	NA	3.0×10^{-9}	10120-83-051[b]
MB-IB	DB-11	266.0	310.0		NA	NA	NA	1.0×10^{-9}	DOE/RL 82-3
MB-IB	DB-12	115.0	156.0		NA	NA	NA	1.0×10^{-5}	DOE/RL 82-3
MB-IB	DB-13	364.2	393.8	29.6	NA	NA	NA	6.5×10^{-5}	10120-83-051[b]
MB-IB	DB-14	280.0	315.0		NA	NA	NA	1.0×10^{-6}	DOE/RL 82-3
MB-IB	DB-15	229.8	257.3	27.4	NA	NA	NA	7.2×10^{-5}	10120-83-051[b]
MB-IB	DB-2	274.0	282.0		NA	NA	NA	1.0×10^{-4}	DOE/RL 82-3
MB-IB	DB-4	416.0	428.0		NA	NA	NA	1.0×10^{-4}	DOE/RL 82-3
MB-IB	DB-5	248.1	276.8	22.9	NA	NA	NA	6.4×10^{-6}	10120-83-051[b]
MB-IB	DB-5	254.0	277.0		NA	NA	NA	1.0×10^{-6}	DOE/RL 82-3
MB-IB	DB-7	182.0	247.5	11.0	NA	NA	NA	2.7×10^{-4}	10120-83-051[b]
MB-IB	DB-7	237.0	247.0		NA	NA	NA	1.0×10^{-4}	DOE/RL 82-3
MB-IB	DB-9	140.5	179.5	30.2	NA	NA	NA	6.0×10^{-6}	10120-83-051[b]
MB-IB	DB-9	153.0	180.0		NA	NA	NA	1.0×10^{-6}	DOE/RL 82-3
MB-IB	DC-14	295.4	330.1	NA	NA	NA	NA	6.7×10^{-7}	10120-83-051[b]
MB-IB	DC-15	305.7	326.7	14.8	NA	NA	NA	3.9×10^{-6}	10120-83-051[b]
MB-IB	DC-16A	425.2	477.9	29.3	NA	NA	NA	4.6×10^{-6}	10120-83-051[b]
MB-IB	RRL-2	415.7	470.6	15.2	NA	NA	NA	2.1×10^{-9}	10120-83-051[b]

NOTE: NA = Not available.

[a] Best estimate identified in referenced document.

[b] Internal Letter 10120-83-051.

TABLE D-4. Equivalent Hydraulic Conductivity for Priest Rapids Flow Top.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
PR-IF	DB-12	159.7	199.0	1.2	NA	NA	NA	2.6×10^{-2}	10120-83-051[b]
PR-IF	DB-12	201.2	215.5	3.0	NA	NA	NA	4.6×10^{-4}	10120-83-051[b]
PR-IF	DB-15	261.5	295.4	11.0	NA	NA	NA	2.4×10^{-4}	10120-83-051[b]
PR-IF	DC-12	370.9	382.2	NA	NA	NA	NA	1.9×10^{-5}	10120-83-051[b]
PR/RZ-IF	DC-12	404.8	415.7	NA	NA	NA	NA	3.3×10^{-5}	10120-83-051[b]
PR-IF	DC-14	359.7	363.3	0.3	NA	NA	NA	2.2×10^{-3}	10120-83-051[b]
PR-IF	DC-14	364.5	370.9	4.3	NA	NA	NA	7.3×10^{-4}	10120-83-051[b]
PR-IF	DC-14	370.9	387.4	2.4	NA	NA	NA	8.3×10^{-4}	10120-83-051[b]
PR-IF	DC-15	350.2	362.4	8.8	NA	NA	NA	4.9×10^{-8}	10120-83-051[b]
PR/RZ-IF	DC-15	371.6	394.1	16.2	NA	NA	NA	3.9×10^{-4}	10120-83-051[b]
PR-IF	DC-16A	515.1	526.7	0.6	3.0×10^{-6}	3.0×10^{-5}	NA	NA	SD-BWI-TI-135
PR-IF	ENYEART	292.6	332.8	3.0	NA	NA	NA	3.2×10^{-2}	10120-83-051[b]
PR-FT	ENYEART	328.0	332.0		NA	NA	NA	1.0×10^{-2}	DOE/RL 82-3
PR-IF	FORD	218.8	236.8	3.0	NA	NA	NA	3.2×10^{-2}	10120-83-051[b]
PR-FT	FORD	226.0	229.0		NA	NA	NA	1.0×10^{-2}	DOE/RL 82-3
PR-FT	McGEE	247.0	250.0		NA	NA	NA	1.0×10^{-3}	DOE/RL 82-3
PR-FT	McGEE	282.0	285.0		NA	NA	NA	1.0×10^{-3}	DOE/RL 82-3
PR-FT	O'BRIAN	209.0	212.0		NA	NA	NA	1.0×10^{-2}	DOE/RL 82-3
PR-IF	O'BRIAN	182.9	213.4	3.0	NA	NA	NA	4.2×10^{-2}	10120-83-051[b]
PR-FT	RRL-2	479.8	522.4	7.6	NA	NA	NA	8.1×10^{-5}	10120-83-051[b]

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal Letter 10120-83-051.

