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MEMORANDUM FOR: Myron Fliegel, Section Leader
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SUBJECT: ROCKWELL HANFORD OPERATIONS DOCUMENT SD-BWI-TI-254 "EFFECTIVE POROSITIES OF BASALT: A TECHNICAL BASIS FOR VALUES AND PROBABILITY DISTRIBUTIONS USED IN PRELIMINARY PERFORMANCE ASSESSMENTS"; LOO ET. AL., 1984

Attached please find a review of the subject document. The review indicates that the document presents an unconvincing rationale for its selection of ranges and distributions for basalt effective porosities. The selection is considered by this reviewer to be non-conservatively biased. I strongly question the appropriateness of the use of the suggested ranges and distributions in repository performance assessment.

I recommend that this review be transmitted to BWIP and other interested parties.

Original Signed By

Matthew Gordon
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Enclosure:
As stated

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DOCUMENT REVIEW: "EFFECTIVE POROSITIES OF BASALT: A TECHNICAL BASIS FOR VALUES AND PROBABILITY DISTRIBUTIONS USED IN PRELIMINARY PERFORMANCE ASSESSMENTS", LOO ET.AL., SD-BWI-TI-154, ROCKWELL HANFORD OPERATIONS, 1984

EXECUTIVE SUMMARY

The subject document presents a rationale for the selection of particular suggested ranges and probabilistic distributions of effective porosity to be used in repository performance assessment. Loo et. al. suggest a range from 10^{-4} to 10^{-2} for basalt flow tops (median 5 x 10^{-3}) and from 10^{-6} to 10^{-3} (median 5 x 10^{-4}) for basalt flow interiors. Loo et. al. suggest the use of a uniform probability distribution to describe the relative likelihoods of effective porosities within each of the two ranges.

Loo et. al. fail to present a convincing rationale for their selection of ranges and distributions of effective porosity. Based on my review of the document, its supporting literature and a consideration of transport in fractured media, I consider that the effective porosity range for the basalt flow tops should be centered about a value at least an order of magnitude lower, and have a lower upper limit, than Loo et. al. suggest. There is insufficient information available to support or refute Loo et. al.'s suggested range and distribution for flow interior effective porosity. Also, the probability distribution might be better characterized as a log-uniform distribution, rather than a uniform distribution.

1 INTRODUCTION: BASIC CONCEPTS

Effective porosity is a key parameter in determinations of ground-water travel time and advective radionuclide transport. For a given head gradient ($\frac{dh}{dl}$) and hydraulic conductivity (K), a smaller effective porosity (n_e) results in a a higher linear fluid velocity (v) according to the following equation (Bear (1979)):

$$V = \frac{-K}{n_e} \frac{dh}{d\ell} \qquad (1)$$

In the field, what is generally measured is transmissivity (KH) and effective thickness (n_eH) for an interval of thickness H. For horizontal flow, equation (1) can be rewritten as:

$$V = \frac{-KH}{n_e H} \frac{dh}{d\ell} \qquad (2)$$

In fractured media such as basalt, the flow of ground water takes place principally through the unfilled fractures (cf., Hsieh et. al.). For horizontal flow the transmissivity of a fractured interval is thus equal to the sum of the transmissivities of the connected fractures. If the number of fractures present is large (how large is as yet undefined) compared to the scale of interest, the medium may be approximated as an equivalent porous medium. The bulk hydraulic conductivity of this equivalent porous medium is defined as the transmissivity of the fractured interval under consideration, divided by the total thickness of the fractured interval. The bulk hydraulic conductivity will be much lower than the conductivity of the fractures themselves.

The bulk hydraulic conductivity is useful for estimating flux across a cross-sectional area of a fractured interval. When calculating groundwater flow velocities, however, one must correct the flux by the effective porosity term. Thus the effective porosity of a fractured medium being treated as an equivalent porous medium is essentially a correction factor which accounts for the fractured nature of the medium. The effective porosity of a fractured interval which has low matrix hydraulic conductivity is equal to the fraction of unfilled fracture volume per bulk volume of rock. The porosity of the rock matrix, called the "primary" porosity, does not affect the advective flow velocity (cf., Hsieh et. al.). (It may affect retardation of solutes through the process of matrix diffusion). Because the matrix porosity is neglected, the effective porosity, or "effective fracture porosity" can be many orders of magnitude less than the total porosity of the basalt, and can be expected to be much less than usually encountered in unfractured media.

