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CRITICAL COMMENTS ON

"REVIEW OF GROUNDWATER TRAVEL TIME ANALYSIS FOR THE REFERENCE REPOSITORY LOCATION AT THE HANFORD SITE",
Terra Therma/Nuclear Waste Consultants (June 13, 1986)

AND ON

"RE-REVIEW OF CLIFTON'S BWIP GROUNDWATER TRAVEL TIME ANALYSIS",
Terra Therma/Nuclear Waste Consultants (January 13, 1987)

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EXECUTIVE SUMMARY

Two reports prepared by Terra Therma/Nuclear Waste Consultants (TT/NWC) for the Nuclear Regulatory Commission (NRC) were reviewed in detail. The first report, entitled "Review of

Groundwater Travel Time Analysis for the Reference Repository Location at the Hanford Site" was submitted on June 13, 1986 as TT/NWC Communication No. 65 in response to written direction from the NRC Project Officer (Mr. J. Pohle (NRC)). The second report is entitled "Re-Review of Clifton's BWIP Groundwater Travel Time Analysis". This second report is a review of the previous review and replies to the NRC Staff's request that:

(1) assumptions made in the TT/NWC evaluation be documented and their impact on the result be evaluated;

(2) an assessment be made of the uncertainties associated with the TT/NWR computed groundwater travel time; and

(3) an evaluation be made of the sufficiency of the data base used for calculating groundwater travel time (GWTT) in both the TT/NWC and the Clifton (1986) reports.

This report will mainly review the second TT/NWC report, which supersedes and corrects an error present in the first one. In these two documents, TT/NWC submit that the computations of total travel time by Clifton (1986) are not conservative and that "... there is significant likelihood that the BWIP will fail the 1000 year travel time rule" (TT/NWC, 1987, p. 9). Our present comments address the main contentions of the two TT/NWC reports. Although TT/NWC raises some valid points, their two main conclusions, namely that: (1) the effective porosity value is overestimated, and (2) that further investigations should be focused on measurements of effective porosity, are open to serious criticism.

A. INTRODUCTION

This is a detailed discussion and critical evaluation of the "Review of Groundwater Travel Time Analysis for the Reference Repository Location at the Hanford Site" (dated June 13, 1986) and the "Re-Review of Clifton's BWIP Groundwater Travel Time Analysis" (dated January 13, 1987), prepared by Terra Therma/Nuclear Waste Consultants (TT/NWC) for the Nuclear Regulatory Commission (NRC). Our comments deal mainly with the Re-review report, which supersedes and corrects an error present in the first report.

In the first part of our review, an analysis of the approach employed by TT/NWC to evaluate groundwater travel time (GWTT) in regards to compliance with Department of Energy (DOE) 10 CFR 960.4.2.1(d) and NRC 10 CFR 60.113.B.(2) is presented. In the second part of our review, the main arguments of the TT/NWC reports are discussed. Finally, recommendations are made concerning future field investigations needed to evaluate GWTT in regards to compliance with cited regulations.

B. MAJOR COMMENTS ON TT/NWC APPROACH

I. "Conservative" Approach and "Statistical" Approach

In their Re-review report (TT/NWC, 1987), TT/NWC discuss the differences between the "conservative" and the "statistical" approaches. The objective of this discussion is to distinguish between the conservative and the statistical approach in reliability analysis, and in particular, in the calculation of GWTT. Their discussion successfully makes this distinction, which after all, is well accepted in reliability or risk analysis. However, a few comments can be made on the TT/NWC work.

On page 13 of the Re-Review (TT/NWC, 1987), it is stated that

> "Both the Clifton and the NWC analysis use a mixture of the 'conservative' approach and the 'statistical' approach: both use the 'statistical' approach for the inclusion of parametric variability and uncertainty into the analyses, and both use the 'conservative' approach for the inclusion in the analysis of uncertainty about flow paths and conceptual models."