TABLE D-5. Equivalent Hydraulic Conductivity for Frenchman Springs Flow Top.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
FS-IF	DB-15	396.2	409.3	10.1	NA	NA	NA	1.1×10^{-5}	10120-83-051[b]
FS-IF	DB-15	412.4	418.5	4.9	NA	NA	NA	8.4×10^{-5}	10120-83-051[b]
FS-IF	DB-15	424.6	439.8	8.5	NA	NA	NA	1.9×10^{-5}	10120-83-051[b]
FS-IF	DB-15	442.0	466.3	21.6	NA	NA	NA	4.6×10^{-6}	10120-83-051[b]
FS-IF	DB-15	524.3	548.6	3.0	NA	NA	NA	2.4×10^{-8}	10120-83-051[b]
FS-IF	DB-15	548.6	588.9	6.1	NA	NA	NA	5.6×10^{-10}	10120-83-051[b]
RZ/FS-IF	DC-12	459.6	467.6	NA	3.5×10^{-6}	5.3×10^{-6}	NA	NA	10120-83-051[b]
FS-IF	DC-12	514.4	521.2	NA	NA	NA	NA	1.4×10^{-5}	10120-83-051[b]
FS-IF	DC-12	582.0	604.7	NA	NA	NA	NA	1.3×10^{-7}	10120-83-051[b]
FS-IF	DC-12	625.0	633.7	NA	8.5×10^{-6}	2.0×10^{-5}	NA	NA	10120-83-051[b]
FS-IF	DC-14	451.1	462.1	3.4	NA	NA	NA	2.4×10^{-5}	10120-83-051[b]
FS-IF	DC-14	480.1	497.4	8.5	NA	NA	NA	4.2×10^{-5}	10120-83-051[b]
FS-IF	DC-14	499.9	520.6	4.9	NA	NA	NA	2.3×10^{-5}	10120-83-051[b]
FS-IF	DC-14	524.3	554.7	5.2	NA	NA	NA	4.8×10^{-5}	10120-83-051[b]
FS-IF	DC-14	554.7	571.5	5.2	NA	NA	NA	5.9×10^{-5}	10120-83-051[b]
FS-IF	DC-14	571.5	604.4	15.5	NA	NA	NA	1.3×10^{-4}	10120-83-051[b]
RZ/FS-IF	DC-15	425.2	449.0	2.4	NA	NA	NA	1.3×10^{-5}	10120-83-051[b]
FS-IF	DC-15	451.4	459.0	5.5	NA	NA	NA	4.2×10^{-4}	10120-83-051[b]
FS-IF	DC-15	458.7	473.4	4.6	NA	NA	NA	1.4×10^{-4}	10120-83-051[b]
FS-IF	DC-15	469.4	485.5	6.1	NA	NA	NA	2.3×10^{-4}	10120-83-051[b]
FS-IF	DC-15	528.8	558.7	27.7	NA	NA	NA	2.7×10^{-7}	10120-83-051[b]
FS-IF	DC-15	559.0	575.2	11.6	NA	NA	NA	1.8×10^{-4}	10120-83-051[b]
FS-IF	DC-16A	576.7	509.6	2.7	3.0×10^{-4}	3.0×10^{-3}	NA	NA	SD-BWI-TI-135
FS-IF	DC-16A	641.6	657.1	3.4	NA	NA	NA	5.6×10^{-6}	10120-83-051[b]
FS-IF	DC-16A	670.9	689.2	2.4	3.0×10^{-4}	NA	NA	NA	SD-BWI-TI-135
FS-IF	DC-16A	690.7	722.7	20.4	3.0×10^{-8}	3.0×10^{-7}	NA	NA	SD-BWI-TI-135
FS-IF	DC-16A	754.7	780.0	17.7	3.0×10^{-5}	3.0×10^{-4}	NA	NA	SD-BWI-TI-135
FS-IF	DC-16A	787.9	802.2	10.1	3.0×10^{-5}	3.0×10^{-4}	NA	NA	SD-BWI-TI-135
RZ/FS-IF	McGEE	335.0	355.7	10.7	1.0×10^{-4}	NA	NA	NA	10120-83-051[b]
FS-IF	McGEE	402.5	420.0	4.6	2.4×10^{-4}	NA	NA	NA	10120-83-051[b]
FS-IF	McGEE	439.8	452.0	6.1	1.8×10^{-4}	NA	NA	NA	10120-83-051[b]
FS-IF	McGEE	481.7	512.1	4.6	2.4×10^{-4}	NA	NA	NA	10120-83-051[b]
FS-IF	McGEE	510.2	533.4	3.0	3.5×10^{-4}	NA	NA	NA	10120-83-051[b]
FS-FT	RRL-2	581.3	677.3	11.6	NA	NA	NA	9.2×10^{-5}	10120-83-051[b]
FS-FT	RRL-2	684.0	805.9	20.1	NA	NA	NA	9.9×10^{-5}	10120-83-051[b]

NOTE: NA = Not available.

[a] Best estimate identified in referenced document.

[b] Internal Letter 10120-83-051.

TABLE D-6. Equivalent Hydraulic Conductivity for Frenchman Springs - Tectonic Breccia Zone.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best*	
FS-TB	RRL-6	640.7	652.6	4.0	3.5×10^{-12}	3.5×10^{-11}	NA	NA	SD-BWI-TI-167

NOTE: NA = Not available.
*Best estimate identified in referenced document.

TABLE D-7. Equivalent Hydraulic Conductivity for Vantage Interbed.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
VA/GR-IF	DC-12	676.0	688.8	NA	1.4×10^{-7}	4.9×10^{-7}	NA	NA	10120-83-051[b]
VA/GR-IF	DC-14	646.2	681.2	12.5	NA	NA	NA	2.1×10^{-5}	10120-83-051[b]
VA/GR-IF	DC-15	639.5	670.0	20.1	NA	NA	NA	1.6×10^{-7}	10120-83-051[b]
VA-IB	DC-16A	814.1	832.1	4.3	3.0×10^{-6}	3.0×10^{-5}	NA	NA	SD-BWI-TI-135
VA-IB	RRL-2	812.3	826.9	5.5	NA	NA	NA	2.8×10^{-7}	10120-83-051[b]
VA-IB	DB-15	588.9	600.8	4.0	NA	NA	NA	1.8×10^{-11}	10120-83-051[b]

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal Letter 10120-83-051.

TABLE D-8. Equivalent Hydraulic Conductivity for Rocky Coulee Flow Top.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
RC-FT	DC-12	734.0	746.0	NA	NA	NA	NA	1.0×10^{-5}	SD-BWI-TY-001
RC/GR-IF	DC-14	717.8	NA	7.3	NA	NA	NA	3.9×10^{-8}	10120-83-051[b]
RC-FT	DC-15	679.0	714.0	NA	NA	NA	NA	1.0×10^{-5}	SD-BWI-TY-001
RC/GR-IF	DC-15	723.0	NA	64.0	NA	NA	NA	3.4×10^{-8}	10120-83-051[b]
RC-FT	DC-16A	864.0	898.0	NA	NA	NA	NA	1.0×10^{-6}	SD-BWI-TY-001
RC-FT	RRL-2	829.0	889.0	NA	NA	NA	NA	1.0×10^{-7}	SD-BWI-TY-001

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal Letter 10120-83-051.

TABLE D-9. Equivalent Hydraulic Conductivity for Cohassett Flow Top.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
CO-FT	DC-12	782.0	811.0		NA	NA	NA	1.0×10^{-7}	SD-BWI-TY-001
CO/GR-IF	DC-12	858.9		NA	4.4×10^{-4}	1.3×10^{-3}	NA	NA	10120-83-051[b]
CO/GR-IF	DC-14	734.6		7.6	NA	NA	NA	7.1×10^{-7}	10120-83-051[b]
CO-GR-IF	DC-14	809.9		23.3	NA	NA	NA	4.9×10^{-9}	10120-83-051[b]
CO-FT	DC-15	760.0	777.0		NA	NA	NA	1.0×10^{-5}	SD-BWI-TY-001
CO-FT	DC-16A	905.3	940.6	14.9	3.0×10^{-8}	3.0×10^{-7}	NA	NA	SD-BWI-TI-135
CO-FB	DC-16A	991.8	1,024.1	21.0	3.0×10^{-11}	3.0×10^{-10}	NA	NA	SD-BWI-TI-135
CO-FT	DC-6	730.0	822.0		NA	NA	NA	1.0×10^{-7}	SD-BWI-TY-001
CO-FT	RRL-14	916.5	959.2	1.8	1.0×10^{-7}	1.0×10^{-6}	NA	NA	SD-BWI-TI-186
CO-FB	RRL-14	1,004.0	1,037.2	6.9	1.0×10^{-9}	1.0×10^{-8}	NA	NA	SD-BWI-TI-186
CO-FT	RRL-2	908.6	920.5	5.8	1.7×10^{-9}	1.2×10^{-8}	7.8×10^{-9}	7.8×10^{-9}	SD-BWI-TI-102
CO-FT	RRL-6	939.1	951.3	4.9	3.5×10^{-12}	3.5×10^{-11}	NA	NA	SD-BWI-TI-167
CO-FB	RRL-6	1,041.2	1,041.2	20.6	3.5×10^{-10}	3.5×10^{-10}	NA	NA	SD-BWI-TI-167

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal Letter 10120-83-051.

