RHO-BW-CR-146 P

Probability Encoding of Hydrologic Parameters for Basalt

Elicitation of Expert Opinions from a Panel of Three Basalt Waste Isolation Project Staff 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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Printed in the United States of America

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DE85 014665

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Date Manuscript Completed: November 1984

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ABSTRACT

The Columbia River basalts underlying the Hanford Site in south-central Washington State are being considered as a possible location for a nuclear waste repository. To evaluate the feasibility of this site, the performance of such a repository, which depends primarily on the hydrologic parameters of the site, must be evaluated for compliance with the applicable licensing regulations and guidelines. In this context, the two hydrologic parameters of particular interest are the effective porosity and the ratio of vertical-to-horizontal hydraulic conductivity, or the anisotropy ratio, of the Cohassett basalt flow interior. The Cohassett basalt flow is the prime candidate horizon for repository studies.

The present study implemented a probability encoding method to estimate the probability distributions of selected hydrologic variables for the Cohassett basalt flow top and flow interior, and the anisotropy ratio of the interior of the Cohassett basalt flow beneath the Hanford Site. All variables were defined at two scales: a megascale (100 to 1,000 meters) and a macroscale (1 to 10 meters). For this purpose, a panel of three Rockwell hydrologists having extensive experience with hydrologic parameters for the Hanford Site was assembled and their opinions were encoded by the SRI International (formerly Stanford Research Institute) probability encoding method.

Site-specific data for these hydrologic parameters are currently inadequate for the purpose of preliminary assessment of candidate repository performance. However, this information is required to complete preliminary performance assessment studies. Rockwell chose a probability encoding method developed by SRI International to generate credible and auditable estimates of the probability distributions of effective porosity and hydraulic conductivity anisotropy.

The results indicate significant differences of opinion among the experts. This was especially true of the values of the effective porosity of the Cohassett basalt flow interior for which estimates differ by more than five orders of magnitude. The experts are in greater agreement about the values of effective porosity of the Cohassett basalt flow top; their estimates for this variable are generally within one to two orders of magnitude of each other. For the anisotropy ratio, the expert estimates are generally within two to three orders of magnitude of each other.

Based on this study, the Rockwell hydrologists estimate the effective porosity of the Cohassett basalt flow top to be generally higher than do the independent experts. For the effective porosity of the Cohassett basalt flow top, the estimates of the Rockwell hydrologists indicate a smaller uncertainty than do the estimates of the independent experts. On the other hand, for the effective porosity and anisotropy ratio of the Cohassett basalt flow interior, the estimates of the Rockwell hydrologists indicate a larger uncertainty than do the estimates of the independent experts.

The primary causes of the prevailing diversity of opinion are the current insufficiency of site-specific data and the absence of any universally accepted conceptual or theoretical basis for estimating these hydraulic parameters.

PREFACE

This report presents the results of one of two probability encoding sessions that were held to obtain expert opinion on values of selected hydrologic parameters. Hydrologic parameters were estimated for effective porosity and anisotropy of hydraulic conductivity of the Cohassett basalt flow beneath the Hanford Site in south-central Washington State.

Two distinct groups of experts participated in separate encoding sessions. For the first phase, a panel of five experts were selected by Analytic & Computational Research, Inc. (ACRi), on the basis of a reputational survey, from among nationally and internationally known hydrologists with extensive experience in groundwater hydrology of fractured rock. These experts were selected and contracted by ACRi rather than by Rockwell. Their probability distributions of values estimated for the pertinent hydrologic parameters were encoded by the SRI International (SRI, formerly Stanford Research Institute) probability encoding method. The details of this encoding session are given in a companion report that complements the work reported in this report.

This report presents the results of a second probability encoding. During this session, a panel of three hydrologists was selected by Rockwell from among the most experienced of Rockwell's hydrologists. The estimates of the selected hydrologic parameters that were provided by these experts were also encoded by the SRI probability encoding process. These results were compared to results obtained from the five nationally recognized experts.

EXECUTIVE SUMMARY

BACKGROUND

The Office of Civilian Radioactive Waste Management (OCRWM) was created by the United States 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 being conducted under the direction of the OCRWM. 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 repository for nuclear waste 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 hydraulic factors including site-specific values of effective porosity and anisotropy of hydraulic conductivity.

Site-specific data on hydraulic properties of basalts at the Hanford Site are insufficient for refined assessment of repository performance. However, the best estimates available for these parameters are needed for preliminary performance assessment studies. Because the values of these parameters will be used for stochastic modeling of repository performance, Rockwell chose the probability encoding method developed by SRI International (SRI) (formerly Stanford Research Institute) to assess, in a quantitative, numerical manner, the probability distributions of these parameters.

The probability encoding was completed for two distinct groups of experts. The first group consisted of five experts **selected by Analytic & Computational Research, Inc. (ACRi)** on the basis of a reputational survey from among nationally and internationally known hydrologists with extensive experience in groundwater hydrology of fractured rock. The details of this portion of the study are given in a companion report.

This report documents the results of probability encoding for a second group of three expert hydrologists **selected by Rockwell** from among the most experienced Rockwell project personnel.

PURPOSE OF THE STUDY

The purpose of this study was to obtain the expert opinion of experienced Rockwell hydrologists on (1) the effective porosity of the Cohassett

basalt flow top and flow interior, and (2) the ratio of vertical-to-horizontal hydraulic conductivity (here termed "anisotropy" ratio) of the Cohassett basalt flow interior beneath the reference repository location of the Hanford Site. Opinions were elicited for a megascale (on the order of 100 to 1,000 m) and a macroscale (on the order of 1 to 10 m).

APPROACH

The study was based upon application of the SRI probability encoding method. The SRI probability encoding method is a process by which decision analysts quantify uncertainty factors that bear importantly on a specific decision. The method has been used extensively for business and governmental decision-making (Merkhofer and McName 1982).

To implement the method for purposes of this report, a panel of three expert hydrologists with extensive site-specific experience in the groundwater hydrology of the Hanford Site was selected by Rockwell (see Appendix B). A carefully prepared questionnaire that followed the format and structural requirements of the SRI process was then administered independently to each panel member by two interviewers experienced in the SRI encoding method. Each personal interview lasted from 4 to 6 h. Background material, providing information on the objectives of the study and measured site-specific test-based values of the pertinent hydrologic parameters, was made available to the panelists during the interviews. However, because the three hydrologists had varied backgrounds and perspectives, they did not necessarily share a common data base. During these interviews, an observer experienced in the methods and parametric requirements of performance assessment models was also present to answer questions from panel members.

RESULTS AND CONCLUSIONS

Encoding of expert judgments on probability distributions for values of six hydrologic parameters was accomplished even though existing field data relevant to assessment of the six parameters are extremely limited. Consequently, the experts interviewed found it necessary to rely extensively on their own concepts of basalt hydrologic properties.

The estimates by the experts indicate a diversity of opinion about the values of average effective porosity and anisotropy ratio. The differences of opinion are appreciably more pronounced at the extreme limits than in the middle of the range of values estimated. The three experts are in greatest agreement for the probability distributions of values of effective porosity of the flow top. For this parameter the agreement is generally within one to two orders of magnitude. A greater diversity of opinion exists about the estimated values of effective porosity of the Cohassett basalt flow interior. For this parameter the estimates range two to five orders of magnitude.

The estimated values of the anisotropy ratio of hydraulic conductivity are generally within two to three orders of magnitude of one another. Two of the three panelists are in almost complete agreement on the estimated values of the anisotropy ratio. Their estimates for this parameter, at both the megascale and the macroscale, are well within a factor of two for almost the entire range of cumulative probability distribution. For effective porosity, on the other hand, the estimated values form three distinct probability distributions.

For the effective porosity of the Cohassett basalt flow top, comparison of the estimates provided by the Rockwell hydrologists with those of the five nationally recognized experts suggests that the Rockwell hydrologists are more certain of their opinions. For the effective porosity and the anisotropy ratio of the Cohassett flow interior, on the other hand, the estimates provided by the Rockwell hydrologists indicate a larger uncertainty than the estimates obtained from the independent experts.

The estimated values obtained by averaging the cumulative probability distributions of the five nationally recognized experts are nearly always well within one order of magnitude of the average of the estimates provided by the Rockwell hydrologists. For the effective porosity and the anisotropy ratio of the Cohassett basalt flow interior, the average values for the two groups of experts are often within a factor of two of each other.

REFERENCE

Merkhofer, M. W. and P. McNamee (1982), The SRI Probability Encoding Process: Experiences and Insights, Technical Report, SRI International, Menlo Park, California.

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1.0 INTRODUCTION

1.1 BACKGROUND

The Office of Civilian Radioactive Waste Management (OCRWM) was created by the United States Government in the mid-1970s for the purpose of investigating the feasibility of storing nuclear wastes in deep geologic formations. Currently, the OCRWM 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) for the U.S. Department of Energy (DOE), is one of several major research and development projects conducted under the direction of the OCRWM. Rockwell is a prime contractor to the 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 be licensable, such a repository must perform in compliance with the applicable regulations and guidelines established by the Nuclear Regulatory Commission (NRC) (10 CFR 60; NRC 1983) and the Environmental Protection Agency (EPA) (40 CFR 191; EPA 1984).