If both Clifton (1986) and TT/NWC (1987) use the conservative approach for inclusion of uncertainty about flow paths and conceptual models, it is not correct that TT/NWC use the statistical approach for inclusion of uncertainty into their analysis. For instance, TT/NWC (1987) use the simple formula

$$t = nL/Ki \qquad (1)$$

where n is the effective porosity, L is the distance to compliance surface, K is the hydraulic conductivity, and i is the hydraulic gradient, to evaluate the GWTT probability distribution P(t) in the flow top of interest. To obtain P(t), TT/NWC (1987) assume that n and K are lognormal and subject to estimation errors only. Consequently, t is lognormally distributed with known mean and variance. As shown in the Yakima Nation comments on the DOE GWTT analysis (Djerrari et al., 1986), this model presumes a vanishing integral scale of transmissivity (as compared to the travel distance). TT/NWC (1987) is aware of this limitation. Furthermore, as demonstrated (Djerrari et al., 1986), the resulting P(t) leads to travel times larger than the one corresponding to a large integral scale. TT/NWC (1987) assumes, ~~correctly,~~ that if the site does not pass the regulatory requirements for the above model, it will definitely fail in the case of a finite integral scale, all other assumptions being the same. This, therefore, demonstrates that the TT/NWC (1987) approach of uncertainty is a conservative approach rather than a statistical aprroach.

On page 13 of TT/NWC (1987), it is stated that the uncertainty (presumably quantified by a variance or confidence interval) in the estimate of uncertainty is usually small compared to the uncertainty in the computed quantity. This statement is erroneous. The estimation variance of the variance or the range can be anything but small. Consequently, the uncertainty regarding estimation variances and confidence intervals can be quite significant.

II. Proper Accounting for Uncertainties In Parameters and Analyses

On page 14 of TT/NWC (1987), it is stated that

> "... the variance of the log of the GWTT is greater if any of the components are positively correlated with each other..."

This implicitly assumes that all components appear with the same sign in the equation which determines the logarithm of GWTT. However, if one considers the following relationship

$$\log(GWTT) = c + \log(be) - \log(T) \qquad (2)$$

where c is a constant, be is the effective thickness, and T is the transmissivity, and also considers the relation defining the variance,

$$\mathrm{Var}[\log(GWTT)] = \mathrm{Var}[\log(be)] + \mathrm{Var}[\log(T)] - 2\,\mathrm{Cov}[\log(be), \log(T)] \qquad (3)$$

it can be seen from relation (3) that a positive correlation between be and T (which may be the most likely case), if taken into account, would reduce the variance of log(GWTT). This fact was illustrated in Clifton (1984).

TT/NWC (1987) concluded:

> "It is significant that the application of this simple approach does indeed produce values of variance for the GWTT that are close to those derived from the Clifton numerical analyses (Appendix D). That these two radically different approaches produce essentially the same estimate of variability in the result is considered to be generally supportive of both, and indicative that the method of computing variance in GWTT does not introduce significant uncertainty into the evaluation of regulatory compliance."

TT/NWC (1987) clearly presented the differences between Clifton's conservative approach and their conservative approach. These differences arise from the two different hypotheses tested. While Clifton tests the hypothesis that there is a high probability that the GWTT exceeds 1,000 years, TT/NWC (1987) test the hypothesis that there is a significant probability that GWTT does not exceed 1,000 years. TT/NWC (1987) appear satisfied that their simple approach produces values of variance for the GWTT that are close to those derived from the Clifton numerical analysis. Obviously, TT/NWC (1987) did not weigh the implications of such a result. Presently, the GWTT cumulative probability distribution functions (CDF) are computed with some degree of uncertainty. The impact of this uncertainty on the outcome of the tested hypothesis is less dramatic in Clifton's case than in the TT/NWC case. This is because Clifton is testing the extreme tail of the GWTT CDF, whereas TT/NWC are testing a higher probability.

For the outcome of the TT/NWC test to hold true, even in the case of large uncertainty in GWTT-derived CDF, the derived CDF must be steep (i.e., small GWTT variance). At the present time, this is unfortunately not the case.

1. Consideration of conceptual models

TT/NWC (1987) discuss four simplifications which, according to them, tend to yield results that overestimate the GWTT. Since the objective of TT/NWC is to reject the hypothesis that the favorable requirement is met, these assumptions are deemed "conservative". A brief discussion of these assumptions follows.

1.1 Flow takes place in the Grande Ronde Basalt

Since the hydraulic conductivity in the flow tops tends to increase as one moves upward from the repository horizon, this assumption tends to underestimate the GWTT. As a result, TT/NWC (1987) claim that the assumption of a flow path occurring in the Grande Ronde Basalt is very unconservative, with respect to Clifton's hypothesis. However, cited evidence indicates that the probability of paths penetrating far into the overlying layers of higher permeability is small. Thus, a probabilistic analysis in which this assumption is removed and a wider range of possible flow paths is taken into account, appropriately weighted by their probabilities of occurrence, might show that the error associated with this assumption is minor. It is recommended that such an analysis be performed since it is the only way to resolve this dispute.