TABLE D-10. Equivalent Hydraulic Conductivity for McCoy Canyon Flow Top.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
MC-FT	DC-12	908.0	961.0	NA	NA	NA	NA	1.0×10^{-9}	SD-BWI-TY-001
GR/MC-IF	DC-12	934.8	961.0	NA	7.1×10^{-10}	9.9×10^{-9}	NA	NA	10120-83-051[b]
MC-FT	DC-14	878.0	907.0	NA	NA	NA	NA	1.0×10^{-8}	SD-BWI-TY-001
MC-FT	DC-16A	1,070.5	1,081.7	NA	NA	NA	NA	NA	SD-BWI-TI-135
MC-FT	DC-7/8	1,039.0	1,060.0	NA	NA	NA	NA	1.0×10^{-8}	SD-BWI-TY-001
MC-FT	DC-7/8	1,043.0	1,055.0	11.3	NA	NA	NA	6.7×10^{-8}	Leonhart et al. 1982

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal Letter 10120-83-051.

TABLE D-11. Equivalent Hydraulic Conductivity for Umtanum Flow Top.

Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
				Min	Max	Mean	Best[a]	
DC-14	932.7	958.3	20.1	NA	NA	NA	2.8×10^{-7}	10120-83-051[b]
DC-14	933.0	958.0		NA	NA	NA	1.0×10^{-6}	SD-BWI-TY-001
DC-15	902.0	949.0		NA	NA	NA	1.0×10^{-5}	SD-BWI-TY-001
DC-6	912.0	938.0		NA	NA	NA	1.0×10^{-7}	SD-BWI-TY-001
RRL-14	1,132.3	1,162.5	8.4	1.0×10^{-8}	1.0×10^{-7}	NA	NA	SD-BWI-TI-186
RRL-14	1,180.8	1,204.6	6.1	1.0×10^{-10}	1.0×10^{-9}	NA	NA	SD-BWI-TI-186
RRL-2	1,170.0	1,185.0		NA	NA	NA	1.0×10^{-5}	SD-BWI-TI-001
RRL-6	1,129.9	1,166.8	29.0	3.5×10^{-9}	3.5×10^{-8}	NA	NA	SD-BWI-TI-167
RRL-6	1,200.6	1,231.4	19.5	3.5×10^{-11}	3.5×10^{-10}	NA	NA	SD-BWI-TI-167

NOTE: NA = Not available.

[a] Best estimate identified in referenced document.

[b] Internal Letter 10120-83-051.

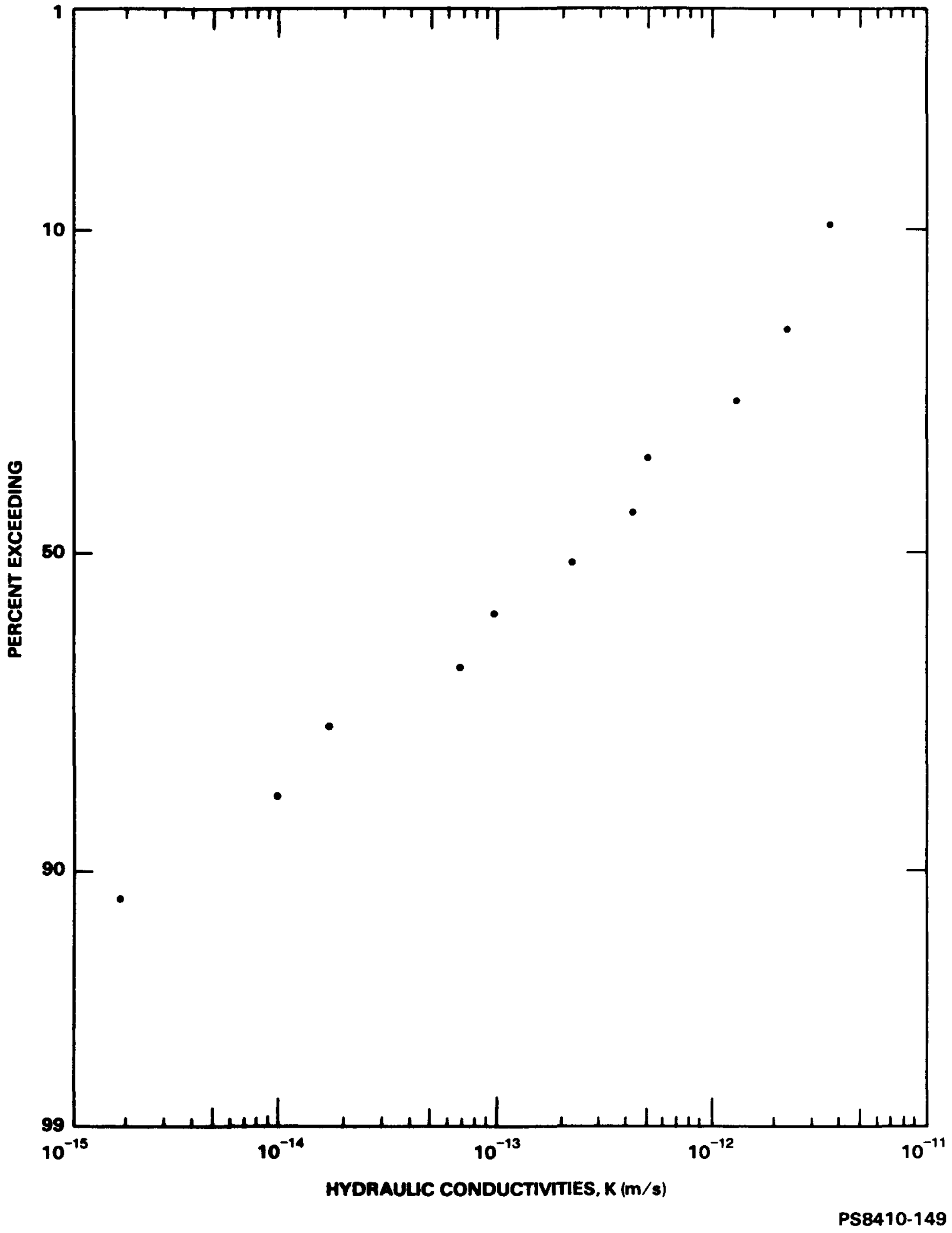

FIGURE D-6. Log-Normal Probability Plot of Hydraulic Conductivities from Dense Basalt Flow Interiors.

The hydraulic conductivity data for the Rocky Coulee, Cohassett and the Umtanum flow interiors of the Grande Ronde basalts are shown in Tables D-12 through D-14, respectively. Note that the flow interior also includes the vesicular (for Cohassett flow only), entablature, and colonnade/entablature zones.

D4.0 VERTICAL CONDUCTIVITY

The results of only one test to determine the vertical hydraulic conductivity of a basalt flow have been reported* (Spane et al. 1983, Appendix A). This conductivity experiment was a ratio test involving two boreholes: DC-4 and DC-5. The interval tested consisted of a 7.9 m section of Rocky Coulee flow interior overlying the Cohassett flow top. The test lasted approximately 8 wk, but did not yield any discernible formation response. A vertical conductivity of less than 1.0×10^{-11} m/s was subsequently estimated.