The main criterion for 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 geology of the site, 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 predicting the rate of corrosion of the waste canisters and the rate of dissolution to 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 rocks with low bulk porosity, such as basalt, storativity values typically are very small.

An important factor for assessing repository performance is the anisotropy of hydraulic conductivity. Although hydraulic conductivity is a second-order tensor, groundwater flow applications often assume that the coordinate axes of flow geometry are aligned with the principal directions of the tensor. For most horizontally or near-horizontally layered rocks, these coordinate axes are oriented in horizontal and vertical directions. Thus, 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 helps determine the geometry, length, and velocity of radionuclide transport pathways 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 field 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

Estimates of anisotropy and effective porosity at the Hanford Site that are known to be representative are not available. In the interim, Rockwell is following a two-faceted approach to obtain preliminary estimates. Field studies are being initiated to obtain more site-specific data. However, appreciable time is needed before these studies produce the required data. Because Rockwell currently requires defensible estimates of values of the hydrologic parameters for use in preliminary performance assessment studies (10 CFR 960, DOE 1984) probability encoding was initiated to obtain estimates of these parameters from experts with extensive experience in the hydrology and geology of the Hanford Site. The estimates derived by this means will be used in preliminary performance assessments of candidate repository subsystems 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 becomes available, in order 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.

In view of the nature of the hydrologic parameters and the need to use the data in conjunction with stochastic modeling of groundwater flow, Rockwell chose the probability encoding method developed at SRI International (SRI) to obtain the probability distributions of these parameters.

Probability encoding was completed for two distinct groups of experts. The first group consisted of a panel of five experts selected by Analytic & Computational Research, Inc. (ACRi) on the basis of a reputational survey from among nationally and internationally known hydrologists having extensive experience with groundwater hydrology of fractured rocks. These experts were selected by ACRi rather than by Rockwell. The estimates of values of the pertinent hydrologic parameters that were provided by the expert panel were encoded by the SRI probability encoding method. The selection of the panel of five expert consultants and probability encoding were conducted in accordance with established principles of the Delphi methodology. The details of this part of the study are given in a companion report (Runchal et al. 1984).

This report is concerned with the probability encoding of opinions of a second group of experts--three of Rockwell's most experienced hydrologists. This panel of three hydrologists was selected by Rockwell on the basis of their extensive experience in measuring and estimating hydrologic parameters at the Hanford Site, and their development of groundwater conceptual models from these data. The three Rockwell hydrologists have varied backgrounds and perspectives. One has extensive field test analysis experience (F. Spane). The second has extensive experience in integration of hydrologic data (R. Gephart). The third (L. Leonhart) has extensive experience in regional surface-water hydrologic investigations. The estimates provided by these experts for the specified hydrologic parameters were then encoded by the SRI process. Delphi methodology was not employed during probability encoding of Rockwell hydrologists because panelists identities were known to one another and budgetary constraints precluded holding a second round.

The specific scope of this study consisted of the following:

1. Reviewing available published information to identify data pertinent to specified hydrologic parameters for the Hanford Site

2. Assembling a panel of three hydrologists with extensive experience in the hydrology and geology of the Hanford Site

3. Eliciting the opinions of these experts on values of hydrologic parameters pertaining to the Hanford Site

4. Encoding the probability distributions of the parameter values

5. Reporting and analyzing the results of the study.

1.3 PERSONNEL AND DIVISION OF RESPONSIBILITIES

To obtain expert opinions on the specified hydrologic parameters, Rockwell contracted with Analytic & Computational Research, Inc. of Los Angeles, California (Supplement to Rockwell Subcontract SA-965; dated July 6, 1984). In turn, ACRi subcontracted with Applied Decision Analysis, Inc. (ADA) to apply the SRI probability encoding method to estimating hydrologic parameters.

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 personnel. Dr. Miley Merkhofer of ADA was the Principal Investigator for the application of the probability encoding method. Ms. Elizabeth Olmsted of ADA acted as the Project Investigator.

2.0 SYNOPSIS OF THE SRI INTERNATIONAL 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 probability encoding sessions vary, depending on participant differences and the nature of the quantity to be assessed. One feature, however, remains the same: the analyst strives from the subject's responses to understand the modes of information processing used by the subject and to infer from this the biases that may 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). The process consists of five stages.

1. Motivating. The motivating stage is designed to establish rapport between the analyst and the subject and to enable the analyst to assess the potential for motivational biases.

2. Structuring. The structuring stage produces the quanititative framework for the assessment.

3. Conditioning. The conditioning stage is a series of steps designed to free the subject from identified biases.

4. Encoding. The encoding stage produces a preliminary probability distribution.

5. Verifying. The verification stage validates the probability 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.

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3.0 SELECTION OF EXPERT PANEL

The expert panel for the encoding of hydrologic parameters was selected by Rockwell. The panel consisted of three Rockwell hydrologists with extensive experience in the hydrology and geology of the Hanford Site. Each panelist had a working familiarity with the site-specific hydrologic data obtained from more than 40 boreholes in the basalts underlying the Hanford Site. In addition, all of the hydrologists were knowledgeable regarding conceptual modeling of the site and input-data requirements of the computer codes being employed for assessment of site performance.

The names of the panelists and their current position are listed in Table 1. Two of the panelists possess doctorate degrees and the third a master degree in hydrology. Summaries of their experience, education, and lists of major publications are given in Appendix B.

TABLE 1. The Panel of Hydrologists.

Name	Current position
Mr. Roy Gephart	Staff Hydrologist, Basalt Waste Isolation Project, Site Analysis Group, Rockwell Hanford Operations, Richland, Washington
Dr. Leo Leonhart	Staff Hydrologist, Basalt Waste Isolation Project, Site Analysis Group, Rockwell Hanford Operations, Richland, Washington
Dr. Frank Spane	Staff Hydrologist, Basalt Waste Isolation Project, Drilling and Testing Group, Rockwell Hanford Operations, Richland, Washington

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4.0 IMPLEMENTATION OF THE PROBABILITY ENCODING METHOD

4.1 DEVELOPMENT OF THE BACKGROUND INFORMATION

During the portion of this study reported in Runchal et al. (1984), a package of three background documents was prepared. These background documents are included in that report as Appendix C. This information was provided to each of the three panelists.

- The first document provided general information on the BWIP and summarized the purpose and scope of the study within the overall objectives of the BWIP.

- The second document reviewed available data pertaining to the specified hydrologic parameters of selected basalt flows beneath the Hanford Site. It 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. Statistics of the transmissivity and hydraulic conductivity data, based on information contained in the draft BWIP site characterization plan, were also part of this data package.

- The third document consisted of the covariance correlation structure of hydraulic conductivity for some of the field measurements.

In addition to the documents provided to the panelists, a questionnaire was prepared (see Runchal et al. 1984) to help the analyst implement the SRI probability encoding method in a uniform manner.

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 candidate horizon flow top and flow interior, and (2) the anisotropy ratio (ratio of vertical to horizontal) of hydraulic conductivity of the candidate horizon flow interior beneath the reference repository location 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). 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 (Table 2). All of the variables were defined with reference to the Cohassett flow of the Columbia River Basalt Group, within the reference repository location of the Hanford Site, because this flow is presently the preferred candidate horizon (Long and WCC 1983).

4.3 OUTLINE OF THE METHODOLOGY

4.3.1 Overview of the Process

During each interview, the SRI probability encoding process was applied to obtain a probability distribution for the values of each of the six hydrologic variables. Two analysts from ADA and one technical expert from ACRi were present for each interview. Each encoding session was conducted without the other two experts being present and lasted from 4 to 6 h.

To promote consistency of the encoding process as applied to each panelist, a formal questionnaire was prepared (see Runchal et al. 1984). The questionnaire structured the interviews into the five stages of the SRI probability encoding process. Each of these stages was repeated for each parameter. The subsections below discuss the 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 and a brief overview of the process was presented. It was explained that the participants' estimates were not to be identified with each expert by name and were to be considered as descriptions of uncertainty about specified parameters, rather than as inputs needed for assessing repository performance. To explore possible motivational biases, each subject was asked to describe his expertise and experience.

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 macroscale or megascale 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 m^3/s 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.

Next, common probability-assessment biases were explained to each expert. The explanation was provided because understanding the sources 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 phenomena 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 mind, even if previous information suggests that the 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 assure consistency in the three interviews.

4.3.3 Structuring

The structuring stage included defining the variable of concern and exploring how the expert thinks about the quantity. The definition of each variable was discussed with the expert. 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
- Any assumptions that the subject makes in thinking about the variable
- The scale at which the variable is measured.