The effective porosity of the fractured interval to be used in performance assessments which apply the "equivalent porous medium" approximation (single- or dual-porosity) is generally much less than the effective porosity of an intact (unfractured) block of rock. This may seem counter to intuition; i.e., how can the presence of fractures in an otherwise tight rock manage to reduce effective porosity? This is explained by the following: Consider a 1-meter thick flow top fractured interval, as shown in Figure 1. This interval contains two orthogonal sets of unfilled fractures, one set as shown in Figure 1a and the other set parallel to the plane of the figure. Consider there to be four fractures per meter for each set, with equal fracture apertures (b) of ten μm. The hydraulic conductivity of each fracture (K_f) is given by (cf., Schrauf and Evans, 1984):

$$
\begin{aligned}
K_f &= (\rho g/\mu)(b^2/12) \\
&= 8 \times 10^{-5} \text{ m/sec}
\end{aligned}
$$

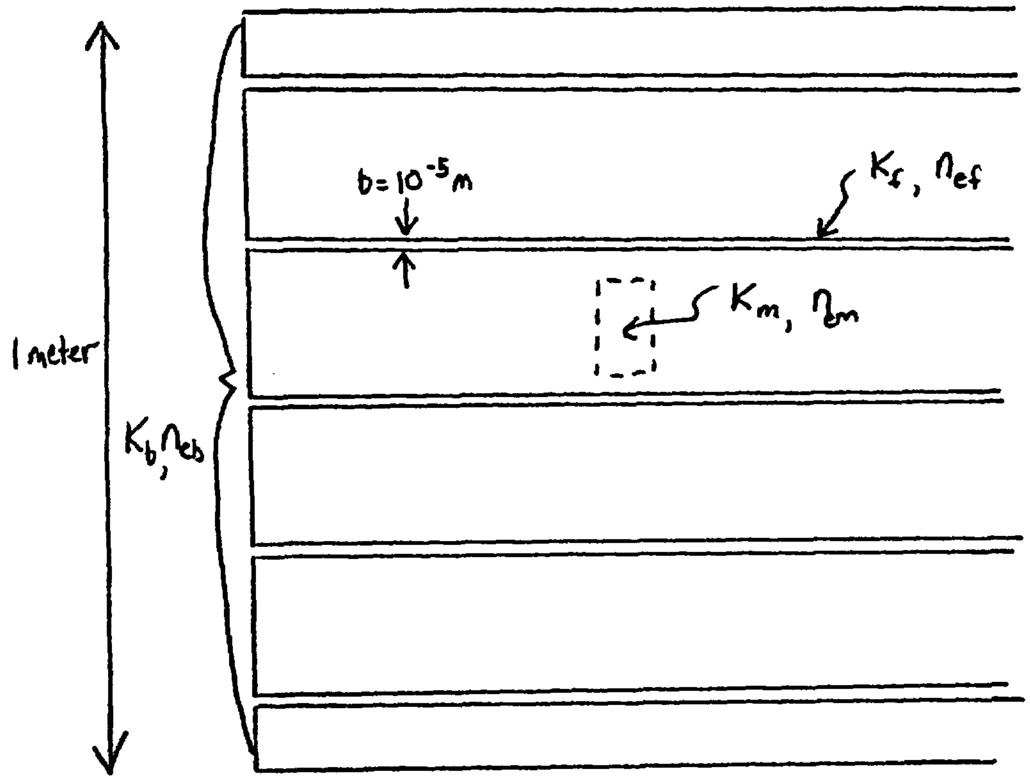

Figure 1a: Conceptual Model of Fractured Medium. Notation explained in text. (Side view, vertical cross-section) not to scale

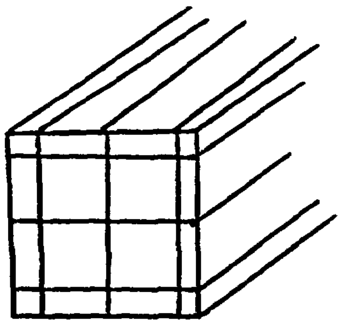

Figure 1b: Head-on view, no scale

FIGURE 1: Definition sketch for fractured interval conceptual model

where ρ is the fluid density, μ is the fluid dynamic viscosity, and g is the gravitational acceleration constant. The transmissivity of each fracture (T_f) is then:

$$\begin{aligned} T_f &= K_f b \\ &= 8 \times 10^{-10} \text{ m}^2/\text{sec}. \end{aligned}$$