Estimation of vertical conductivity through numerical simulation has been the subject of several studies. Tanaka et al. (1974) report values ranging from 1.0×10^{-12} to 1.0×10^{-10} m/s in their numerical analysis of vertical conductivities for the Columbia Basin Irrigation Project. MacNish and Barker (1976) predict a vertical conductivity value as low as 1.0×10^{-8} m/s in their study of the Walla Walla River Basin.

D5.0 POROSITY

The available porosity data are based on the results of two tracer tests performed in boreholes DC-7 and DC-8. The straddled interval was located within the McCoy Canyon flow top (depth interval 1,038 to 1,062 m in borehole DC-8). In an analysis of the tracer tests, Leonhart et al. (1982) give a value of 3.2×10^{-3} (in meters) for the product nH, where n is the effective porosity and H is the thickness of the contributing interval (Gelhar 1982). Assuming 11.3 m for H, the effective porosity would be equal to 2.8×10^{-4}. In a critical re-analysis of the tracer experiments, Leonhart et al. (1984) note the highly heterogeneous nature of the formation tested and suggest that there could be narrow zones of high hydraulic conductivity in the tested interval. Assuming a contributing-zone thickness of 11.3 m and a homogeneous formation, they report a value of 1.6×10^{-4} for n. The effective porosity is somewhat higher, however, because of the presence of highly conductive zones. Some other estimates of porosities for the reference repository location and for various strata within the Columbia River Basalt Group are summarized in Table D-15.

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*As of the end of 1983.

TABLE D-12. Equivalent Hydraulic Conductivity for Rocky Coulee Flow Interior.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best*	
RC-FI	DC-4	882.1	896.6	14.6	5.6×10^{-14}	1.2×10^{-13}	8.8×10^{-14}	8.8×10^{-14}	

*Best estimate identified in referenced document.

TABLE D-13. Equivalent Hydraulic Conductivity for Cohassett Flow Interior.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best*	
CO-CE	DC-16A	941.2	992.4	51.2	3.0×10^{-10}	3.0×10^{-9}	NA	NA	SD-BWI-TI-135
CO-CE	DC-16A	961.3	991.8	30.5	3.0×10^{-14}	3.0×10^{-13}	NA	NA	SD-BWI-TI-135
CO-FI	RRL-14	957.1	1,009.8	8.2	1.0×10^{-14}	1.0×10^{-14}	NA	NA	SD-BWI-TI-135
CO-VZ	RRL-2	931.8	966.8	4.9	1.9×10^{-12}	5.6×10^{-11}	2.9×10^{-11}	5.6×10^{-11}	SD-BWI-TI-090
CO-CE	RRL-2	967.7	988.8	21.0	1.6×10^{-13}	2.8×10^{-12}	2.3×10^{-13}	2.3×10^{-13}	SD-BWI-TI-109
CO-FI	RRL-6	953.7	1,015.6	61.9	3.5×10^{-16}	3.5×10^{-3}	NA	NA	SD-BWI-TI-167

NOTE: NA = Not available.
*Best estimate identified in referenced document.

TABLE D-14. Equivalent Hydraulic Conductivity for Umtanum Flow Interior.

Layer	Well	Test interval (m below ground surface)		Effective interval (m)	Values of hydraulic conductivity (m/s)				Reference
					Min	Max	Mean	Best[a]	
GR/UM-FT	DC-15	902.5	948.8	36.6	NA	NA	NA	7.4×10^{-7}	10120-83-051[b]
UM-FI	DC-3	1,092.0	1,108.0	30.5	NA	NA	NA	1.0×10^{-13}	SD-BWI-TY-001
UM-FI	DC-6	938.0	989.0	4.9	NA	NA	NA	1.0×10^{-13}	SD-BWI-TY-001
UM-FI	RRL-14	1,164.0	1,190.9	27.4	1.0×10^{-16}	1.0×10^{-14}	NA	NA	SD-BWI-TI-186
UM-EN	RRL-2	1,146.7	1,159.8	13.1	7.4×10^{-13}	1.7×10^{-11}	1.3×10^{-12}	1.3×10^{-12}	SD-BWI-TI-107
UM-FZ	RRL-2	1,152.4	1,166.5	1.8	1.2×10^{-4}	5.2×10^{-4}	2.2×10^{-4}	5.2×10^{-4}	SD-BWI-TI-089
UM-FI	RRL-6	1,166.5	1,200.3	33.8	3.5×10^{-16}	3.5×10^{-13}	NA	NA	SD-BWI-TI-089

NOTE: NA = Not available.
[a] Best estimate identified in referenced document.
[b] Internal letter 10120-83-051.

Some of the values reported in Table D-15 are believed by Summers et al. (1978) to be too large due to the fact that they are matrix estimates and are not representative of elementary volumes. Porosity has also been estimated on the basis of geophysical logging and core methods (Agapito et al. 1977; Raymond and Tillson 1968). With regard to the distribution of porosity, Crosby and Mellot (1973) concluded that there is wide variability within the basalts, but that zones of relatively high and constant porosity may persist over wide areas.

TABLE D-15. Reported Estimates of Porosity.

Source	Rock unit	Estimated value
DOE/RL 1982 (Page 5.2-3)	Interbed	Less than 10
	Flow top	Less than 5
	Colonnade/entablature	Less than 1
LaSala and Doty (1971) LaSala et al. (1973)	Sedimentary interbed	20*
	Fractured basalt zone	16
	Vesicular basalt	5
	Dense basalt	Less than 1

*Actual values are probably less than 10%.

D6.0 SOME DETAILS OF TEST DATA PRESENTED IN TABLES D-3 THROUGH D-15.

D6.1 ABBREVIATIONS USED

The following abbreviations are used in Tables D-3 through D-15.

Rock unit		Basalt flow types	
CO	Cohassett flow (old name = Middle Sentinel Bluffs)	CE	Colonnade-entablature
FS	Frenchman Springs member	EN	Entablature
GR	Grande Ronde Basalt	FB	Flow bottom
MB	Mabton interbed	FI	Flow interior
MC	McCoy Canyon flow	FT	Flow top
PR	Priest Rapids flow	FZ	Fracture zone
RC	Rocky Coulee flow	IB	Interbed
RZ	Roza flow	IF	Interflow
UM	Umtanum flow	TB	Tectonic breccia
VA	Vantage interbed	VZ	Vesicular zone

D6.2 THE SOURCES OF DATA

The corresponding citations for sources of data referenced in Tables D-3 through D-15 are summarized in Table D-16.

TABLE D-16. Citations Corresponding to Data Sources.