4.3.4 Conditioning

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

- 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 familiarity with, and preference for, different approaches. All of these approaches to encoding are well established and are routinely used by decision analysts. Further details of these approaches are given in Appendix A. After a number of values sufficient to sketch a reasonably smooth cumulative probability distribution curve were elicited, inconsistencies or discontinuities were checked and the distributions were 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 into intervals of equal likelihood 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 stages. An example of one such consistency check was to ask the expert if the expected value for the macroscale variable should be equal to its value at the megascale. Most of the experts believed that the expected values at each of the two scales ought to be equal or nearly equal. Some experts, however, offered arguments for why the expected values at the macroscale may differ from those at the megascale.

The encoding session was concluded when each expert stated that the probability distribution curves provided an accurate representation of his professional judgment as to the level of his uncertainty, based on the information available at the time of assessment.

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5.0 RESULTS AND DISCUSSION

5.1 EFFECTIVE POROSITY FOR THE COHASSETT BASALT FLOW TOP

5.1.1 Megascale

The experts' cumulative probability distributions of average effective porosity for the Cohassett basalt flow top at the megascale are presented in Figure 1. The estimates of the three Rockwell experts are identified in the figure by the letter codes "F" through "H."* This figure also shows curves labeled "A" through "E." These curves were obtained from the five independent experts (see Runchal et al. 1984). Comparative features of the two sets of curves are described in Section 5.5. Estimates of the BWIP experts range from just over 2×10^{-5} to 7×10^{-1}. Some salient characteristics of these distributions from the five independent and three Rockwell experts are summarized in Table 3. According to the three experts, the median values (values for which there is a 50% chance of a lower value and a 50% chance of a higher value) range from 7.1×10^{-3} to 8.9×10^{-2}. In general, the estimates are within one to two orders of magnitude of each other. The experts seem to be in closer agreement about the high values of the parameter than the low values. The highest values deemed possible by the experts are all clustered above 10^{-1}; however, the low values range over two orders of magnitude, from 2×10^{-5} to 3×10^{-3}.

5.1.2 Macroscale

The opinions on the Cohassett basalt flow top average effective porosity for the macroscale are presented in Figure 2. These probability distributions trend in a manner similar to that for the megascale, but the highest values approach unity and the lowest values are well below 10^{-8}. The median values range from 6.8×10^{-3} to 10^{-1}. The estimates at the upper end of the range are closely clustered and approach the maximum theoretical value of one. Estimates at the lower end range more than five orders of magnitude, from under 10^{-8} to 10^{-3}. As was the case for the megascale, the three probability distributions are distinct from each other.

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*The alphabetical order of the letter code does not necessarily correspond to the order of listing in Table 1.

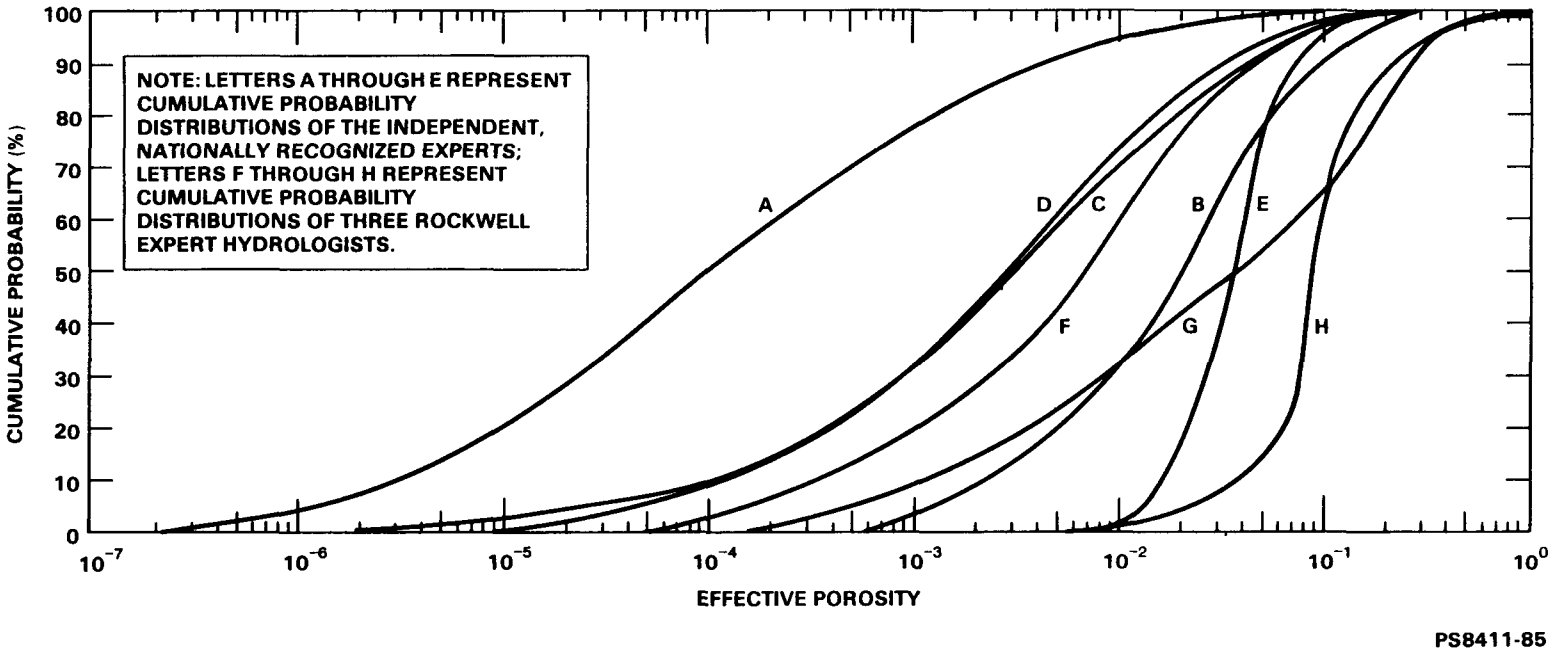

FIGURE 1. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Megascale.

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

Probability and scale	Rockwell hydrologists			Independent experts				
	Expert F	Expert G	Expert H	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)								
10%	3.1×10^{-4}	1.2×10^{-3}	3.9×10^{-2}	3.0×10^{-6}	2.5×10^{-3}	1.0×10^{-4}	1.2×10^{-4}	1.6×10^{-2}
Median	7.1×10^{-3}	3.7×10^{-2}	8.9×10^{-2}	1.0×10^{-4}	2.0×10^{-2}	2.9×10^{-3}	3.1×10^{-3}	3.5×10^{-2}
90%	4.0×10^{-2}	2.0×10^{-1}	2.5×10^{-1}	4.0×10^{-3}	9.0×10^{-2}	4.0×10^{-3}	3.0×10^{-2}	7.0×10^{-2}
Macroscale (1-10 m)								
10%	1.9×10^{-4}	6.0×10^{-4}	3.0×10^{-2}	3.3×10^{-7}	1.0×10^{-3}	1.0×10^{-5}	4.5×10^{-5}	6.0×10^{-3}
Median	6.8×10^{-3}	2.8×10^{-2}	1.0×10^{-1}	1.0×10^{-4}	1.9×10^{-2}	9.5×10^{-4}	1.8×10^{-3}	2.5×10^{-2}
90%	6.2×10^{-2}	2.2×10^{-1}	3.5×10^{-1}	5.0×10^{-2}	1.2×10^{-1}	3.7×10^{-2}	3.0×10^{-2}	8.5×10^{-2}

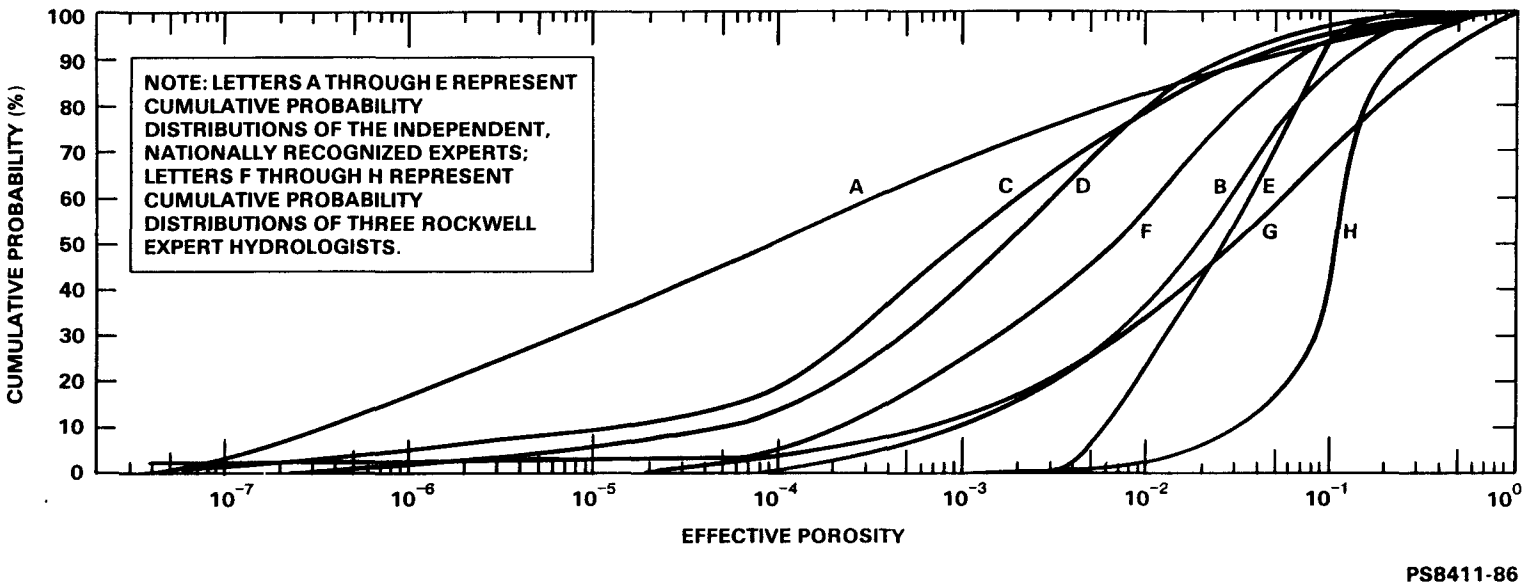

FIGURE 2. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Macroscale.