The total transmissivity of all of the fractures in the interval is 6.4×10^{-9} m²/sec (T_f x (4 fractures/set in interval) x (2 sets)). The effective porosity of each open fracture (n_{ef}) is 1.0. Assume that the hydraulic conductivity of the intact rock blocks (called the rock matrix) between the fractures has been found to be 10^{-12} meters/second, and that the effective porosity of the rock matrix (n_{em}) is 0.5% (or 0.005). The transmissivity of the entire rock matrix in the interval is thus 10^{-12} m²/sec (K_m x 1 meter interval). The total transmissivity of the interval is the sum of the total transmissivities of all of the fractures and all of the matrix.

Thus far we have considered the medium in Figure 1 in terms of discrete fractures surrounded by discrete rock matrix blocks. Now consider treatment of the interval as an "equivalent porous medium," which has been BWIP's general approach for performance assessment. Since the matrix hydraulic conductivity is much less than the fracture hydraulic conductivity, it is commonly assumed that substantially all fluid flow occurs within the fractures (cf., Nguyen, 1983). In our sample case, this appears to be true, since the fractures contribute 99.98% of the total interval transmissivity. The equivalent porous medium "bulk" hydraulic conductivity is then defined by the transmissivity of each fracture times the number of fractures in the interval (N) divided by the total width (H) of the interval, or (Freeze and Cherry, 1979):

$$\begin{aligned} K_b &= (2\rho g/\mu)\ (Nb^3/12H) \\ &= 1.6 \times 10^{-9} \text{ m/sec} \end{aligned}$$

with the factor of two appearing because there are two sets of contributing fractures. Note that K_b is more than four orders of magnitude less than K_f. Since flow is occurring predominately through the fractures, the effective porosity of this interval is equal to the volume of the fractures divided by the total volume, or:

$$\begin{aligned} n_{eb} &= (2Nb/H) \\ &= 8 \times 10^{-5}. \end{aligned}$$

Note that the effective porosity of the bulk fractured medium (n_{eb}) is almost two orders of magnitude less than the matrix effective porosity (n_{em}). It is this bulk (equivalent porous medium) effective porosity that Loo et. al. are attempting to determine in the subject document. The validity of this approach rests on the assumption that the flux through the small volume of highly conductive fractures is much larger than the flux through the larger volume of very tight matrix rock. This assumption is generally considered to be appropriate for hard crystalline rocks such as basalt or granite (cf., Hsieh et. al., 1983). Evidence from the two Hanford site field tracer tests further suggests that the flux in the brecciated or fractured basalt flow tops is dominated by the fractures. Based on this evidence, and on the available literature, this assumption is considered likely to be valid for flow tops as well as flow interiors.

It is important to note (for reasons to be discussed later) that for equation (2) to hold, the interval thickness used in the transmissivity estimate must be the same as the interval thickness used in the effective thickness estimate. Similarly, if equation (1) is to be used, the measured effective thickness and transmissivity must be divided by the same interval thickness to arrive at the appropriate K and n_e values.

The "effective porosity" of a rock sample differs from the sample's "apparent porosity" and its "total porosity". The definitions of the three quantities are provided below:

$$n_t = \frac{\text{total volume of voids}}{\text{bulk volume of rock}}$$

$$n_a = \frac{\text{volume of interconnected voids}}{\text{bulk volume of rock}}$$

$$n_e = \frac{\text{volume of interconnected voids contributing to flow}}{\text{bulk volume of rock}}$$

In general, $n_e \leq n_a \leq n_t$. In fractured media, n_e may be much less than n_t, and could be less than n_a. It is also important to note that the apparent porosity n_a includes non-isolated dead end fractures, and non-isolated matrix porosity. There has been no generic relationship established between n_e and either n_a or n_t. This relationship is specific to the unit being tested, if it can be established at all.