Referenced data source	Reference citation
SD-BWI-TI-89	Strait and Spane 1983a
SD-BWI-TI-90	Strait and Spane 1983b
SD-BWI-TI-95	Strait and Spane 1982a
SD-BWI-TI-102	Strait and Spane 1983c
SD-BWI-TI-105	Strait and Spane 1982b
SD-BWI-TI-107	Strait and Spane 1982c
SD-BWI-TI-109	Strait and Spane 1982d
SD-BWI-TI-130	Strait and Brown 1983a
SD-BWI-TI-131	Strait and Brown 1983b
SD-BWI-TI-135	Deidiker 1983
SD-BWI-TI-136	Spane et al. 1983
SD-BWI-TI-142	Strait and Brown 1983c
SD-BWI-TI-167	Patterson 1983
SD-BWI-TI-175	Thorne and Spane 1983
SD-BWI-TI-186	Patterson 1984
SD-BWI-TI-188	Grisak and Leonhart 1984
DOE/RL 82-3	DOE-RL 1982
SD-BWI-TY-001	Long 1983
Internal letter 10120-83-051	Bruce 1983
NUREG-0960	NRC 1983
RHO-BW-CR-131 P	Gelhar 1982
RHO-BW-SA-220 P	Leonhart et al. 1982

D6.3 SOME GENERAL COMMENTS ON THE SOURCES OF DATA

Document	Comment
SD-BWI-TI-89, -90, -95, -102, -105, -107, -109	Preliminary results.
SD-BWI-TI-135	Equivalent hydraulic conductivity subject to change.
SD-BWI-TI-167 SD-BWI-TI-186	Estimates of hydraulic conductivity are preliminary. Observed values were generally lower than those predicted and fall within the lower end of the range previously reported for the Columbia River Basalt Group. Hydrologic testing and analysis of data is continuing.
SD-BWI-TY-001	Data from borehole DC-16A are preliminary and have not been reviewed or validated. The conductivities are rounded-off estimates. The values are believed to be within an order of magnitude. Final review of field data is not completed.
DOE/RL 82-3	Many of the values of hydrologic properties presented are given to the nearest order of magnitude. Peer review and full documentation of all test results are not completed.
Internal letter 10120-83-051	This document is a Rockwell internal letter and has not been released as a formal Rockwell document. Estimates of hydrologic parameters should, therefore, be considered preliminary.
RHO-BW-CR-131 P	Because some of the conditions of the pulse test were not fully defined, the results of this interpretation are considered to be preliminary.

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APPENDIX E

INTERNAL LETTER 10120-83-051

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RHO-BW-CR-145 P

Internal Letter **Rockwell International**

Date February 11, 1983 No . 10120-83-051

TO: (Name Organization, Internal Address)
. Those Listed

FROM: (Name, Organization, Internal Address, Phone)
. S. R. Bruce

Subject . Preliminary Estimate of Selected Hydrologic Properties

Enclosed is an updated compilation of estimates of transmissivity, equivalent hydraulic conductivity, and head measurements for boreholes BWIP has test. These are provided to you as general information and are intended for internal use only. Intervals denoted with an asterisk (*) contain data which have not been released through SD or ST documentation and should, therefore, be considered preliminary. Document numbers are provided for released data. Due to space limitiations, all data are in English units; conversions factors are furnished below. This updates the compilation provided to you on the letter dated June 30, 1982. This compilation will be updated semi-annually.

Transmissivity: $ft^2/day = 1.08 \times 10^{-6}\ m^2/s = 1.08 \times 10^{-2}\ cm^2/s$

Equivalent hydraulic conductivity: $ft/day = 3.53 \times 10^{-6}\ m/s = 3.53 \times 10^{-4}\ cm/s$

ft = 0.3048 m

S. R. Bruce

S. R. Bruce, Scientist
Drilling and Testing Group

SRB: cam

cc: R. C. Arnett
R. G. Baca
W. R. Brown
W. H. Chapman-Riggsbee
S. M. Baker
P. M. Clifton
R. E. Gephart
G. S. Hunt
R. L. Jackson
L. S. Leonhart
R. B. Mercer
R. D. Mudd
W. W. Pidcoe
W. H. Price
F. A. Spane
D. L. Starr
R. R. Strait
Rec. Ret. (2) L341

NOTES

Data denoted by an asterisk (*) are unverified until released in SD or ST documentation.

Data denoted by a question mark (?) indicate uncertainty in evaluation.

ZONE IDENTIFICATION:

IB = Interbed (includes underlying flow top unless otherwie noted)
IF = Interflow FT(s) = Flow top(s) FB = Flow bottom
C/E = Colonnade/Entablature E = Entablature C = Colonnade

OBSERVED HEAD COMMENTS:

S = Head was measured by surface-based instrumentation.
D = Head was computed from downhole pressure transducer system.
GAS = Gas present in borehole.

Borehole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmissivity (ft^2/day)	Equivalent Conductivity (ft/day)	Observed Head (ft) MSL
669-52-48	Rattlesnake Ridge	IB	145-195	145-195	37	0.8	
					SEE RHO-ST-38		
669-53-50	Rattlesnake Ridge	IB	146-193	146-193	590.1	12.6	
					SEE RHO-ST-38		
669-51-46	Rattlesnake Ridge	IB	120-165	120-165	69.1	1.5	
					SEE RHO-ST-38		
669-52-46	Rattlesnake Ridge	IB	165-225	165-225	161.5	2.7	
					SEE RHO-ST-38		
669-50-45	Rattlesnake Ridge	IB	133-178	133-178	152.8	3.4	
					SEE RHO-ST-38		
669-50-48	Rattlesnake Ridge	IB	213-250	213-250	324.7	8.5	
					SEE RHO-ST-38		
669-47-50	Rattlesnake Ridge	IB	260-295	260-295	733.2	20.9	
					SEE RHO-ST-38		
669-S11-E12A	Levey	IB	225-282	238-265	19.9	0.7	
					SEE RHO-BWI-LD-27		
*BH-16	Selah	IB	820-925	870-920	80.4	1.6	
*BH-17	Asotin	IF	1025-1096	1029-1044	0.5	0.03	
*OBRIEN	Priest Rapids	IF	600-700	686-696	1.2E5	1.2E4	
*FORD	Priest Rapids	IF	718-777	742-752	9.0E4	9.0E3	
*ENYEART	Priest Rapids	IF	960-1092	1078-1088	9.0E4	9.0E3	

NOTES:

* Data is unverified until released through SD or ST documentation.

IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow   FT(S) = Flowtop(s)   FB = Flowbottom
C/E = Colunnade/Entablature

S = Measured from surface   D = Measured from downhole

GAS = Gas present in borehole

Stu Strait 1/27/83
J R Bruce 1/27/83

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE		
					Transmis-sivity (ft^2/day)	Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
DC-6	*Grande Ronde	COMPOSITE	2260-4333		92		
	*Grande Ronde	IF	2396-2697	2405-2449 2454-2480 2496-2511 2546-2568	27.5	2.3E-2	424 S
	*Grande Ronde	IF	2697-2893	2694-2791 2799-2860	10.8	6.8E-2	426 S
	*Umtanum	FT	2992-3078	3036-3064	4.9E-1	1.8E-2	441 S
	*Umtanum	CE	3077-3244	3077-3244			
	*Umtanum	FB	3242-3529	3258-3294 3329-3363 3378-3390	9.5	1.2E-1	443 S
	*Grande Ronde	IF	3530-3824	3533-3550 3570-3583 3599-3602 3609-3617 3620-3651 3662-3673 3686-3802	82.8	4.2E-1	445 S
	*Grande Ronde	CE	3824-4169	3824-4169			
	*Grande Ronde	IF	4169-4333	4184-4219	1.2	3.4E-2	460 S

NOTES:

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IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colunnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