5.2 EFFECTIVE POROSITY FOR THE COHASSETT BASALT FLOW INTERIOR

5.2.1 Megascale

The cumulative probability distribution curves of expert estimates for the average effective porosity in the Cohassett basalt flow interior at the megascale are given in Figure 3. The estimated values generally are significantly lower than the corresponding values for the flow top. The highest estimates approach 10^{-1} and the lowest values are less than 10^{-8}. These curves exhibit three distinct probability distributions. As shown in Table 4, the estimated median values range from 10^{-5} to 9.8×10^{-8}. Again, as was the case for the flow top effective porosity estimates, the experts are more in agreement at the upper end of the range of values than at the lower end. At the upper end the estimates differ by just over one order of parameter value magnitude, whereas at the lower end, the distributions range over more than five orders of magnitude.

5.2.2 Macroscale

The estimates of average effective porosity for the Cohassett basalt flow interior at the macroscale are shown in Figure 4. These estimates are very similar to those at the megascale, although they span a somewhat larger range than do the values at the megascale. The highest value is greater than 10^{-1}, whereas the lowest value is less than 10^{-8}. However, the median of the estimated values (Table 4) is not appreciably different from the median value at the megascale; these estimates range from 8.2×10^{-6} to 9.8×10^{-3} and are almost identical to those for the megascale.

5.3 ANISOTROPY RATIO OF HYDRAULIC CONDUCTIVITY FOR THE COHASSETT BASALT FLOW INTERIOR

5.3.1 Megascale

The experts estimates of the anisotropy ratio for the Cohassett basalt flow interior at the megascale are shown in Figure 5. Except for values of cumulative probability in excess of 90%, the three sets of estimates are consistently within two orders of magnitude of each other.

The median values range from approximately 0.5 to 50 (Table 5). Experts F and G are in almost complete agreement over the entire range of values; their estimates are consistently within a factor of two of each other. The highest values for the three estimates range from just over 10^2 to almost 10^5. The lowest values range from approximately 10^{-3} to 10^{-1}.

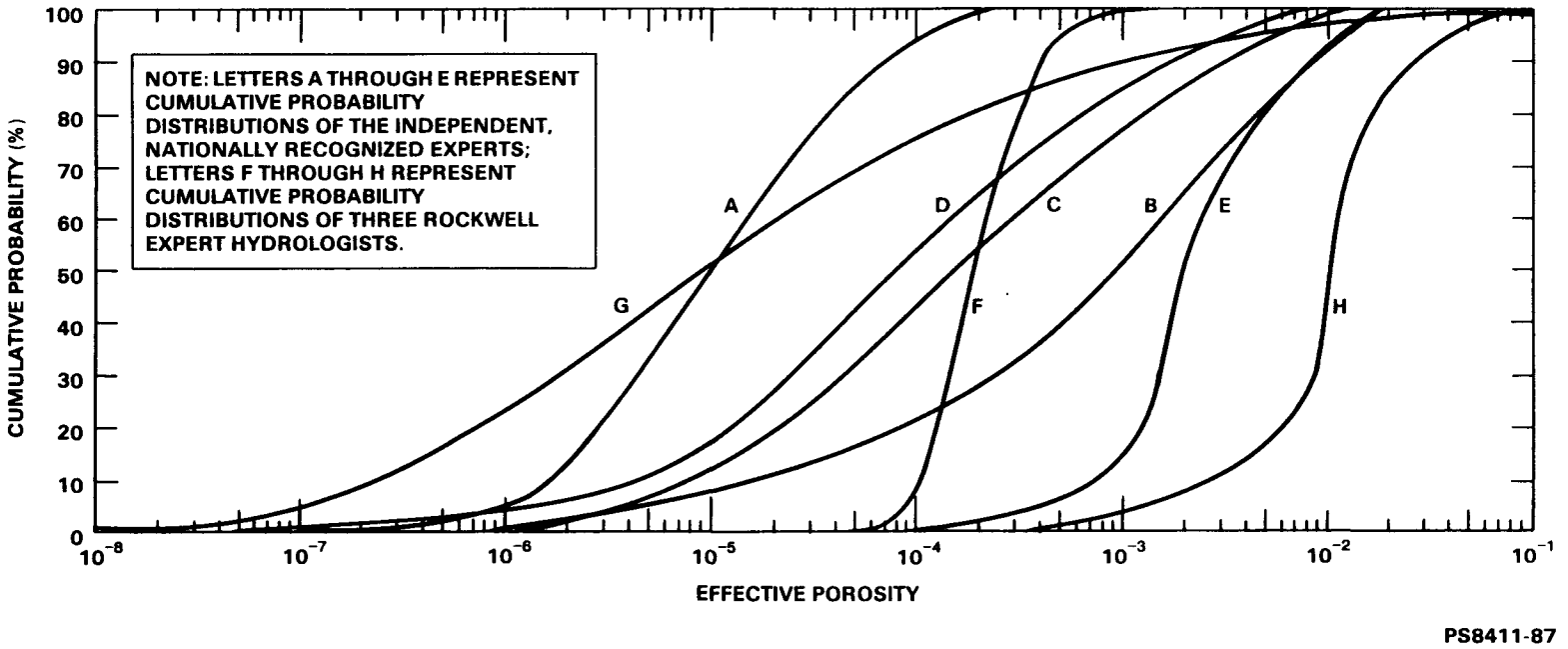

FIGURE 3. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Megascale.

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

Probability and scale	Rockwell hydrologists			Independent experts				
	Expert F	Expert G	Expert H	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)								
10%	1.1×10^{-4}	2.2×10^{-7}	3.0×10^{-3}	1.6×10^{-6}	1.4×10^{-5}	8.5×10^{-6}	4.5×10^{-6}	8.0×10^{-4}
Median	2.0×10^{-4}	1.0×10^{-5}	9.8×10^{-3}	1.0×10^{-5}	9.0×10^{-4}	1.6×10^{-4}	7.2×10^{-5}	1.9×10^{-3}
90%	4.1×10^{-4}	1.3×10^{-3}	2.5×10^{-2}	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%	1.1×10^{-4}	1.1×10^{-7}	2.5×10^{-3}	2.1×10^{-7}	1.1×10^{-5}	3.0×10^{-6}	3.0×10^{-6}	1.6×10^{-4}
Median	2.0×10^{-4}	8.2×10^{-6}	9.8×10^{-3}	9.0×10^{-6}	1.0×10^{-3}	1.0×10^{-4}	1.0×10^{-4}	2.5×10^{-3}
90%	1.0×10^{-3}	3.0×10^{-2}	4.4×10^{-3}	5.0×10^{-4}	1.3×10^{-2}	4.0×10^{-3}	4.0×10^{-3}	1.5×10^{-2}

