WILLIAMS & ASSOCIATES, INC.

P.O. Box 48, Viola, Idaho 83872 (208) 883-0153 (208) 875-0147

Hydrogeology • Mineral Resources Waste Management • Geological Engineering • Mine Hydrology

'87 JAN -5 P12:12

December 31, 1986
Contract No. NRC-02-85-008
Fin No. D-1020
Communication No. 105

Mr. Jeff Pohle
Division of Waste Management
Mail Stop 623-SS
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

RE: BWIP

Dear Jeff:

A copy of the review of the following document is enclosed.

1. Loo, W.W., and Arnett, R.C., December 1984, Effective Porosity of Basalt: A Technical Basis for Values and Probability Distributions Used in Preliminary Performance Assessments. Rockwell Hanford Operations, Richland, WA, ST-BWI-TI-254.

Please contact me if you have any questions concerning this review.

Sincerely,

Gerry V. Winter

GVW:sl

WM Record File Wm. Res D1020 WEA

WM Project 10, 11, 16
Docket No.
PDR ✓
LPDR ✓ (B, N, S)

Distribution:
J Pohle
Sac
(Return to WM, 623-SS)

3562

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: ST-BWI-TI-254

DOCUMENT: Loo, W.W., and Arnett, R.C., December 1984, Effective Porosity of Basalt: A Technical Basis for Values and Probability Distributions Used in Preliminary Performance Assessments. Rockwell Hanford Operations, Richland, Washington.

REVIEWER: Williams & Associates, Inc., Gerry Winter

DATE REVIEW COMPLETED: December 22, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report defines three types of porosity: total, apparent, and effective porosities. Total porosity equals the total volume of voids within the sample divided by the total volume of the sample. Apparent porosity is defined as the total volume of interconnected voids divided by the total volume of the sample. Apparent porosity is usually smaller than total porosity. Effective porosity is defined as the volume of void space <u>that contributes to flow</u> (presumably at some predetermined time scale) divided by the total volume of the sample. The distinction between apparent porosity and effective porosity is apparent from the definition for effective porosity. Time scale is a critical factor in this difference, although it is implied, not stated. Based on these definitions, apparent porosity is always greater than effective porosity unless all of the interconnected pore space contributes to the flow of groundwater at the time scale of interest.

The report discusses the technical bases for the values and probability distributions of effective porosity that have been estimated for the basalt flow tops and basalt flow interiors at the Hanford site in the state of Washington. The values of porosity and their distributions are based on estimates of porosity from technical references, on estimates of porosity from field and laboratory measurements of the basalts at the Hanford site, and on estimates of porosity and probability distributions based on probability encoding of expert opinions. Probability encoding is explained subsequently herein. Information from these sources was reviewed; expected ranges of effective porosity values range from 10^{-4} to 10^{-2} for basalt flow tops and 10^{-6} to 10^{-3} for basalt flow interiors. The report concludes that the values are biased toward low values.

Several significant problems exist with the report under review. The report bases the estimates of porosity on a few BWIP site samples that have been analyzed in the laboratory. The distributions of porosity presented in the appendix to the report are not conclusive based on the sample sizes used in the report. The report fails to address the significant differences in scale represented by tests on cores and on the in-situ tracer test. The use of probability encoding of expert opinions does not seem warranted based on the limited data base available for basalts. The existing data base for basalts consists primarily of hydraulic conductivity and transmissivity values. Only one site in a basalt flow top has been tested in situ at the BWIP site for effective porosity. All other tests were conducted on cores evaluated in the laboratory.

<u>BRIEF SUMMARY OF DOCUMENT</u>:

The report compiles estimates of effective porosity or related quantities from six sources:

"o Hydrology textbooks and journal articles
- o Technical reports issued by organizations other than the BWIP
- o Laboratory measurements by the BWIP of basalt cores
- o Calculations based on fracture characteristics of the pertinent basalts
- o Survey of expert opinion within BWIP and a group of independent nationally-known hydrologists
- o Determinations from tracer experiments conducted by BWIP" (p. 9).

The report states that the influence of these sources was weighted in approximately the inverse order to that of the listing.

The report defines total, effective, and apparent porosities. Total porosity is defined as the volume of the voids within the total volume of the sample divided by the volume of the sample. Effective porosity is defined as the volume of the void space that contributes to flow (at some time scale) divided by the volume of the sample. Apparent porosity is defined as the volume of interconnected voids divided by the total volume of the sample. The report states that the distinction between effective porosity and other forms of porosity is that effective porosity is dependent on those voids that are hydraulically active and contribute to fluid transport (at some time scale). Apparent porosity is always greater than effective porosity unless all of the interconnected pores contribute to flow.