2 CRITIQUE OF LOO ET. AL. (1984)

Loo et al. (1984) base their suggestion of ranges and distribution of effective porosity to be used in modeling on the following:

1) generic values for basalt in literature
2) tests of Hanford basalt core
3) a calculation using observed fracture characteristics
4) two tracer tests
5) solicitation of expert opinion

Loo et al's treatment of each of these sources is critiqued below:

2.1 Effective Porosities Derived from Technical References

Loo et al. cite literature values of total and apparent porosities (Section 3.0). As noted above, these quantities are not directly comparable to effective porosity, and are, in fact, larger than effective porosity.

Loo et al. selectively cite some total porosity values from basalts provided in Freeze and Cherry (1979) (between 0.1 and 10%). Loo et. al. fail to cite the following information, provided in the same text (p. 408) regarding effective porosities of fractured rocks:

> "The effective fracture porosity of fractured rocks and of consolidated cohesive materials that are fractured, such as jointed till, silt, or clay, is normally very small. Values on the order of 1-0.001%, or 10^{-2} to 10^{-5} expressed as a fraction, are not unusual. Although the porosities are small, the groundwater velocities can be large."

The only document cited by Loo et al. which appears to discuss "effective porosities" is Guzowski et. al.'s (1972) compilation of total and effective porosities of basalts from laboratory tests throughout the world. However, as Loo et. al. note (p. 18), "Guzowski et. al. refer to effective porosities, but the meaning is consistent with apparent porosities as defined herein." Further, laboratory tests have inherent limitations which result in non-conservative (high) estimates of effective porosity, as discussed in the next section.

Based on the above, the literature values cited by Loo et. al. are considered to be of little or no use in estimating the effective porosity of Hanford basalts, even as a "first-order approximation." To be used as a first-order approximation, Loo et. al. must propose some relationship between effective porosities and total or apparent porosities.

2.2 Effective Porosity Estimates Derived from Laboratory Experiments

Loo et. al. cite laboratory data collected by Colorado School of Mines (CSM) and Foundation Sciences Inc. (FSI). The data represent total and apparent porosities. As discussed above, there is no clear basis of comparison for total or apparent porosities with effective porosities.

The laboratory experiments were performed on Hanford basalt cores. It is stated that intact rock samples were used for the laboratory analyses. Through-running fractures, which may be important on a scale larger than the intact cores, may not be represented in the intact cores. Thus a test for effective porosity performed on an intact lab sample would actually yield the effective porosity of the matrix, which would be much higher than the effective porosity of the fractured interval, which governs the fluid velocity. On the other hand, if a smaller but non-zero number of through-running fractures is contained in the sample than is representative of the field, an effective porosity determination on the lab sample may be smaller than that in the field. In any case, by measuring apparent rather than effective porosities, the matrix porosity is included in the laboratory determination, thus yielding higher values of effective porosity.

Core samples are generally disturbed by the drilling process and are likely to have more fractures than an intact in-situ rock sample. This would cause higher (non-conservative) total, apparent and effective porosity estimates.

The laboratory tests were performed at atmospheric pressure with no adjustment for in-situ conditions. This is likely to result in high (non-conservative) estimates since the absence of the overburden lithostatic load allows the decompression of the sample and opening of fractures. The release of the high lithostatic pressure during coring may even induce new fractures in the sample, similarly to the discing phenomenon frequently encountered during coring.

Based on the above discussion, the utility of the laboratory core analyses in estimating the effective porosities is considered to be strongly questionable. Loo et. al. must provide a relationship between apparent porosities and effective porosities, between disturbed core properties and in-situ properties, and between sample properties at atmospheric pressure and in-situ pressure.

Loo et. al. (1984) suggest that the values from laboratory estimates are useful for approximating "the upper limit of in-situ effective porosities for the basalts" (page 27). This statement is true in the sense that the effective porosities can not be any larger than the laboratory values. However, the statement is untrue in the sense that there is no basis for assuming that the effective porosities can be as large as the laboratory values. This is important, since the probability distribution chosen by Loo et. al. to describe the effective porosity is dominated by the upper limit, as discussed in more detail below. A high upper limit will therefore yield very non-conservative results.