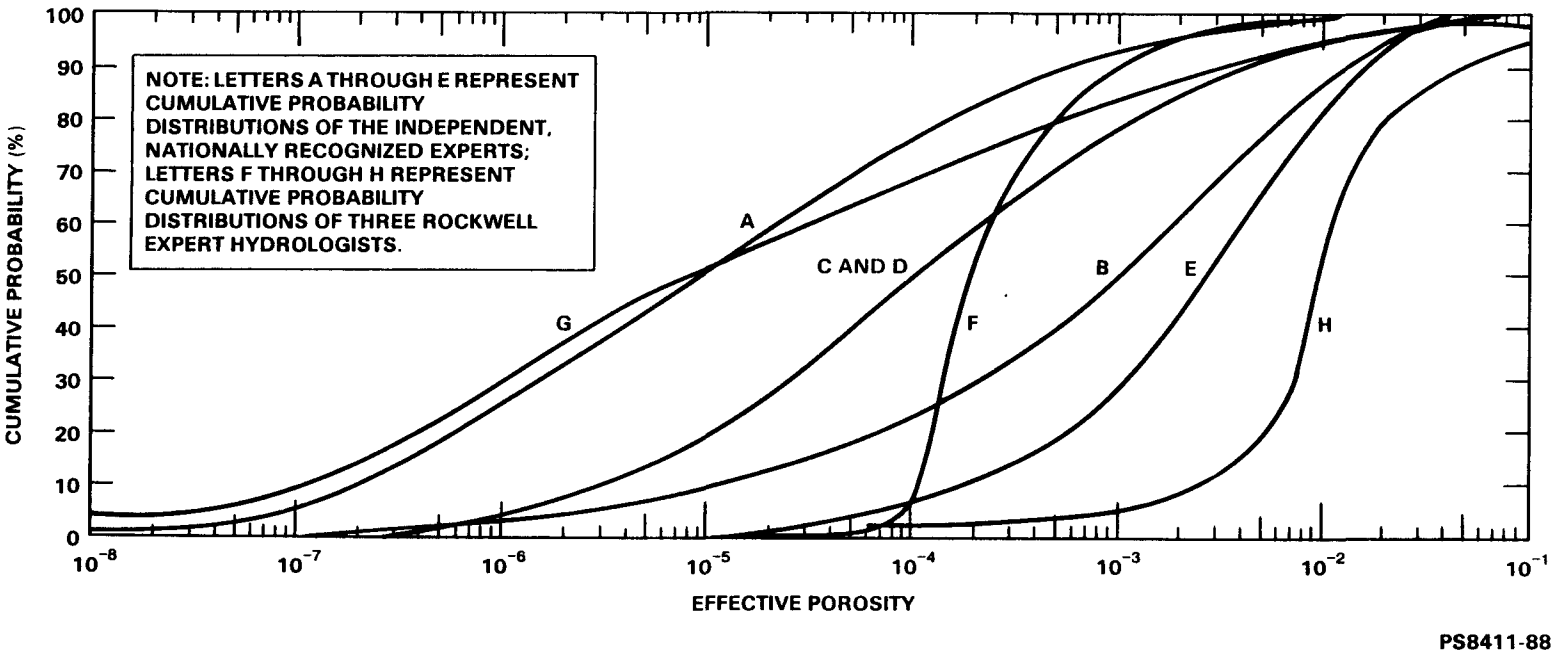

FIGURE 4. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Macroscale.

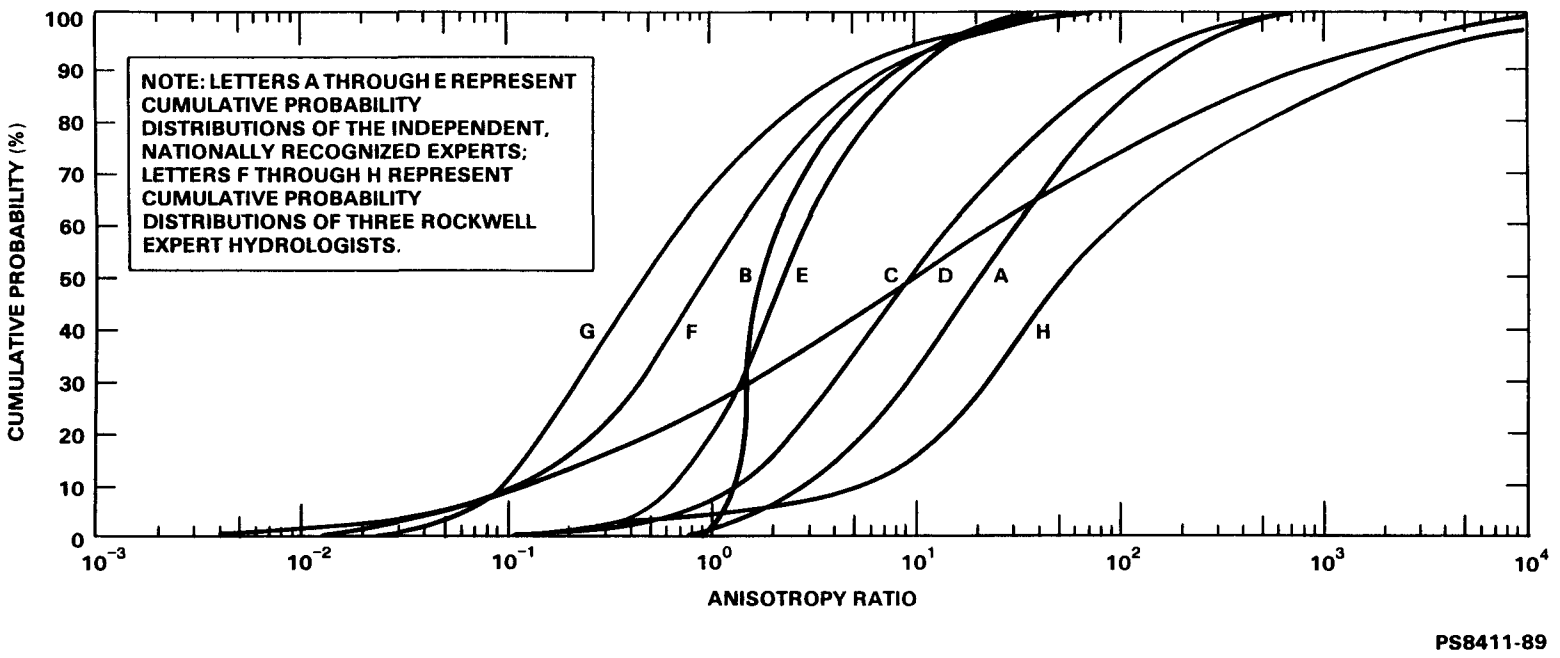

FIGURE 5. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Hydraulic Conductivity Anisotropy Ratio at Megascale.

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

Probability and scale	Rockwell hydrologists			Independent experts				
	Expert F	Expert G	Expert H	Expert A	Expert B	Expert C	Expert D	Expert E
Megascale (100-1,000 m)								
10%	0.12	0.10	6.0	3	1.3	0.15	0.13	0.65
Median	1.0	0.46	50	20	1.8	10	10	2.3
90%	7.0	5.0	2,000	170	9	120	850	10
Macroscale (1-10 m)								
10%	0.025	0.045	2.0	1	1.4	1.1	0.20	1.0
Median	0.98	0.60	60	20	10	10	10	5.3
90%	24	14	60,000	300	130	110	2,000	50

5.3.2 Macroscale

The estimates for the Cohassett basalt flow interior anisotropy ratio at the macroscale are shown in Figure 6. In general these probability distributions are very similar to those at the megascale, although they depict a greater uncertainty. As was the case for the megascale, the experts' estimates over most of the probability range (up to 80% cumulative probability) are generally within two orders of magnitude of each other. Experts G and F are again in almost complete agreement with each other. The median values (see Table 5) are almost identical to those for the megascale and range from 0.6 to 60. The highest estimated anisotropy value exceeds 10^5 and the lowest value approaches 10^{-3}.

5.4 DISCUSSION

The results indicate that the three panelists have diverse opinions about the likely values of average effective porosity and anisotropy ratio. For the anisotropy ratio, two of the experts are in close agreement but the third panelist holds a diverse opinion. Comments made independently by the panelists indicate that a lack of consensus would directly reflect diversity in the information bases and conceptual models of the experts.

For the effective porosity parameters, the agreement among panelists improves significantly at the upper end of the probability distribution. For the anisotropy ratio, the reverse is true. The three experts have effective porosity probability distributions that are in agreement to within one to two orders of magnitude at 90% cumulative probability. At 10% cumulative probability, the agreement is only to within four orders of magnitude. For the anisotropy ratio on the other hand, the agreement at 10% cumulative probability is within two orders of magnitude but decreases to almost three orders of magnitude at 90% cumulative probability.

5.5 COMPARISON OF RESULTS WITH RESULTS FROM THE FIVE INDEPENDENT, NATIONALLY RECOGNIZED EXPERTS

5.5.1 Comparison of Individual Probability Distributions

This section compares the opinions of the Rockwell hydrologists with those of the five independent hydrologists (see Runchal et al. 1984). The probability distributions of the three Rockwell hydrologists (curves marked F through H) with those of the five independent experts (curves marked A through E) are compared in Figures 1 through 6.