Frank Spane 1/26/83
S R Bruce 1/26/83

Borehole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmissivity (ft^2/day)	Equivalent Conductivity (ft/day)	Observed Head (ft) MSL
DC-14	*Elephant Mt	IF	368-475	393-415	4.4	0.1	378 S
	*Rattlesnake Ridge	IB	475-538	491-531	20.0	0.5	400 S
	*Selah	IB	675-768	701-757	246	3.9	407 S
	*Asotin #1	IF	880-907	887-904	1413	83.1	492 S
	*Asotin #2	IF	910-922	916-922	2630	438	492 S
	*Asotin #3	IF	925-969	945-965	470	23.5	
	*Mabton	IB	969-1083		20.3	0.19	488 S
	*Priest Rapids #1	IF	1180-1192	1188-1189	628.9	628.8	494 S
	*Priest Rapids #2	IF	1196-1217	1200-1214	2900	208	493 S
	*Priest Rapids #3	IF	1217-1271	1220-1228	1880	236	494 S
	*Roza	IF	1285-1341	1296-1338	9340	222	493 S
	*Frenchman Spgs #1	IF	1480-1516	1494-1505	76	6.9	485 S
	*Frenchman Spgs #2	IF	1575-1632	1600-1628	334	12	490 S
	*Frenchman Spgs #3	IF	1640-1708	1680-1696	106	6.6	488 S
	*Frenchman Spgs #4	IF	1720-1820	1736-1744 1759-1768	228.9	13.5	488 S
	*Frenchman Spgs #5	IF	1820-1875	1836-1853	286.4	16.8	486 S
	*Frenchman Spgs #6	IF	1875-1983	1888-1906 1927-1960	1946	38.2	439 S
	*Vantage/ G.Ronde #1	IF	2120-2205	2144-2167 2192-2200 2206-2216	236	5.9	469 S
	*Grande Ronde #2	IF	2355-2405	2368-2392	2.6E-1	1.1E-2	435 S
	*Grande Ronde #3	IF	2410-2513	2451-2476	4.2	0.2	444 S
	*Grande Ronde	IF	2657-2874	2687-2704	0.1	1.4E-3	435 S

#4			2732-2756 2826-2858			
*Grande Ronde #4B	IF	2760-2874	2826-2858	6E-2	1.9E-3	435 S
*Grande Ronde #5	IF	2880-2975	2894-2953	2.4E-1	4.1E-3	436 S
*Umtanum	IF	3060-3144	3072-3138	5.5	8E-2	441 S
*Grande Ronde #7	IF	3180-3225	3200-3215	4.2	2.9E-1	440 S
*Grande Ronde #8	IF	3260-3335	3278-3331	66	1.2	441 S

NOTES:

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IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colonnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

					BEST ESTIMATE		
Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	Transmissivity (ft^2/day)	Equivalent Conductivity (ft/day)	Observed Head (ft) MSL
DB-1	*Mabton	IB	976-990		1956	140	
	*Priest Rapids	IF	1080-1139		366		
DB-2	*Mabton	IB	900-924	900-924	1553	64.7	
	*Roza	C/E	1192-1273	1192-1273	E-5	1.2E-7	
	*Roza	FT	1166-1190	1168-1180	12-23	1-1.9	
	*Priest Rapids	COMPOSITE	1028-1190	1028-1060 1100-1110	303.3	7.2	
DB-4	*Mabton	IB	1360-1403	1363-1403	1553	38.8	
DB-5	*Mabton	IB	814-908	833-909	136	1.8	
DB-7	*Mabton	IB	597-812	776-812	2787	77.4	
DB-9	*Mabton	IB	461-589	490-589	146	1.7	
DB-10	*Mabton	IB	794-893	843-893	0.23	5.2E-3	
DB-11	*Mabton	IB	709-1036	866-1008	0.12	8.4E-4	679+-1 S
	*Priest Rapid	FT	1020-1046	1045-1046			945+-1 S
	*Priest Rapid	IF	1036-1210	1199-1210			957+-1 S
DB-12	*Mabton	IB	376-513	376-513	1624	11.8	
	*Priest Rapid	IF	524-653	586-590	29000	7250	
	*Priest Rapid	IF	660-707	679-689	1300	130	
DB-13	*Elephant Mt	IF	378-381		6126	2042	
	*Rattlesnake Ridge	IB	463-536		214	2.9	
	*Selah	IB	720-739		511	26.9	
	*Cold Creek	IB	867-942		1050	11.7	
	*Mabton	IB	1195-1292	1195-1292	1742	18.3	
DB-14	*Rattlesnake Ridge	IB	210-288	210-288	10.5	0.1	
	*Selah	IB	449-492	452-492	80.5	2.0	
	*Cold Creek	IB	616-664	618-664	9301	180.5	

J.R. Bruce 11/29/83

*Mabton	IB	917-1034	917-1034	153.5	1.4

NOTES:

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IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colonnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	BEST ESTIMATE Equivalent Conduc-tivity (ft/day)	BEST ESTIMATE Observed Head (ft) MSL
RRL-2	*Mabton	IB	1364-1544	1399-1449	3E-2	6E-4	418 S
	*Priest Rapids	FT	1574-1714	1689-1714	6E2	23	401 S GAS
	*Roza	FT	1735-1773	1749-1759	2.5E3	249	404 S GAS
	*Upper Frenchman Spgs	FTS	1907-2222	1922-1947 2104-2112 2217-2222	1E3	26	402 S GAS
	*Lower Frenchman Spgs	FTS	2244-2644	2270-2294 2380-2410 2490-2502 2618-2624	2E3	28	400 S GAS
	*Vantage	IB	2665-2713	2672-2690	1.7	8E-2	399 S
	*Upper Grande Ronde	FT	2719-2913	2720-2760 2823-2840	14	.24	397 S GAS
	*Cohassett	FT	2981-3020	2993-3007	1E-2	6E-4	397 S
	Cohassett vesicular zone in middle of flow	^	3057-3172	3083-3099	2.6E-4 SEE SD-BWI-TI-090	1.6E-5	NA
	Umtanum COMPOSITE	FT	3568-3781	3596-3754	480 SEE SD-BWI-TI-105	3.1	406 S GAS
	*Umtanum lower portion of composite test interval	FT	3725-3781	3741-3749	3.7	0.46	407
	*Umtanum fracture zone in lower entablature	^	3781-3827	3814-3822	700	85	407 S GAS
	Umtanum	E	3762-3805	3762-3805	1.6E-5 SEE SD-BWI-TI-107	3.7E-6	NA
	Cohassett	CE	3175-3244	3175-3244	4.4E-6 SEE SD-BWI-TI-109	6.4E-8	NA
	Cohassett	FB	3247-3344	3255.5-3330	770 SEE SD-BWI-TI-095	9.9	406 GAS
	*Umtanum	FB	3837-3889	3839-3864	110	4.4	407

NOTES:

* Data is unverified until released through SD or ST documentation.