2.3 Effective Porosity Estimates from Fracture Characteristics

Assuming two orthogonal sets of vertical fractures in basalt flow interiors, Loo et. al. use a variation of the cubic law relationship to calculate an equivalent fracture effective porosity, based on measurements of the bulk hydraulic conductivity and fracture frequency. Loo et. al. estimate that the fracture abundance ranges from 4 fractures per meter (as measured in RRL-2 Cohassett interior cores) to 18 fractures per meter (as measured across a horizontal traverse of upper Cohassett flow surface exposure). It is not clear whether the "upper Cohassett flow" includes the flow top. If so, the fracture abundance may not properly reflect conditions in the flow interior. Also surface exposures could be more fractured than flows at depth, due to weathering and the absence of lithostatic loading. Cores may also have higher fracture abundance than in-situ flows, due to mechanical drilling disturbances and stress-relief-induced fractures, as discussed in Section 2.2.

Based on the "4 to 18 fractures per meter" range, and an assumption that "unfilled fractures make up at most 20% of all fractures," Loo et. al. arrive at an estimate of unfilled fracture abundance between 0.8 and 3.6 fractures per meter. Loo et. al. have thus assumed that the maximum percentage of unfilled fractures (20%) exists. This is non-conservative in that if a lower percentage of unfilled fractures exist, the resultant effective porosity estimate, as well as calculated groundwater travel times, would also be lower.

As discussed above, the assumptions made by Loo et. al. would tend to overestimate the fracture frequency, thus leading to overestimates of effective porosity. Therefore, Loo et. al.'s conclusion that the resultant estimate of effective porosity would be on "the low end of the range for dense basalt effective porosity" is questionable.

2.4 Effective Porosities Determined by Tracer Tests

Two tracer tests have been performed on the Hanford site at boreholes DC-7/8. (Loo et. al. claim that both tests were performed within the McCoy Canyon flow top; however, the documentation of the earlier test provided in Gelhar (1982) suggests that the tested zone may have actually been the overlying "Grande Ronde #9" flow.) Gelhar (1982), describing the analysis of the earlier test, has been reviewed by Gordon and Coleman (April 1984). Gordon and Coleman raised some questions about the earlier test, almost all of which related to inadequate documentation. The methodology behind the test, however, was endorsed by Gordon and Coleman. NRC considers that direct field testing, when feasible, is always preferable to generic estimates or expert opinion.

The values of effective thickness (nH) derived from both tracer tests were very low (between 0.0018 and 0.003m for a total logged thickness of 11.3 m). Loo et. al. note that the effective interval thickness may be less than the total logged thickness of 11.3 m, resulting in a range of estimates of effective porosity between 1.6×10^{-4} to 3.3×10^{-3}. The use of the lower end of the estimated effective interval thickness (1 meter) is responsible for the higher end of the effective porosity estimate (3.3×10^{-3}). Site characterization and repository performance assessment are generally performed at scales of at least tens of meters. It is inappropriate to consider the higher end of this range as representative of effective porosities to be used in performance assessment.

It must be remembered that the validity of equation (2) rests on the interval thickness (H) used for transmissivity and for effective thickness being identical. If measured transmissivities are converted to hydraulic conductivities, and effective thicknesses to effective porosity, the interval thickness used in this conversion must also be identical. Therefore, the value of effective porosity used in transport calculations could be assumed to be anywhere in the range noted, as long as the hydraulic conductivity is adjusted accordingly (directly proportionally increased with use of the higher effective porosity valves). By the same token, as long as measured transmissivities and measured effective thicknesses for the same interval thicknesses are used in equation (2), no adjustment for "effective" interval thickness is necessary.

Loo et. al. note that the measured effective porosities may apply only to a "thinner, less indurated zone within the tested interval," and may not be representative of the larger-scale effective porosity of the flow top, which is presumably more indurated. The more indurated zones would presumably have a lower effective porosity. Therefore, it is not clear why Loo et. al. assume the tracer test results to be indicative of the low end of the effective porosity range.

The measured values are the best estimators currently available for effective porosity of the Hanford basalts. Therefore, it is recommended that BWIP provide more weight to the measured values in future performance assessments than suggested by Loo et. al.

2.5 Effective Porosities Derived from Poll of Expert Panel

For further estimates of effective porosity, Loo et. al. describe the results of poll of a panel of five experts. It is highly unusual to utilize expert opinion to guess at values of quantities that are directly measurable. As Loo et. al. state, expert opinion should not be used as a substitute for field data. The problems with the usage of expert opinion are evidenced by the wide disparity in their opinions (Davis (1984)).