Laboratory measurements were made of both apparent and total porosities of basalt core samples. A standard technique was used for the determination of porosities (Foundation Science Inc., 1980). The report states that the apparent porosity of the basalt core samples was determined using NX diameter cores approximately 4 inches long. The total volume of interconnected voids and the total volume of the sample were determined from measurements of the dry, water saturated, and submerged weights of the specimen. Total porosity was calculated whenever grain density data were available (p. 12).

Porosity was estimated from fracture characteristics. Porosity was estimated by rearranging the equation developed by Snow (1968) which defines equivalent hydraulic conductivity based on fracture abundance and fracture aperture width. Several assumptions are inherent in the calculation of porosity based on fracture aperture and spacing. These assumptions are

"o All fluid flow is along open fractures; there is no intergranular or rock matrix permeability,
o Open (unfilled) fractures are interconnected throughout the path of interest,
o Sets of fractures are smooth-walled and parallel,
o Flow is laminar and linear,
o Rock is rigid (not deformable, low swelling and shrinking potential), and
o All fracture aperture widths are equal" (p. 14).

The report states that the first three assumptions are of particular interest; these three assumptions may very well be violated to a significant degree in a real world situation.

The report discusses the use of tracer tests as a direct means for assessing groundwater velocities. Groundwater velocities can be used to calculate values of effective porosity and dispersivity. The report notes that "Tracer-test data obtained from measurements of travel time across a relatively small injection and observation well distance may not be valid when extrapolated (to a larger scale) as being representative of conditions for relatively large areas" (p. 15). Problems exist with tracer tests because the induced hydraulic gradients are usually abnormally high. This test is particularly difficult to implement in a fractured system; nonlinear flow may be induced as a result of the high artificial hydraulic gradients.

The report describes the use of expert opinion. Two methodologies are described. The Delphi method consists of selecting a panel of experts on the matter in question; an iterative procedure is used with the administration of a questionnaire to each panel member. The second method is the probability encoding process. The process is explained in the report as being regarded as state-of-the-art by the decision analyses community. The process is conducted as a joint undertaking by an expert in the area of interest. The analyst serves as an interviewer and attempts to understand, from the interviewees responses, those modes of information processed and used by the interviewee to infer what biases are likely. The analyst attempts to minimize the effect of these biases on the probabilities derived from the interview.

The report summarizes porosity data obtained from technical references. The report states that porosity values for dense basalts range from 0.1% to 1% or more based on values presented in several textbooks. The textbooks suggest that interflow structures may have porosities as high as 10%. Technical publications and papers indicate that effective porosity values range from 0.047% to 18%. The document notes that it is difficult to associate these values with any particular basalt structure such as a flow top or a flow interior. Total porosity values for Columbia Plateau basalts are quoted as ranging from 0.55% to 37.8%. The document states that Columbia Plateau basalts have apparent porosities that range from 0.1% to 2.8%. The document cites an INTERA Environmental Consultants' report which estimates the range of porosity based on laboratory analysis of basalt; porosity values derived from that source range from 0.1% to 25%. A GeoTrans report is cited as presenting a range of 3% to 35%. The document states that specific hydrogeologic units were not identified in the INTERA or GeoTrans reports.

The document states that technical literature provides guidance on the probability distributions of important hydrogeologic parameters. The document states that hydraulic conductivities and transmissivities are lognormally distributed for a given hydrogeologic unit. The document states that porosities are usually reported to be normally distributed. Lognormal distributions of apparent porosities may occur in fractured crystalline rock (p. 22).

The report summarizes data derived from field and laboratory measurements of porosities for the Hanford site basalts. Approximately 599 core samples were tested for apparent porosity; 359 samples were tested for total porosity. Laboratory measurements were made of both apparent and total porosities of basalt core samples. A standard technique was used for the determination of porosities (Foundation Science Inc., 1980). The report states that the apparent porosity of the basalt core samples was determined using NX diameter cores approximately 4 inches long. The total volume of interconnected voids and the total volume of the sample were determined from measurements of the dry, water saturated, and submerged weights of the specimen. Total porosity was calculated whenever grain density data were available (p. 12). The document states that most of the measurements were made on the Pomona Member of the Saddle Mountains Formation and on Grande Ronde basalt. Two porosity tests were performed on Wanapum Formation samples. The core samples were obtained primarily from boreholes RRL-2, RRL-6, and RRL-14 (p. 23). The core samples were obtained from the four candidate horizons (Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows). Samples were obtained from four portions of the flows whenever possible. The four portions included the flow top, the vesicular zone, the entablature, and the colonnade. The report states that the apparent porosity of the flow tops ranges from 7% to 35% (p. 23). The document states that apparent porosities of the other portions of the basalt flow range from 0.1% to 17%. Tests on cores were conducted at atmospheric pressure without adjustment for in-situ conditions. Core from highly fractured rock were not available for testing due to poor core recovery. This omission constitutes a major problem inherent in measuring porosity on core samples.