IB = Interbed (includes underlying flowtop unless otherwise noted)

S R Strait 2/2/83
L R Bruce 2/2/83

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	BEST ESTIMATE Equivalent Conduc-tivity (ft/day)	BEST ESTIMATE Observed Head (ft) MSL
DC-16A	*Rattlesnake Ridge	IB	668-835	684-808	1738	14.0	448.3 S
	*Selah	IB	928-1021	942-1005	10.6	0.2	438.8 S
	*Cold Creek	IB	1080-1212	1106-1204	3.9	4.0E-2	418.4 S
	*Mabton	IB	1395-1566	1419-1515	129	1.3	420.4 S
	*Priest Rapids	IF	1690-1726	1708-1710	4.3	2.2	381.7 S
	*Roza	IF	1760-1828	1771-1785	2.1E4	1.5E3	402.6 S
	*Frenchman Spgs #1	IF	1892-2000	1947-1956	4.2E3	4.7E2	402.3 S GAS
	*Frenchman Spgs #2	IF	2105-2156	2125-2136	17.3	1.6	402.9 S GAS
	*Frenchman Spgs #3	IF	2236-2261	2236-2244	1.5E3	2.5E2	401.0 S GAS
	*Frenchman Spgs #4	IF	2266-2371	2278-2290 2310-2322 2326-2344 2346-2371	40.0	0.6	403.0 S GAS
	*Frenchman Spgs #5	IF	2476-2559	2500.5-2559	2.4E3	6.9E1	402.4 S GAS
	*Frenchman Spgs #6	IF	2585-2632	2599-2632	868.8	24.1	402.2 S GAS
	*Vantage	IB	2671-2730	2706-2716 2716-2719 2719-2720	124	8.9	401.6 S GAS
	*Grande Ronde #2	IF	2670-2822	2706-2720	124	8.9	400+-2 S GAS
	*Grande Ronde #3	IF	2835.5-2946		E2 to E-1		400+-1 S GAS
	*Cohassett	FT	2970-3026	2962-3014 3024-3048	2.8	5.8E-2	400+-2
	*Cohassett	FB	3254-3360	3280-3344	E-2 to E-3		400+-2

NOTES:

* Data is unverified until released through SD or ST documentation.

S.R. Strait 2/9/83
S R Bruce 2/9/83

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	BEST ESTIMATE Equivalent Conduc-tivity (ft/day)	BEST ESTIMATE Observed Head (ft) MSL
DC-12	*Priest Rapids #1	IF	1217-1254		122	5.5	406 S
	*Priest Rapids/Roza	IF	1328-1364		122	9.4	405 S
	*Roza/Frenchman Spgs	IF	1508-1534		10-15	1.0-1.5	406 S
	*Frenchman Spgs #3	IF	1687.5-1710		41	4.1	406 S
	*Frenchman Spgs #7	IF	1909.5-1984		0.9	3.8E-2	406 S
	*Frenchman Spgs #8	IF	2050.5-2079		34-78	2.4-5.6	406 S
	*Vantage/ G. R. #1	IF	2218-2260		0.8-2.8	3.9E-2to 1.4E-1	403 S
	*Grande Ronde #2	IF	2267-2301		2-4	0.2-0.3	406 S
	*Grande Ronde #4	IF	2408-2446		85-130	3.9-5.9	407 S
	*Grande Ronde #5	IF	2565-2661.5		0.1-0.8	5.0E-3to 4.0E-2	NA
	*Grande Ronde #6	IF	2818-2843		1000-3000	125-375	407 S
	*Grande Ronde #7	IF	2838-2863		580-660	48-55	407 S
	*Grande Ronde #9	IF	2978-3153		0.1-0.2	1.3E-3to 2.5E-3	NA
	*Grande Ronde #10	IF	3067-3153		7.8E-3 to 1.1E-1	2.0E-4to 2.8E-3	NA
	*Grande Ronde #11	IF	3199-3282		E-3?to E-4?	E-4?to E-5?	NA
	*Grande Ronde #12	IF	4021-4070		500-700	17.5to 24.5	407 S
	*G. R. Composite	COMPOSITE	3341-4070		500-700	0.7-1.0	406 S
	*G. R. Composite	COMPOSITE	4084-4455		E2	0.3	407 S
	*G. R.	COMPOS	4344-4455		E2	0.9	408 S

9 Feb '83

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	BEST ESTIMATE Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
McGEE	*Upper Priest Rapids	IF	812-822		22900	2290	
	*Lower Priest Rapids	IF	925-935		2.3E4	2.3E3	
	*Roza	IF	1028.5-1096	1070-1090	>E3	>50	913 S
	*Roza-Frenchman Springs	IF	1099-1167	1125-1160	>E3	>28.6	908 S
	*Frenchman Springs #1	IF	1320.5-1378	1325-1340?	>E3	>66.7	911 S
	*Frenchman Springs #2	IF	1404-1440	1400-1420	>E3	>50	911 S
	*Frenchman Springs #3	IF	1443-1483	1450-1470	>E3	>50	911 S
	*Frenchman Springs #5	IF	1580.5-1680	1595-1610	>E3	>66.7	911 S
	*Frenchman Springs #6	IF	1674-1750	1708-1718	>E3	>100	914 S

NOTES:

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Head measurements are average because of seasonal groundwater withdrawals in the Cold Creek valley.

IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colunnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

C. S. Cline
1/26/83

S R Bruce
1/26/83

Borehole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmissivity (ft^2/day)	Equivalent Conductivity (ft/day)	Observed Head (ft) MSL
DB-15	*Rattlesnake Ridge	IB	150-222	166-222	342	6.1	409.4 S
	*Selah	IB	370-422	400-422	8.5	.4	407.7 S
	*Cold Creek	IB	510-616	518-616	2000	20.4	407.7 S
	*Asotin/ Umatilla	IF	684-682	665-682	900	53	407.8 S
	*Umatilla	IF	680-754	689-754	1080	16.6	407.7 S
	*Mabton	IB	754-844	754-844	1840	20.4	406.5 S
	*Priest Rapids	IF	858-969	918-954	2410	66.9	410.0 S GAS
	*Roza	IF	1045-1105	1061-1105	1770	40	409.7 S GAS
	*Roza	CE	1110-1147	1110-1147	3.8E-5	1.0E-6	NA
	*Squaw Creek	IB	1236-1289	1257-1289	NA	NA	408.7(?) S
	*Frenchman Spgs #2	IF	1300-1343	1310-1343	104	3.15	408.3 S
	*Frenchman Spgs #3	IF	1353-1373	1357-1373	382	23.9	409.7 S
	*Frenchman Spgs #4	IF	1393-1443	1415-1443	165	5.5	411.6 S
	*Frenchman Spgs #5	IF	1450-1530	1459-1530	90.3	1.3	409.6 S
	*Frenchman Spgs #6	IF	1570-1683	1579-1587	850	10.5	408.4 S GAS
	*Frenchman Spgs #7	IF	1720-1800	1746-1756	6.7E-2	6.7E-3	405.9 S GAS
	*Frenchman Spgs #8	IF	1800-1932	1862-1882	3.1E-3	1.6E-4	404.9 S
	*Vantage	IB	1932-1971	1958-1971	6.6E-5	5.1E-6	NA

NOTES:

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IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom

S.R. Strait 2/9/83
SR Bruce 2/9/83

*Grande Ronde #5	IF	2492-2548	2520-2544	E2	E0	391 S GAS
*Grande Ronde #6	IF	2651-2700	2659-2663	E1?	E0?	390 S
*Grande Ronde #7	IF	2692-2763	2729-2735 2757-2761	E0?	E-1?	390 S
*Grande Ronde #8	IF	2813-2868	2828-2865	E0 to E1	E-1 to E0	391 S
*Grande Ronde #9	FT	2961-3113	2985-3105	E1	E-1	399 S
*Grande Ronde #10	FB	3245-3296	3252-3290	E0	E-1	368 S
*Grande Ronde #11	IF	3301-3412	3334-3389	E0	E-2	394?S
*Grande Ronde #12	IF	3611-3636	3616-3629	E-2	E-4	NA
*Grande Ronde #13	IF	4138-4243		E0	E-1	404 S