The expert consultants considered that the rock matrix porosity would substantially contribute to the effective porosity of the fractured medium (Davis, 1984). However, Loo et. al. note that the two in-situ tracer tests performed indicated "no dual-porosity response". What Loo et. al. mean by this statement is that no matrix diffusion appeared to take place, and that the flux and velocity of the tracer appeared to be dominated by the fractures. This observed response may be due to the short duration and small scale of the test. However, the test results provide some evidence that the fractures may be dominating the flux and fluid velocity, and that the volumetric fracture effective porosity is the porosity value which should be used in the transport calculations. The panel, therefore, may have overestimated the contribution of matrix porosity to effective porosity, thus yielding the rather higher-than-measured estimates.

The expert panel provided effective porosities to be applied at each of two scales: "macro" (up to tens of meters) and "mega" (up to hundreds of meters). Due to the potential lack of connectedness of fractures on larger scales, it is surprising that the experts' median of macro-scale effective porosity is higher than the median of mega-scale effective porosity.

2.6 Probabilistic Distribution Assigned to Effective Porosity

Loo et. al. suggest the use of a uniform distribution to represent the probability density function of effective porosity for each of the two rock types (flow interiors and flow tops). They note that a "uniform distribution is likely to be appropriate because it reflects an assumption that any value in the range is as likely as any other value." Loo et.al. make this assumption despite the evidence from apparent porosity data presented in Appendix A which "suggests that a long-normal probability distribution may be considered to represent values of effective porosity for flow interiors." I would agree with Loo et. al. that the evidence for a log-normal distribution is inconclusive. However, the evidence suggests that a log-normal distribution would be reasonable and conservative.

Alternatively, the assumption of a log-uniform distribution, which is suited for parameters with unknown distribution but which have ranges of uncertainty spanning several orders of magnitude, is considered reasonable and more appropriate than a uniform distribution. A uniform distribution assumption for the given effective porosity ranges implies a mean (and median) of 5×10^{-3} for flow tops and 5×10^{-4} for the flow interiors. A log-uniform distribution implies a median of 1×10^{-3} for flow tops and 3×10^{-5} for the flow interiors.

Figure 2 presents a comparison of the cumulative distribution function (CDF) of a log-uniform distribution with a uniform distribution for the Loo et.al. range of basalt flow interior effective porosities. The abscissa indicates the probability that the effective porosity will be less than or equal to the value of effective porosity on the axis for the given distribution. The CDF of the log-uniform distribution is linear (sometimes called "triangular") on the log scale. It is evident from this figure that the uniform distribution assigns a very low probability to low values of effective porosity within the assigned range. In fact, the CDF of the uniform distribution would remain essentially unchanged regardless of the lower limit of the range. For example, if the lower limit of the range were decreased from 10^{-6} to 10^{-35} or even 10^{-135}, the median of the distribution would still be 5×10^{-4}. Thus, the choice of the upper limit is the controlling factor when the uniform distribution is assigned. I consider this appropriate only in cases where the upper limit is chosen reasonably and conservatively, which I do not consider to be the case for Loo et. al. for reasons described in the previous section.

As an additional note, it is useful to distinguish here between uncertainty in the median value, which is represented by the ranges provided by Loo et. al, and the spatial variation of actual values in the field. Ideally, the uncertainty range should reflect the expected spatial variation. Since there are only one or two data points, it is not possible to reliably estimate the spatial variance in effective porosity for the Hanford site basalts. Loo et. al. do not make any statements about the range in spatial variance (or standard deviation) of values of effective porosity. If the spatial variation is much less than the range of uncertainty in the median values, the uniform distribution assigned to the uncertainty range is not appropriate and non-conservative for use in spatial variation performance studies.

3 SUMMARY AND CONCLUSIONS

The rationale for the selection of the ranges of basalt flow top and basalt flow interior effective porosities is not well-supported by Loo et. al. The upper limits of the ranges are higher than can be supported by existing data. The importance of the upper limit is compounded by the choice of a uniform probability distribution, which essentially ignores values on the low end of the ranges. The ranges and the distributions suggested by Loo et. al. are very non-conservative based on existing data. I consider that the in-situ test data should be weighted far more heavily than literature values of "total" porosity, expert opinion, or core analyses of "apparent" porosity in the suggestion of a range; as a median, for example, rather than a lower limit. The choice of