The report presents histograms (in an appendix) that were constructed from the apparent porosity data obtained from core samples from boreholes RRL-2, RRL-6, and RRL-14. The document concludes, based on visual inspection of the histograms, the following:

"o Frequencies of flow tops apparent porosities are generally symmetrically (perhaps normally or uniformly) distributed,

o Frequencies of basalt flow interior apparent porosities (colonnades and entablatures) generally appear to be assymetrically (perhaps log-normally) distributed" (p. 27).

The report states the following limitations of such laboratory data:

"1) The porosities measured are apparent and are larger than the effective porosities.

2) Samples were not tested under in-situ conditions.

3) Individual samples are representative of only small volumes of rock" (p. 27).

The report describes the calculation of vertical fracture porosity based on equations contained within the document. Fracture abundance is approximately four fractures per meter in the upper 15 m of the Cohassett flow interior. The fracture frequency is based on core samples from borehole RRL-2. The document states that the fracture abundance across a horizontal section of the upper Cohassett flow is approximately 18 fractures per meter. Unfilled fractures constitute at most 20% of all fractures. The unfilled fracture abundance ranges from about 0.8 to 3.6 fractures per meter. The fracture porosity of the Cohassett basalt flow interior conducive to vertical flow is approximately 10^{-5}; this vertical fracture porosity is based on the assumption that there are 3.6 fractures per meter. A fracture abundance of 0.8 per meter yields a fracture porosity of 4×10^{-6}. The document attributes the smaller porosity to that which would be representative of horizontal fracture porosity (p. 28).

The document describes the two field scale groundwater tracer experiments that were conducted at boreholes DC-7 and DC-8 within the McCoy Canyon flow top. The boreholes are located approximately 24 km from the site of the exploratory shaft. The boreholes are approximately 16.7 m apart at the McCoy Canyon flow top. The interpreted thickness of the flow top that contributes to flow is about 11.3 m. Core data and dynamic logging techniques indicate that the primary zone of lateral hydraulic conductivity may be as small as 1 m. The document states that breakthrough of the tracer during the experiment was abrupt which is characteristic of the type of response that would be expected within a fracture type flow model. The document states that the projected mass balance from tracer recovery indicates that dual porosity was not evident at the time scale of the experiment. Estimates of effective thickness of the McCoy Canyon flow top are between 0.0018 and 0.0030 m, based on analysis of the DC-7/8 tracer experiment. Effective thickness is defined as the product of effective porosity and the appropriate thickness (p. 30). The range in estimated effective porosity is 1.6×10^{-4} to 3.3×10^{-3}. Transmissivity calculated from the tracer experiment is 7.5×10^{-7} m^2/sec and storativity is 3×10^{-5}. The document states some limitations of the tracer test. The document states that the results "cannot be unequivocally extrapolated to different locations and scales" (p. 31).

The document outlines the results of the survey of experts. The Delphi method and the probability encoding technique of SRI were used. The purpose of this study was to obtain unbiased expert estimates of effective porosity of basalt flow tops and flow interiors and the hydraulic anisotropy ratios of the flow interior of the Cohassett flow. Values were obtained from the panel on a macroscale of 1 to 10 m and on a megascale of 100 to 1,000 m (p. 32). Five independent experts and three Rockwell experts were used in the process. The document states that "Because the quantity of relevant field data was limited, the experts found it necessary to rely extensively on their own conceptual models and broad professional experience" (p. 32). The panel of independent experts included Stanley Davis, Paul Fenske, Lynn Gelhar, Shlomo Neuman and Charles Wilson. The in-house (Rockwell) experts included Roy Gephart, Leo Leonhart, and Frank Spane. The document presents the 10 percentile, the median value, and the 90 percentile for the megascale and the macroscale. The values are tabulated for each expert although the opinions are not identified by their source. The mean and median of the experts' opinions are presented also. The document states that the mean effective porosity of the median values on a megascale for the Cohassett flow top is 2.4×10^{-2}. The median value is 1.4×10^{-2}. The mean of the median values of effective porosity for the Cohassett flow top on a macroscale is 2.3×10^{-2}; the median value is 1.3×10^{-2}. The mean of the median values of all expert opinions for effective porosity for the Cohassett dense basalt interior is 1.6×10^{-3} for the megascale and 1.7×10^{-3} on the macroscale.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The document is important to the Waste Management Program because it documents the available data on effective porosities and apparent porosities for the basalts at the Hanford site. Effective porosities are required for the calculation of groundwater travel time. This document includes expert opinion as well in-situ measurements at one location within one basalt flow top. The compilation of textbook, technical report, expert opinion, and core analysis plus one in-situ tracer test constitute the sum of the knowledge of porosities for basalts at the Hanford site at this time.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