It is noted that the TT/NWC (1987) argument is based on a partial interpretation of NRC regulatory rules and Department of Energy (DOE) siting guidelines. TT/NWC (1987) claim on page 18 that

> "As the regulatory rule (10 CFR 60) is written in terms of the 'fastest path' and the siting guidelines (10 CFR 960) are written in terms of 'any pathway', it might be reasonable when considering the regulatory test to look at pathways that enter the Wanapum as likely being the fastest, and to therefore include them in the analysis."

This is a quite singular interpretation of the regulatory text.

The regulatory rule (NRC 10 CFR Part 60 paragraph 60.113.B.(2)) states:

> "Geologic Siting:
> The geologic repository shall be located so that the pre-waste-emplacement groundwater travel time along the fastest pathway of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such a travel time as may be approved or specified by the Commission."

whereas the siting guidelines (DOE 10 CFR Part 960 paragraph 960.113.B.(2)) state:

> "A site shall be disqualified if the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment is expected to be less than 1,000 years along any pathway of likely and significant radionuclide travel."

In the above regulations, the term "likely" has been clearly cited. This means that the "fastest pathway" or "any pathway" should be weighted by its probability of occurrence. Obviously, if the "fastest path" is considered, no matter how small its probability of occurrence, it is highly probable that no site would qualify. For the usually assumed forms of probability distributions of hydraulic conductivity (e.g., lognormal), there is a finite (although very small) probability that each and every layer will be penetrated.

TT/NWC (1987) state on page 9 that

> "It is considered that the fastest path would in all likelihood involve the higher permeability flows of the Wanapum formation."

This statement has not been substantiated by any evidence and is gratuitous. TT/NWC (1987) should substantiate such a statement by demonstrating that the total travel time along such a path (which must account for (i) the travel time through the layered sequence of Grande Ronde Basalts, and (ii) the horizontal travel time in the Wanapum) is effectively less than the travel time along a pathway that occurs in the Cohassett flow top, for example, as considered by Clifton (1986).

1.2 Flow is mainly in the flow tops

If one ignores the delay caused by flow in the dense basalt interiors, the resulting GWTT would be underestimated. TT/NWC (1987) cited studies in which the degree of underestimation is presumed to be in the range of 5% to 10%. Consequently, this assumption would be on the conservative side in Clifton's testing hypothesis. It should be noted, however, that among the referenced studies, TT/NWC cited Clifton (1986). Figure 6 of Clifton (1986) displays the CDF of GWTT in basalt dense interiors (for different values of vertical to horizontal hydraulic conductivity ratios identifed as alpha). In Figure 7, Clifton shows the CDF of GWTT in Grande Ronde flow tops (for two sets of transmissivity statistical paramaters, calculated from a sample of transmissivities, including and not including data from boreholes DC-14 and DC-15). In order to assess the nonconservatism of the simplification that TT/NWC undertook by ignoring the GWTT in the flow interior, a GWTT characterized by a 60% chance of being exceeded has been derived from these curves. Following TT/NWC conservatism, the GWTT in basalt interiors has been extracted from the curves that overestimate the travel time (i.e, alpha equal to one). Whereas, the GWTT in Grande Ronde flow tops has been derived from the curve corresponding to the statistics obtained by excluding DC-14 and DC-15 transmissivity values. This simple operation yielded a GWTT of 35,500 years for the flow interiors and 79,400 years for the flow tops. The time spent in the flow interiors (following the TT/NWC conservative approach) is not a small percentage of the travel time spent in the flow tops, as stated by TT/NWC. This percentage has been found equal to be equal to 44% for the case of a 60% exceedance probability, and is even higher for greater exceedance probabilities. It is not a coincidence that TT/NWC turned to the regulations and stated that

> "Thus from a regulatory point of view, it seems reasonable to ignore the GWTT in the flow interiors on the grounds that it will never be able to be supported."

1.3 Flow in the vicinity of the RRL may be in any direction

The meaning of and/or justification for this assumption is not clear.