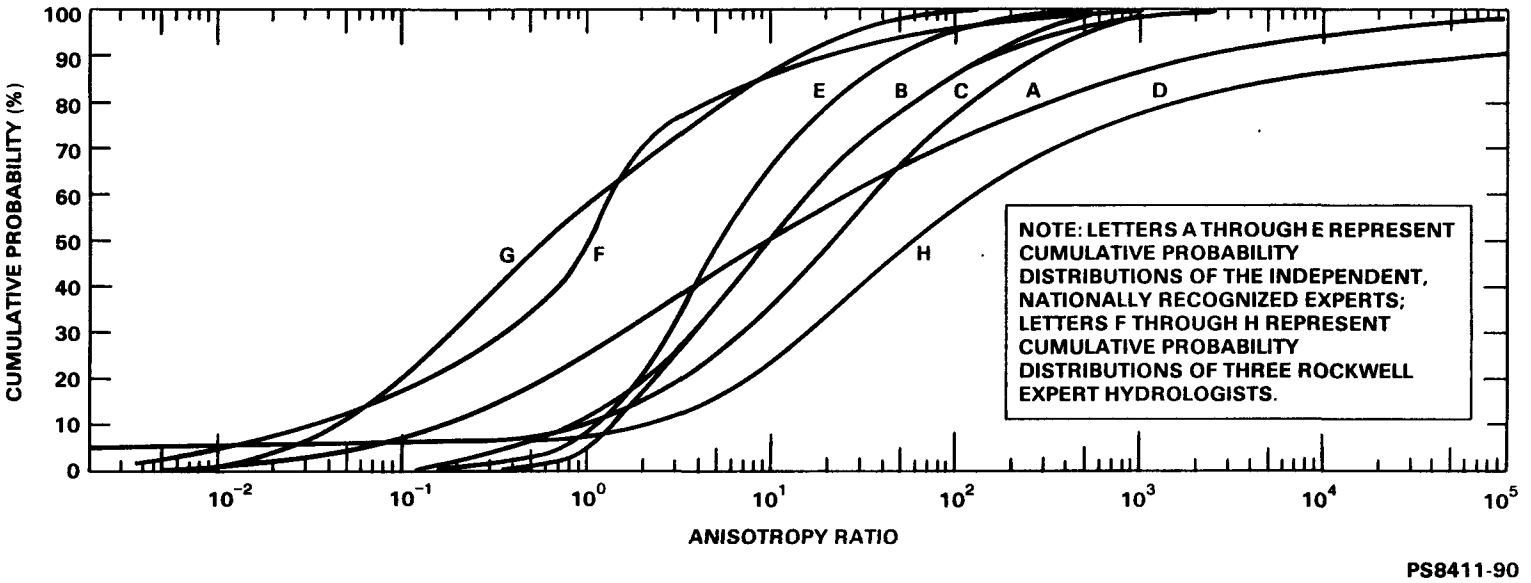

FIGURE 6. Comparison of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Hydraulic Conductivity Anisotropy Ratio at Macroscale.

At any given cumulative probability, the Rockwell hydrologists tend to estimate higher values for the Cohassett basalt flow top effective porosity than do the independent experts (Figures 1 and 2). The highest estimate of one of the Rockwell hydrologists is nearly an order of magnitude higher than the highest estimates of the independent experts. The lowest estimates of Rockwell hydrologists are generally one to two orders of magnitude higher than the lowest estimates of the independent experts.

A comparison of values estimated for the Cohassett basalt flow interior effective porosity is shown in Figures 3 and 4. The highest estimate of one of the Rockwell hydrologists is again approximately one order of magnitude higher than the highest estimates of the independent experts. However, the lowest estimates by Rockwell hydrologists are closer to the lowest estimates provided by one of the independent experts than they were for the flow top estimates. In fact, for cumulative probabilities of less than approximately 50%, the estimates of one of the Rockwell hydrologists (Expert G) are below the estimates given by independent experts. Thus, values of this parameter are considered to be more uncertain by the Rockwell hydrologists than by the independent experts.

For the anisotropy ratio, the estimates provided by the Rockwell hydrologists are similar to the estimates of the independent experts (see Fig. 5 and 6) but the highest values deemed possible by the Rockwell experts are higher and the lowest values lower than the values estimated by the independent experts.

5.5.2 Comparison of Averages of Probability Distributions

The opinions of all eight experts span a wide range of values as indicated by Figures 1 through 6. Aggregation of probability distributions is sometimes used to summarize the opinions of different experts for the purpose of decision analysis. Although much research has been conducted in this area during the past 15 yr, no single decision analysis methodology has been found for aggregating expert opinion on probability 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 complex assumptions whose appropriateness must be judged on a case-by-case basis.

One approach to aggregating expert judgments is averaging. For example, the cumulative probability distributions elicited from individual experts may be averaged on a point-by-point basis. Two possibilities for averaging were considered:

1. Averaging the probability values for a specific value of the parameter

2. Averaging the values of a parameter for a specific cumulative probability.

Because the present study was structured to obtain the panelists' assessment of the cumulative probability (dependent variable) for 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 the other experts. Thus, the range of parameter values estimated by the experts is preserved by averaging the probability values. **This approach is ad hoc.** The resulting distributions are averaged values, are not indicative of consensus among the panelists, and may ignore other significant aspects of differences of opinion. For illustration, the results of such averaging for the six hydrologic variables, assuming equal weighting for each expert's opinion, are shown on Figures 7 through 12. To compare the estimates obtained from the independent experts with those provided by the Rockwell hydrologists, the averaging of opinions of parametric values was performed separately for each group of experts.

The average estimated value of the independent experts is almost always well within one order of magnitude of the average estimated value provided by the Rockwell hydrologists (see Fig. 7 through 12). In fact, for the effective porosity and the anisotropy ratio of the Cohassett basalt flow interior, the averages are often within a factor of two of each other. The only exceptions occur for cumulative probability values less than 2% or greater than 98%.

The trimodal nature of the average of probability distributions in Figures 9 and 10 essentially reflect the three distinct distributions of the three experts. The other curves (shown in Figures 7, 8, 11, and 12) appear smooth because those individual distributions are more in agreement.

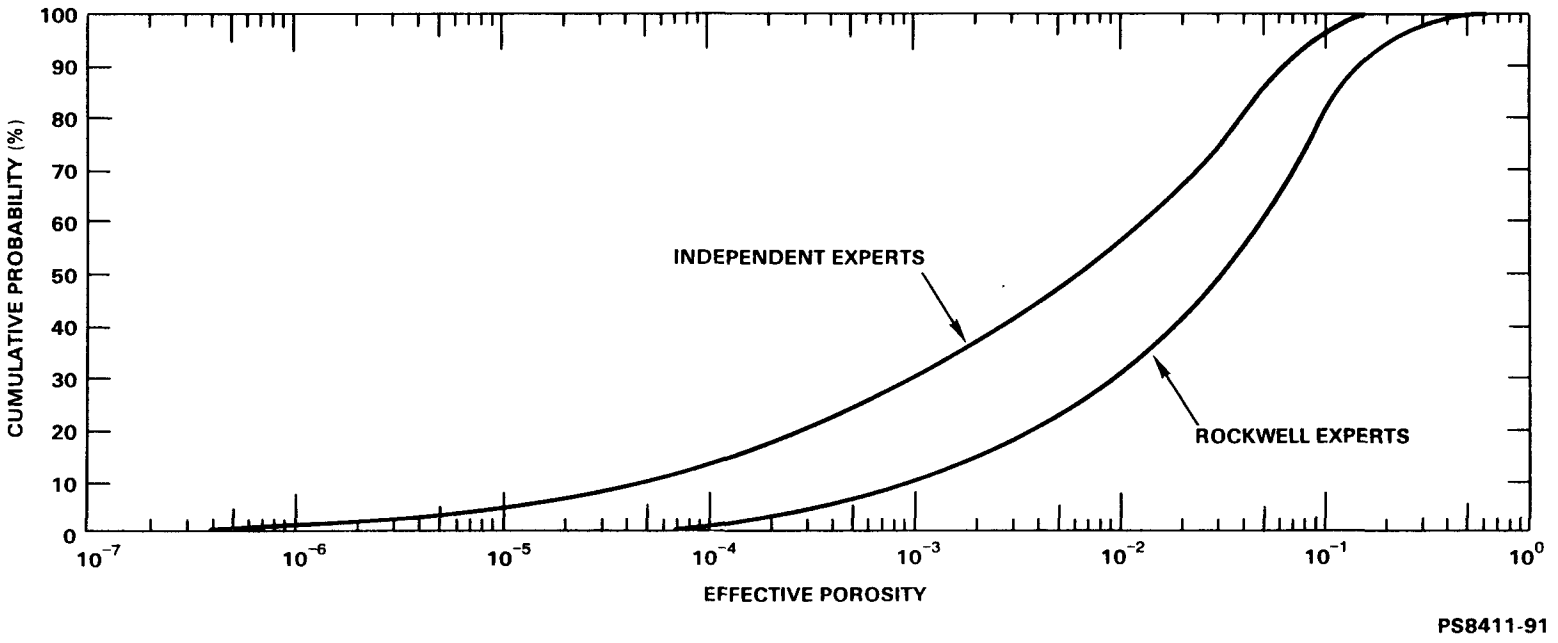

FIGURE 7. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Megascale.