NOTES:

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II = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colunnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

R.L. Jackson 2-3-83

S. R. Bruce 2/3/83

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
DC-15	*Levey	IB	275-343	284-312	150	5.4	369 S
	*Rattlesnake Ridge	IB	416-496	437-493	155	2.8	384 S
	*Selah	IB	599-629	601-617	35.2	2.2	356 S
	*Esquatzel	IF	630-660	631.5-648	29.9	1.8	356 S
	*Cold Creek	IB	713-787	721.5-785	32.5	0.5	359 S
	*Mabton	IB	1003-1072	1015.5-1064	54	1.1	384 S
	*Priest Rapids	IF	1149-1189	1150-1179	E-1 to E0	E-3 to E-2	386 S
	*Priest Rapids/Roza	IF	1219-1293	1232-1285	E2 to E3	E0 to E1	387 S GAS
	*Roza	IF	1357-1390	1240-1286	E2	E0	386 S GAS
	*Roza	C/E	1295-1353	1295-1353	NA	NA	NA
	*Roza/Frenchman Spgs	IF	1395-1473	1407-1415	E0	E-2	386 S
	*Frenchman Spgs #2	IF	1481-1506	1485-1503	E3	E1	386 S GAS
	*Frenchman Spgs #3	IF	1505-1553	1520-1535	E2	E0	386 S GAS
	*Frenchman Spgs #4	IF	1540-1593	1559-1579	E3	E1	386 S GAS
	*Frenchman Spgs #5	IF	1735-1833	1739-1830	E1	E-1	386 S GAS
	*Frenchman Spgs #6	IF	1834-1887	1842-1880	E3	E1	386 S GAS
	*Frenchman Spgs #7	IF	1999-2092	2059-2079	NA	NA	NA
	*Grande Ronde #2	IF	2098-2198	2104-2170	E0	E-1	389 S
	*Grande Ronde #3	IF	2227-2343	2247-2252 2265-2293	E3	E1	388 S GAS
	*Grande Ronde #4	IF	2372-2487	2242-2452	E0	E-1	391 S

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
RRL-14	*Cohassett	FT	3017-3147	3104-3110	E0 to E1	E-1 to E0	407 GAS
	*Cohassett	C/E	3140-3313				
	*Cohassett	FB	3294-3403	3321-3398.5	E-1 to E0	E-3 to E-2	407 GAS
	*Umtanum	FT	3715-3814	3719.5-3792	E0 to E1	E-2 to E-1	405 GAS

R.L. Jackson 2-3-83

S R Bruce 2/3/83

NOTES:

* Data is unverified until released through SI or ST documentation.

IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colunnade/Entablature E = Entablature C = Colunnade

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

					BEST ESTIMATE		
Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	Transmis-sivity (ft^2/day)	Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
RRL-6	*Frenchman Springs	Tectonic Breccia	2102-2141	2123 2136	E-5 to E-4	E-7 to E-6	
	*Cohassett	FT	3081-3121	3091-3107	E-5 to E-4	E-7 to E-6	
	*Cohassett	Com-posite Interior	3129-3332	3129-3332	E-8 to E-5	E-8 to E-11	
	*Cohassett	FB	3330-3416	3343-3410	E-3 to E-2	E-5 to E-4	
	*Umtanum	FT	3707-3828	3715-3810	E-1 to E0	E-3 to E-2	
	*Umtanum	C E	3827-3938	3827-3938	E-6 to E-7	E-10 to E-9	

R.L. Jackson 2-3-83
SR Bruce 2/3/83

NOTES:

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IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colonnade/Entablature

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

					BEST ESTIMATE		
Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	Transmis-sivity (ft^2/day)	Equivalent Conduc-tivity (ft/day)	Observed Head (ft) MSL
DC-3	*Umtanum	C/E	3584-3635	3584-3635	E-6	E-8	NA

Ron Jackson 2-3-83
S.R. Bruce 2/3/83

NOTES:

* Data is unverified until released through SD or ST documentation.

IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FB = Flowbottom
C/E = Colunnade/Entablature E = Entablature C = Colunnade

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

Bore-hole	Formation	Zone	Packed Interval (ft)	Effective Depth Interval (ft)	BEST ESTIMATE Transmis-sivity (ft^2/day)	 Equivalent Conduc-tivity (ft/day)	 Observed Head (ft) MSL
DC-7/8	*McCoy Canyon	FT	3410-3478	3422-3459	E-1	E-2	>406
DC-7	*Composite Grande Ronde	IF	4115-5008	4115-5008	E0	E-3	>401
	*Composite Grande Ronde	IF	4120-4257		E-3	E-5	NA
	*Grande Ronde	IF	4261-4434	4301-4320 4326-4409	E-3	E-5	NA
	*Composite Grande Ronde	IF	4444-4615		E-1?	E-3?	>407
	*Grande Ronde	IF	4684-4827	4693-4702 4709-4811	E0	E-3	402
	*Composite Grande Ronde	IF	4830-5008	4830-5008	E-1	E-3	391?

Ronald L. Jackson 2-3-83
S. R. Bruce 2/3/83

NOTES:

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IB = Interbed (includes underlying flowtop unless otherwise noted)
IF = Interflow FT(S) = Flowtop(s) FI = Flowbottom
C/E = Colunnade/Entablature E = Entablature C = Colunnade

S = Measured from surface D = Measured from downhole

GAS = Gas present in borehole

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APPENDIX F

POSSIBLE CORRELATION RANGE OF LOG-TRANSMISSIVITY IN GRANDE RONDE BASALT FLOW TOPS

(Provided by the panel of experts)

This is a summary of the results of preliminary studies about the correlation structure of log-transmissivity (log-T) in Grande Ronde Basalt flow tops completed by Pacific Northwest Laboratory (PNL) and Rockwell Hanford Operations (Rockwell) (Table F-1).

The data set examined consists of 42 transmissivities from individual flow tops in 10 boreholes around the Hanford Site. The maximum number of data from any one flow top is 11. The minimum separation distance between adjacent boreholes is about 2 km.

Isotropic sample semi-variograms, using data from all available flow tops were constructed by both PNL and Rockwell. Pacific Northwest Laboratory used a distance class of 5 km in their calculation and concluded that log-T was uncorrelated. Rockwell used a distance class of 1 km in order to get finer resolution in the less-than-5 km lag range. The results of the Rockwell study are presented in Table F-1 for an average lag of up to 8 km. Given that the variance of log-T is 3.35 (log to base 10), and assuming that log-T is a second-order stationary, spatial stochastic process, the results in Table F-1 for lag numbers 3 and 4 tend to indicate that the correlation range of log-T may be no more than about 2.5 km.

TABLE F-1. Rockwell's Isotropic Sample Semi-Variogram of Log-Transmissivity from Grande Ronde Basalt Flow Tops.

Lag no.	No. data pairs	Average distance (m)	Semi-variogram
1	2	305	4.93
2	0	0	0.00
3	53	2,252	4.62
4	18	2,587	3.68
5	12	4,143	2.02
6	0	0	0.00
7	0	0	0.00
8	0	0	0.00
9	2	7,620	8.28

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