1.4 Flow path is highly heterogeneous with respect to flow parameters

It is not clear as to what is meant by "highly heterogeneous flow paths". A reasonable justification for the use of all Grande Ronde hydraulic conductivity data is presented in Appendix F of the TT/NWC (1987) report. Beyond that, however, it is stated on page 21 (TT/NWC, 1987) that

> "there is great heterogeneity in the point values of transmissivity in any flow top, and that any path of flow will pass through a wide variety of different transmissivity sections."

The point intended in the quoted statement is unclear. However, it certainly provides no justification for neglecting spatial variability or for using the average value of measured log transmissivity as effective log transmissivity, as done in TT/NWC (1987).

It is claimed on page 22 that

"If the analysis performed using these simplifications produces a result which has an acceptable level of regulatory confidence, then the uncertainty associated with the conceptualization used in the analysis is not significant, no matter how large."

The quoted statement is, at best, unclear. In fact, it appears to be in contradiction to the purpose of the conservative assumptions associated with the TT/NWC hypothesis, as presented on page 11. A more correct statement would be as follows:

"If the analysis performed using these simplifications produces a result on the basis of which the basalt site is disqualified, then the uncertainty associated with the conceptualization used in the analysis is not significant",

since presumably, relaxing these assumptions would tend to further reduce GWTT.

However, if some important assumptions made in the Re-review (1987) were relaxed, they would result in a significantly increased GWTT. Consequently, the GWTT would not be conservative with respect to the hypothesis tested in the reviews. For example:

a. As noted earlier, a positive correlation between transmissivity and effective thickness would reduce the variance of the probability distribution of GWTT.

b. Relaxation of the assumption of a spatially constant transmissivity or hydraulic conductivity would tend to increase GWTT. In the calculations presented in the reviews, spatial variability is neglected. The effect of accounting for spatial variability, as clearly seen from theoretical studies and as illustrated in Clifton's report (1986), would be to increase flow resistance which would result in a larger GWTT.

2. Representativeness of parameters along flow paths

TT/NWC (1987) state on page 28:

> "... early evaluation of the large scale perturbations resulting from drilling indicate that the geometric means of the spot date do indeed give a reasonable estimate of the gross hydraulic conductivity of flow tops in the Grande Ronde."

This statement is incomprehensible.

Clifton (1986) used the geometric mean of all measurements from Grande Ronde flow tops, 0.153 m2/day, or according to TT/NWC, 0.150 m2/day. TT/NWC (1987) note, as one case, the geometric mean of the Strait and Mercer (1986) Grande Ronde data, 0.12 m2/day (page 29), and the geometric mean of the Cohassett flow bottom, Cohassett flow top, and Rocky Coulee flow top, 0.101 m2/day. This last set was the one preferred by TT/NWC.

Furthermore, TT/NWC (1987) decided to deal with hydraulic conductivities and effective porosities rather that the transmissivities and effective thicknesses used by Clifton (1986). Since flow-resistance data are in terms of transmissivity, hydraulic conductivities are calculated by assuming that the flow top thickness is 10 meters, even though data indicate a highly variable thickness. For the case examined in the TT/NWC re-review, the geometric mean conductivity is equal to 1.17 x 10E-7 m/sec and the standard deviation (SD) of log (base 10) conductivity is equal to 1.87. Since the sample contained 16 measurements, the SD of the estimation error of the mean log hydraulic conductivity is 1.87/15, namely 0.483.

Regarding the hydraulic gradient, Clifton (1986) assumes a constant value of 0.0002. TT/NWC (1987) use this value as the geometric mean with a SD of the log gradient equal to 0.3. For illustration, if the gradient is assumed to be lognormally distributed, the 95% confidence interval would be 0.00005 to 0.0008. Representation of the gradient as a random variable with these moments accounts for the lack of knowledge concerning the exact value of the actual gradient and is, in principle, quite appropriate. Furthermore, the assumed values would not have a major effect on the calculated CDF of GWTT. For example, the variance of log (GWTT) would be increased by about 3% as a result of accounting for variability in the gradient. This fact has been acknowledged by TT/NWC (1987).

The section on effective porosity is confusing. A detailed review of this section appears in Section C.II of this report.