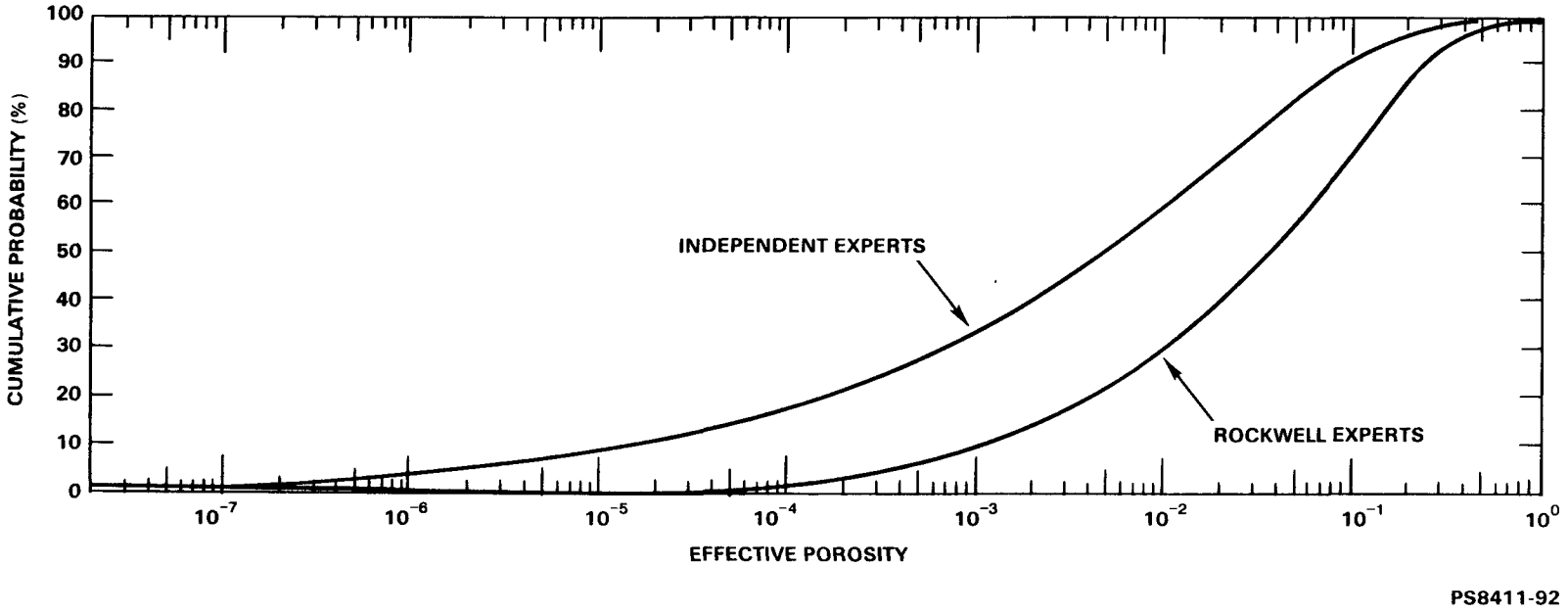

FIGURE 8. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Top Average Effective Porosity at Macroscale.

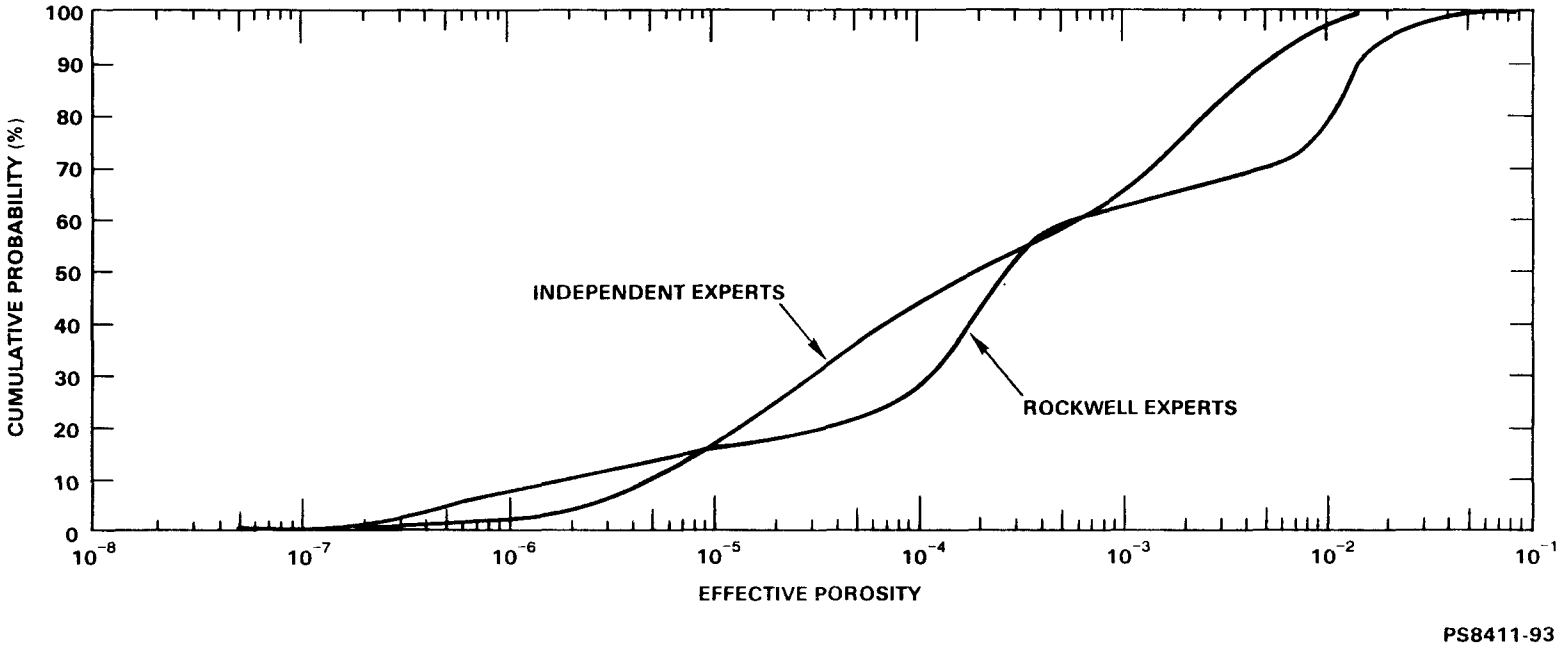

FIGURE 9. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Megascale.

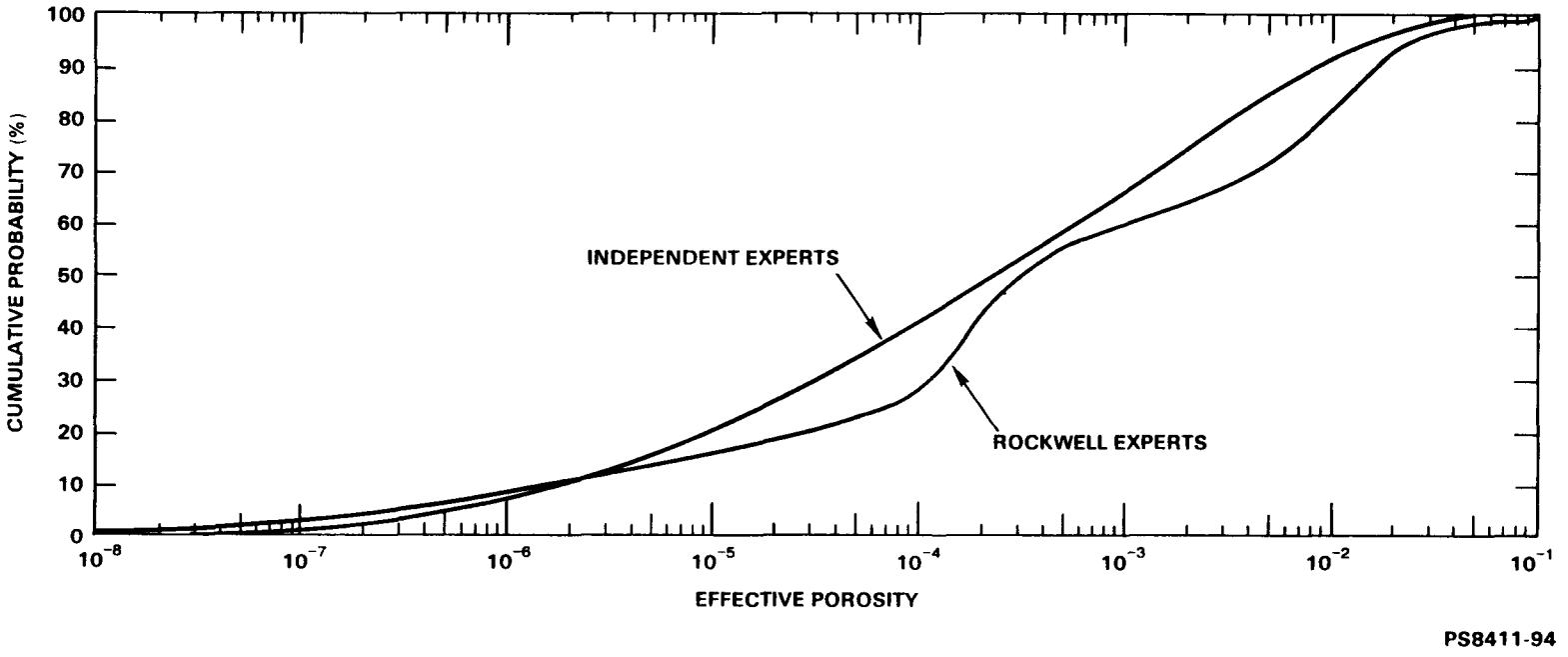

FIGURE 10. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Average Effective Porosity at Macroscale.