Apparent porosity values obtained from basalt core samples are appended to the report as histograms. The histograms include distributions for all the candidate horizons as well as histograms for specific portions of a given basalt flow. The apparent porosity distribution for the Cohassett flow top is obtained from three wells (RRL-2, RRL-6, and RRL-14). Only 26 representative core values are available for apparent porosity. The samples are not independent; the samples are too small to be significant. The sampling is biased because the samples obtained for a given portion of a flow were obtained from only three holes. The number of samples that is portrayed as being representative of the portion of the flow that was cored and tested is not represented accurately.

The histograms of apparent porosity values included at the front of Appendix A are derived from core; they were obtained from all the candidate basalt flows for the specified portion of the flow. This procedure increases the number of samples used for the distribution. The number of samples is still restrictive because most of the samples were obtained from only three boreholes. For instance, 122 laboratory determinations of apparent porosity are shown on the histogram from the candidate horizons in the Grande Ronde basalts within the flow tops which includes the flow top breccia. The 122 samples were obtained from boreholes RRL-2, RRL-6 and RRL-14.

The report does not discuss the problem of scale adequately. The difficulty in extrapolating from the scale of a core sample to the larger scale that is required for predicting travel time is noted in the document. The problem of extrapolating from the scale of a tracer test to the scale required for predicting travel time is stated in the document. However, the report fails to address how the divergent scales of measurements for porosity can be combined into a meaningful distribution of values that can be used to predict travel time.

The discussion on probability distributions for porosity is incomplete. The document refers to published papers which suggest that porosity is distributed normally. The document also cites another reference which states that porosity may be lognormally distributed in a fractured crystalline rock. These references and the document under review fail to discuss adequately the problem of scale with respect to the distribution of porosity values. The distribution of porosity is a scale problem which is especially relevant to a fractured media. The scale of sampling and testing may readily determine the distribution of porosity values for a given medium at a given site.

The use of expert opinion to determine approximate values of porosity is of questionable value. Valid expert opinion on the porosities of basalt is difficult to acquire because of the lack of experience of the majority of hydrogeologists in field testing basalt rocks. We believe that the use of expert opinions should be minimized for the quantification of porosities because very few experts exist.

REFERENCES CITED:

Foundation Sciences Inc., 1980, Thermal/Mechanical Properties of Pomona Member Basalt--Full-Scale Heater Test #1 (Area 1). Rockwell Hanford Operations, Richland, WA, RHO-BWI-C-77.

Foundation Sciences Inc., 1980, Thermal/Mechanical Properties of Pomona Member Basalt--Full-Scale Heater Test #2 (Area 2). Rockwell Hanford Operations, Richland, WA, RHO-BWI-C-85.

Foundation Sciences Inc., 1980, Thermal/Mechanical Properties of Pomona and Umtanum Basalts--Elevated Temperature Comparative Triaxial Test. Rockwell Hanford Operations, Richland, WA, RHO-BWI-C-91.

INTERA Environmental Consultants, Inc., 1983, Porosity, Permeability and Their Relationship in Granite, Basalt, and Tuff. Prepared for Battelle Memorial Institute, Office of Nuclear Waste Isolation, Columbus, OH, ONWI-458.

Mercer, J.W., Thomas, S.D., and Ross, B., 1983, Parameters and Variables Appearing in Repository Siting Models. Prepared by GeoTrans, Inc. for the U.S. Nuclear Regulatory Commission, NUREG/CR-3066.

Snow, D.T., 1968, Rock Fracture Spacings, Openings, and Porosities. Journal of the Soil Mechanics and Foundation Division, Proceedings of the American Society of Civil Engineers, January 1968, p. 73-91.