On page 38 of the TT/NWC (1987) report, the reviewers return to the issue of the fastest path and claim that since the transmissivity of the lower Wanapum flow top is about one hundred times greater than the transmissivity of the upper Grande Ronde flow tops, the groundwater velocity in the Wanapum must be one hundred times greater as well. Of course, such a statement cannot be made with reference to the effective porosity. It is conceivable that the effective porosity in the lower Wanapum flow top is much higher than that of the upper Grande Ronde flow tops. It is also reiterated that focusing on the fastest path, no matter how small its probability of occurrence, might lead to overly conservative results.

3. Comments on Appendix A

Appendix A of TT/NWC (1987) contains the original TT/NWC (1986) review. Discussion of this review will be less detailed than that of the re-review and will be limited to issues not already addressed.

On page 4 of TT/NWC (1986), it is stated that

> "Clifton calculates that the probability of exceedance of 10,000-year travel times is greater than 99 percent for all variations of parameter uncertainty and spatial variability ..."

This statement is not accurate.

Section 5.2.1 seems pointless and Equation (3) is incorrect.

Section 5.2.2.3, porosity of flow tops, is of considerable interest since, as discussed earlier, the assumed median value of porosity is the most important reason for producing a result different from that of Clifton's. TT/NWC (1986) argues that the effective porosity should be lognormally distributed. Lognormality is more reasonable than normality since, if nothing else, it accounts for the skewness of the distribution. Given the large coefficient of variation, normality would result in a very sizeable probability of negative porosities.

There are several limitations associated with the rough check on the calculation of the horizontal GWTT (Section 5.2.3.1). First, hydraulic conductivity is taken to be equal to the sample average value. Depending on the value of the correlation length, the variance, and the boundary conditions, the effective hydraulic conductivity can be considerably larger than the sample average value. The numerical simulations by Clifton (1986) calculate the effective transmissivity much more accurately. Second, there may be considerable positive correlation between log transmissivity and log effective thickness which would reduce the variance of computed travel time.

4. Comments on Appendix C

Appendix C of TT/NWC (1986) reviews some basic results related to the calculation of means and variances of variables which are the summation of other variables with known means, variances, and correlation coefficients. TT/NWC (1987) actually deal with the sample moments. The relations presented by TT/NWC (1987), however, hold for the population moments only if the sample size N is assumed to increase without bound. Some comments:

a. Equation (8) should be written

X'' = SUM(square(Xi))/(N-1) - (N/N-1) square(X'2)

b. In calculated sample moments (e.g., equation 8), it is assumed that measurements are uncorrelated. This is often not the case. For example, if the range is about 3 km and two measurements are located within 1 km of each other, they are correlated. In this case Equation (8) underestimates the variance of the stochastic process. Unbiased estimators, which can be seen as generalizations of this equation, are described in Kitanidis and Lane (1985).

C. COMMENTS ON MAIN TT/NWC CONCLUSIONS

The following section will mainly refer to the TT/NWC (1987) Re-review, which supersedes and corrects an error present in the first review. In these two documents, TT/NWC submits that the computations of total travel time by Clifton (1986) are not conservative and that "there is a significant likelihood that the BWIP site will fail the 1000 year travel time rule" (p.9). In the following comments, the main contentions of the TT/NWC reports are discussed.

I. General Comment

TT/NWC (1987) use the simple formula (equation (1))

$$t = nL/Ki$$

where n is the effective porosity, L is the distance to compliance surface, K is the hydraulic conductivity, and i is the hydraulic gradient to evaluate the GWTT CDF, P(t), in the flow top of interest. To obtain P(t), TT/NWC (1987) assume that n and K are lognormal and subject to estimation errors only. As a result, t is lognormally distributed with known mean and variance.

As discussed earlier, this model presumes a vanishing integral scale of transmissivity. The resulting P(t) leads to larger travel times than the ones corresponding to a large integral scale. TT/NWC (1987) assumes, incorrectly, that if the site does not pass the regulatory requirements for this model, it will definitely fail them in the case of a finite integral scale, all other factors being equal.

However, based on equation (1), the TT/NWC (1987) conclusion that the 1000 year criterion is not likely to be satisfied does not seem to be warranted. Since TT/NWC (1987) divergence from the data adopted by Clifton (1986) is minor with respect to the path length, the hydraulic conductivity, and the hydraulic gradient, our discussion will focus on the effective porosity, or equivalently the effective thickness, which is the cornerstone of TT/NWC argument.