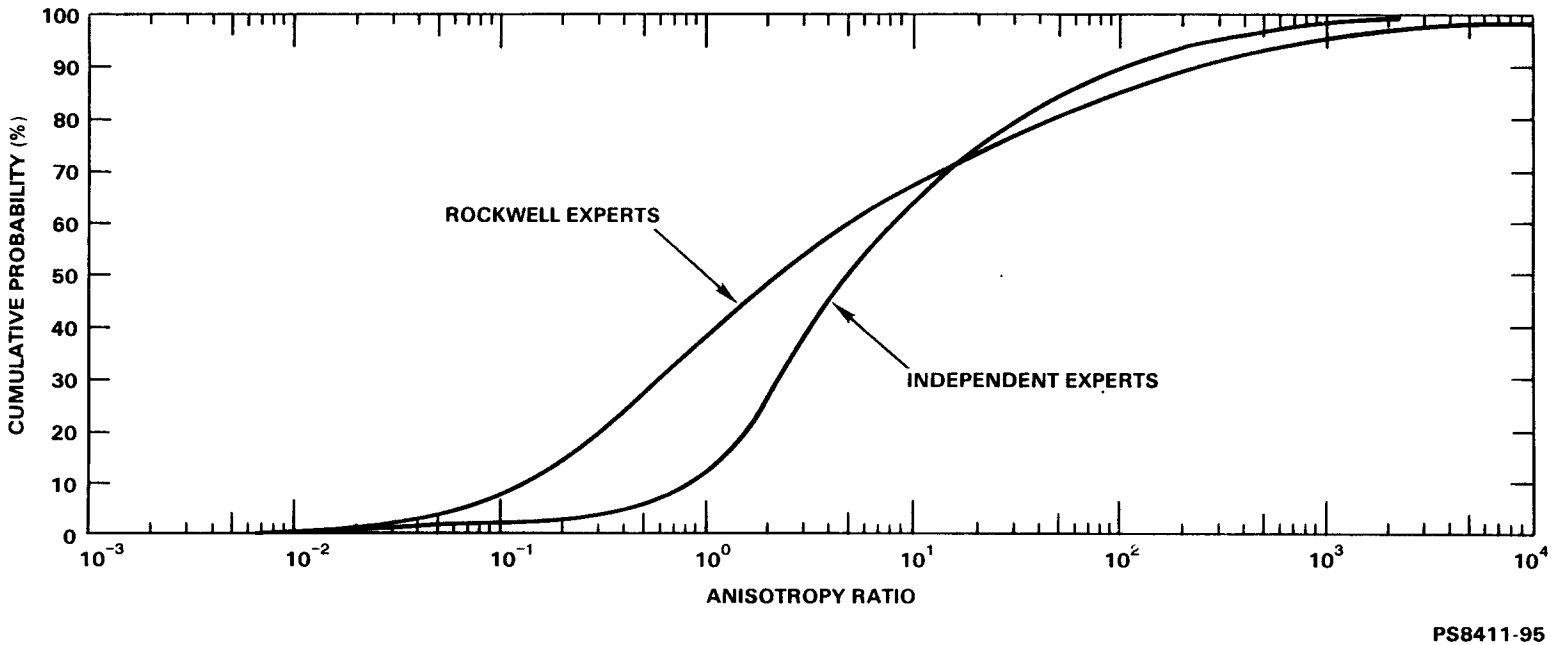

FIGURE 11. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Hydraulic Conductivity Anisotropy Ratio at Megascale.

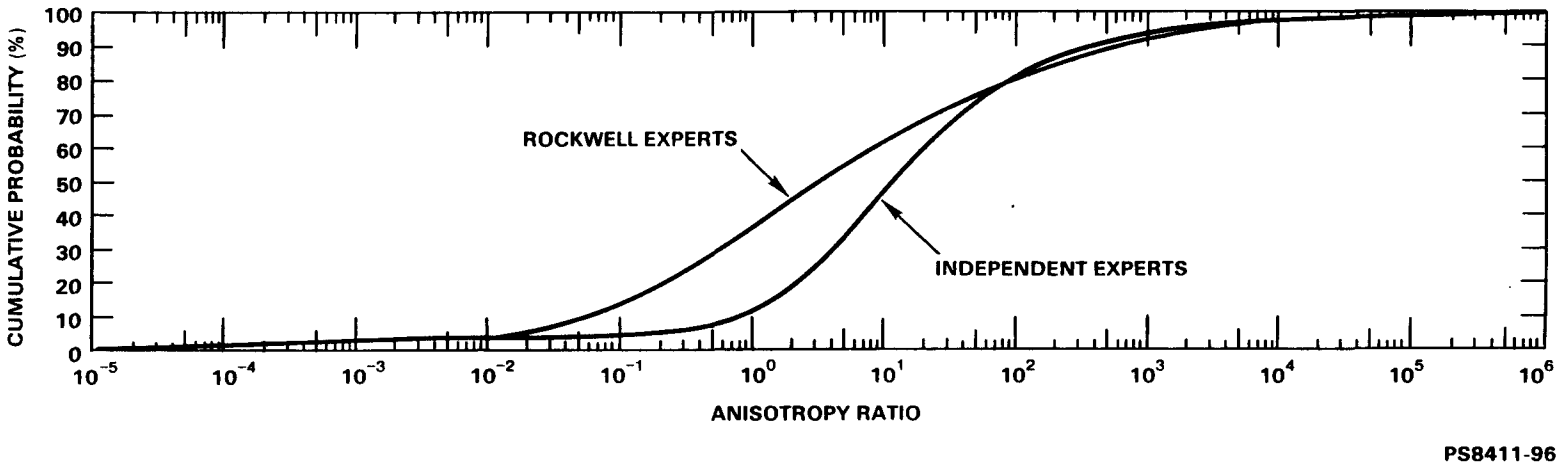

FIGURE 12. Comparison of Averages of Cumulative Probability Distributions of Two Groups of Expert Hydrologists for Estimated Values of Cohassett Basalt Flow Interior Hydraulic Conductivity Anisotropy Ratio at Macroscale.

6.0 OBSERVATIONS AND CONCLUSIONS

The following observations and conclusions are made.

- Probability encoding of expert judgments concerning the six hydrologic parameters was successfully accomplished in that the experts regarded their cumulative probability distributions as accurate presentations of their professional opinions.

- Most site-specific data relevant to estimation of values of the six parameters considered are currently not sufficient for even preliminary performance assessment. Consequently, the experts interviewed found it necessary to rely extensively on their own concepts and pertinent field experience.

- There is considerable difference of opinion among the experts as to the estimated values of the parameters and their ranges. This difference is most pronounced at the extremes of the cumulative probability distribution range.

- The three Rockwell experts are in most agreement for the probability distributions of the Cohassett basalt flow top effective porosity values. For this parameter the agreement is generally to within one or two orders of magnitude. In contrast, opinion is most diverse about the estimated values of the effective porosity of the Cohassett basalt flow interior. For this parameter the estimates range from two to five orders of magnitude. In contrast, the estimated values of the anisotropy ratio are generally within two to three orders of magnitude.

- Two of the three Rockwell panelists are in almost complete agreement on the estimated values of the anisotropy ratio. Their estimates for this variable, at both the megascale and the macroscale, are well within a factor of two for almost the entire range of cumulative probability. For the effective porosity parameters, on the other hand, the estimated values form three distinct probability distributions.

- The agreement among the three 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.

- In general, the Rockwell hydrologists estimate the effective porosity of the Cohassett basalt flow top to be higher than that estimated by the independent experts. For the effective porosity of the Cohassett basalt flow top, the estimates of the Rockwell hydrologists indicate a smaller uncertainty than the estimates of the five independent experts.

- On the other hand, for the effective porosity and anisotropy ratio of the Cohassett basalt flow interior, the estimates provided by the Rockwell hydrologists indicate a larger uncertainty than the estimates provided by the five independent experts.

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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 in 1979 by the Decision Analysis Department of SRI International (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 on 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 certain 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 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 regions 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 probability 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 EXPERT PANEL MEMBERS

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1972 to 1973	Graduate Research Assistant, Geology Department, Wright State University, Dayton, Ohio

Honors and Awards:

Rockwell Hanford Operations Engineer of the Year, 1980
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Acceptance to National Association of Geology Teachers' Cooperative Field Training Course, 1971
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Professional Activities:

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Publications:

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