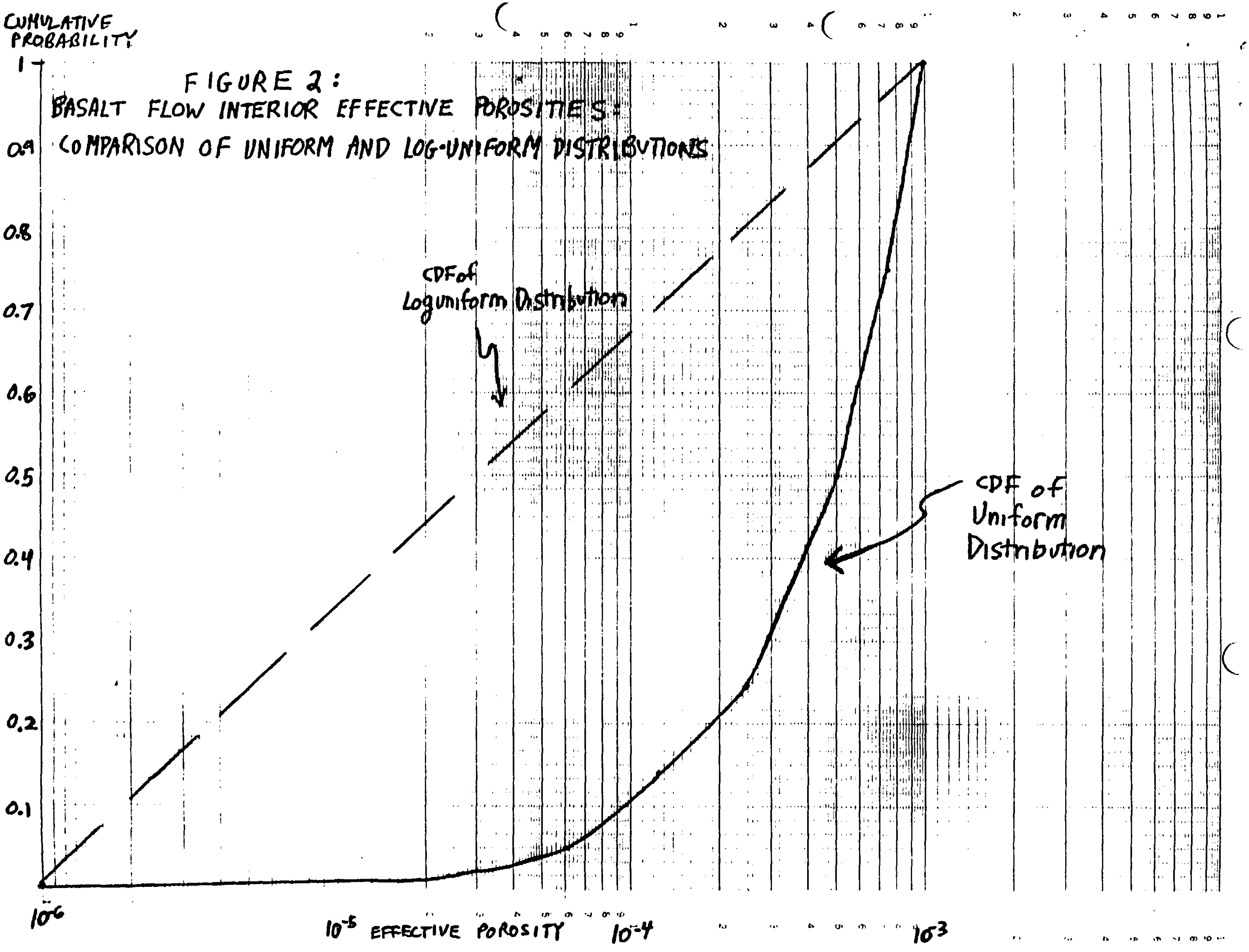

FIGURE 2: BASALT FLOW INTERIOR EFFECTIVE POROSITIES: COMPARISON OF UNIFORM AND LOG-UNIFORM DISTRIBUTIONS

effective porosity values to be used in performance assessment is a critical one, and Loo et. al's highly non-conservative suggestions should be rejected for use in repository performance assessments.

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Acknowledgement: The reviewer benefitted from discussions with Neil Coleman and Dan Goode, also of the Hydrology Section, during the preparation of this review.

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