II. Effective Porosity

The range of effective porosity adopted by Clifton (1986), namely 0.0001 to 0.01 is based on the analyses of five, and later, of eight experts (Runchal et al., 1984a, 1984b). Most of the experts regard the value determined by the tracer test at DC7/8 as relatively low and presume that at the megascale, the effective porosity is larger. It is true that in the Runchal et al. (1984a) report, which summarizes the results of five external experts, the detailed calculations underlying the proposed probability distribution function (PDF) of effective porosity are not reproduced. Nevertheless, in view of their reputation and experience, one is entitled to presume that the experts have used the best available tools in order to assess the PDF of the effective porosity.

The TT/NWC (1986) cast doubts on the reliability of the experts, saying for instance, "it is suggested that nobody is an 'expert' in this particular field" (p. 19). In contradiction to this statement, TT/NWC (1987) indulge, however, in speculating about the PDF of effective porosity at great length. These speculations will now be reviewed.

The largest divergence between Clifton (1986) and TT/NWC (1987) is in the assumed geometrical mean of the effective porosity which is given in TT/NWC (1987, p. 34) at the bottom, namely 0.00016. In contrast, Clifton (1986) assumes a value of

0.005. It should be noted first that the geometric mean for Clifton's distribution, i.e., rectangular between a minimum of 0.0001 and a maximum of 0.01, is equal to 0.0039, rather than 0.005. Still, the ratio between the two, i.e., 0.0039/0.00016, is approximately 24.

To support this difference in estimation, TT/NWC (1987) invoke two reasons:

a. They quote a recent article on effective porosity of fractured granodiorite by Brotzen (1986, see TT/NWC, 1987, p. 31). A correlation between these data and hydraulic conductivity are plotted in Figure 2 of TT/NWC (1987, p. 33) as a dark band. Strangely enough, if the geometric mean of hydraulic conductivity, namely K=0.00000014 m/sec is plotted on the graph, the corresponding effective porosity lies between 0.0006 and 0.0036, with an average of 0.002. This value is smaller than Clifton's average only by a factor of 2.5. Thus, TT/NWC (1987) ignore the same data that they are using to support their claim.

b. The second line of reasoning is based on the use of a parallel plate model relationship between hydraulic conductivity and effective porosity, which is forced to pass through the only measured value for DC-7/8, namely n=0.00016. It should be mentioned first that in the analysis of the tracer test the effective porosity is given a broad range, depending on the assumed value of the contributing thickness. The one adopted by TT/NWC (1987) is a lower bound, based on the assumption that the entire thickness of the flow top contributes equally to conveying the fluid. In the analysis of the well log, it was shown that it is possible that only one tenth of the thickness conveys fluid effectively, leading to a value of effective porosity ten times larger (Leonhart et al., 1985). Besides, the parallel plate model is a gross oversimplification which does not account for the fact that fractures are filled or for the complex geometry of the fracture system. If the fracture aperture, a, is computed from the parallel plate theory by using the formula

a = square root of (12 x niu x T/g/be) (4)

where niu is the coefficient of kinematic viscosity (0.00000055 m2/sec), T is the transmissivity (0.000000081 m2/sec), g is the gravity (9.81 m/sec2), and b e is the effective thickness (0.0025 m), the result is a=0.015mm, which is much lower than the average of 0.226 mm reported by Lindberg (1986). Furthermore, the use of the model is precluded by the main findings of Lindberg (1986), namely that fissures were filled and very few voids were detected. A model of flow through fissures that are filled with clay (which could be the case for 89% of the fissures at Hanford, as reported by Lindberg, 1986) leads to different results from those of the parallel plate theory.

Concluding the discussion of this point, it seems that the arguments employed by TT/NWC (1987) to refute the range of effective porosity values adopted by Clifton (1986) are untenable.

III. Porosity Probability Distribution

TT/NWC (1987) argue at length that the estimate of the effective porosity is lognormal, whereas they say that Clifton (1986) has adopted a normal one (p.34). As mentioned before, Clifton (1986) assumes a rectangular distribution, for reasons he makes clear. It is true that on the basis of existing data, it is difficult to recognize the nature of the PDF. A lognormal PDF is reasonable to assume if n is fully correlated to K, but such a correlation is not warranted. Besides, lognormality avoids the negative values present in a normal distribution of sufficiently large variance. In view of this uncertainty, the salient question is whether the assumed shape of the PDF has a major impact upon the GWTT CDF. It was shown (Djerrari et al., 1986) that the impact is quite small, but TT/NWC (1986) claim that the difference between the normal mean and lognormal mean may be quite large (p. 20). This divergence stems from the way in which various PDF's are compared. In Djerrari et al. (1986), it was assumed that the influence of the shape should be assessed by taking various PDF's with the same mean and variance. The raison d'etre of such an approach is that in the absence of sufficiently many data to validate the shape of the PDF, at best one can extract the mean and the variance from a few measurements. In contrast, TT/NWC (1987) fit the PDF of the effective porosity by assuming that the two bounds of Clifton's rectangular distribution, i.e., nmin=0.0001 and nmax=0.01, represent the range for the 95% interval of confidence, which pulls the highly asymetrical lognormal distribution towards the lower effective porosities. This manipulation of the bounds (taken quite arbitrarily by Clifton (1986) for a rectangular distribution) is highly questionable.

D. MINOR COMMENTS

In Table 2 of TT/NWC (1987), under STATISTICS OF LOGARITHMS, GEOM MEAN should be replaced by MEAN. TT/NWC (1987) seem to refer to Figure 4 rather than 5 (p. 29, line 10 from the bottom). The geometric mean transmissivity is in units of m2/day and not in units of m2/s as mentioned on page 29 (TT/NWC, 1987, 8 lines from the bottom) and page 30 (8 lines from the top). On page 30, line 13 from the top of TT/NWC (1987), "log mean hydraulic conductivity" should be "mean of the log hydraulic conductivity". The same comment applies to page 31, "log mean gradient" should be "mean log gradient". Finally, the date of the report should be January 13, 1987 rather than January 13, 1986.

E. CONCLUSIONS AND RECOMMENDATIONS

The main differences between the TT/NWC reviews and Clifton's report are in the assumed geometric mean of the effective porosity. TT/NWC uses a value 24 times smaller than the value assumed in Clifton's report. As a result of this assumption groundwater travel times calculated by TT/NWC would be about 24 times shorter than those calculated by Clifton.

TT/NWC neglect spatial correlation in the log transmissivity and thus, overestimates effective log transmissivities. As a result, travel times calculated by TT/NWC are on the low side.

Although TT/NWC raise some valid points, the arguments they employed to refute the range of effective porosity adopted by Clifton are untenable.

There is a consensus among various investigators that additional field tests are needed in order to arrive at more reliable estimates of GWTT. It is obvious that additional information must be obtained regarding appropriate values and variability of effective thickness and porosity. However, at the same time, a more complete probabilistic analysis is required. This analysis would also suggest the kind of data that would be most useful in the analysis.

In view of the cost and duration of such tests, it is crucial to concentrate the efforts on those tests which have a large impact on the estimation of GWTT. As a result of their conclusions concerning the effective porosity, TT/NWC (1987, p. 39) recommend that field investigations focus on measurements of effective porosity.

In contrast, Clifton's (1986) simulations and the analytical approach of GWTT CDF (Djerrari et al., 1986) show that the probability distribution of GWTT is very sensitive to the assumed correlation length. Therefore, the determination of the transmissivity integral scale, by measurements of transmissivity, is regarded as of paramount importance. Although a few more values of measured n are recommended, by no means should they come at the expense of transmissivity. The danger is that if the porosity data are such that the site passes the GWTT requirement for a zero integral scale, as assumed by TT/NWC, the opposite might be true for a finite integral scale.

Uninformed conservativism does not necessarily lead to good decisions. In the case of the nuclear waste isolation projects, it could easily lead to the decision to disqualify all sites. For the Hanford Site, a combination of conservative assumptions about the flow path, the value of the effective porosity, the correlation length of the log transmissivity, lack of correlation between log transmissivity and log effective thickness, and the unconditional probabilities approach followed would yield results which would suggest that the site should be disqualified. Instead, what is needed is to pursue a more complete probabilistic analysis in parallel to site characterization efforts.

Regulatory agencies should specify the needed safety levels more accurately (e.g., in terms of probabilities that the pre-emplacement travel time exceeds 1,000 years). Then the nature of uncertainties should be understood and incorporated in the analysis. For example, no matter how many measurements are obtained, the uncertainty about the correlation length of log transmissivity would always be large.

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