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HANFORD SITE

BASELINING AND LHST SCHEDULING:

REVIEW/ASSESSMENT/INDEPENDENT VERIFICATION

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BASELINING AND LHST SCHEDULING:

REVIEW/ASSESSMENT/INDEPENDENT VERIFICATION

1. LOGISTIC AND RATIONALE OF PROPOSED MONITORING LOCATIONS

1.1 PRIOR TO CONDUCTING LHST, BWIP NEEDS TO DEMONSTRATE HOW PROPOSED MONITORING FACILITIES (QUANTITY AND LOCATIONS) WILL PROVIDE NECESSARY HYDRAULIC HEADS AND RESPONSE DATA NEEDED FOR SITE CHARACTERIZATION

1.2 BWIP SHOULD ASSESS THE LIMITATIONS OF THE PRESENT NETWORK AT HANFORD AND IMPROVE THE NETWORK TO ACCOMPLISH THE OBJECTIVES OF LHS TESTING

* GEOSTATISTICAL ANALYSIS ON EXISTING NETWORK
* TIME SERIES ANALYSIS TO CHARACTERIZE THE ADEQUATE MEASUREMENT SAMPLING FREQUENCY

1.3 ESTABLISHING THE BASELINE SHOULD NOT BE RESTRICTED TO THE NEIGHBORHOOD OF THE ES BUT SHOULD EXTEND TO THE PASCO BASIN BETWEEN THE RRL AND THE COLUMBIA RIVER.

2. PROPOSED SCHEDULING AND TIME FRAME FOR PRE-ES TESTING AND MONITORING

2.1 BASELINE MONITORING AFTER DRILLING OF NEW BOREHOLES

2.1.1 SUFFICIENCY OF THE FOUR MONTH PERIOD PLANNED FOR ALLOWING NOISE DUE TO DRILLING ACTIVITIES TO DECAY

2.1.2 IMPACT ON SCHEDULING

ASSESSMENT OF NOISE IDENTIFICATION TECHNIQUES

DELAY ON SCHEDULING

2.2 RATIONALE BEHIND THE LENGTH OF TESTING

FOUR LAYERS TO BE TESTED IN 12 MONTHS

TWO KINDS OF TESTS WILL DISTURB THE SYSTEM

- TRACER TESTS
- LHS TESTING

2.2.1 TRACER TEST

QUASI-STEADY STATE ESTABLISHMENT

TEST DURATION

- CONDUCT TEST UNTIL THE TRACER CONCENTRATION IS AT THE BACKGROUND CONCENTRATION OR BELOW DETECTION LIMIT

RECOVERY TO PRE-TRACER TEST CONDITIONS

2.2.2 LARGE-SCALE PUMPING

DURATION OF TEST - DURATION OF OBSERVATION

IN CASE OF HYDRAULIC CONNECTION

- TIME OF RECOVERY OF PRE-PUMPING CONDITIONS

2.2.3 PLAN OF EMERGENCY ACTION IN A FORM OF A DECISION TREE

IMPACT ON SCHEDULING

2.3 IDENTIFICATION OF PARAMETERS

2.3.1 ASSUMPTIONS UNDERLYING THE TEST DESIGN

EQUIVALENT POROUS MEDIUM IS ASSUMED IN THE DESIGN OF THE TRACER AND PUMPING TESTS

2.3.2 TEST INTERPRETATION AND PARAMETER IDENTIFICATION

MODELING FOR TEST INTERPRETATION

* CONCEPTUALIZATION
* NUMERICAL ANALYSIS APPROACH WILL NOT YIELD A UNIQUE SOLUTION
* DOE SOLUTION FOR THIS LAST CONCERN: INCREASED DATA BASE
    - INCREASED DATA BASE MAY NOT HELP IF THE SYSTEM IS VERY COMPLEX
    - TIME CONSTRAINT (HOW MUCH CAN WE INCREASE THE THE DATA BASE WITH THE PROPOSED SCHEDULING?)

3. ASSESSMENT OF THE PROPOSED LHST IN TERMS OF OBJECTIVE ONE

CAN OBJECTIVE ONE BE MET?

OBJECTIVE ONE: COLLECT DATA ON GEOHYDROLOGIC CONDITIONS THAT WILL BE CHANGED BY SITE CHARACTERIZATION ACTIVITIES

* AMONG THESE GEOHYDROLOGIC CONDITIONS IS THE HYDRAULIC HEAD FIELD

* IS THE PROPOSED MONITORING NETWORK ABLE TO PROVIDE ADEQUATE PREDICTION OF THE HEAD FIELD?

TO ANSWER THIS QUESTION, WE CONSIDERED THE PRIEST RAPIDS MEMBER

THIS LAYER IS THE ONE THAT HAS THE MOST MONITORING FACILITIES

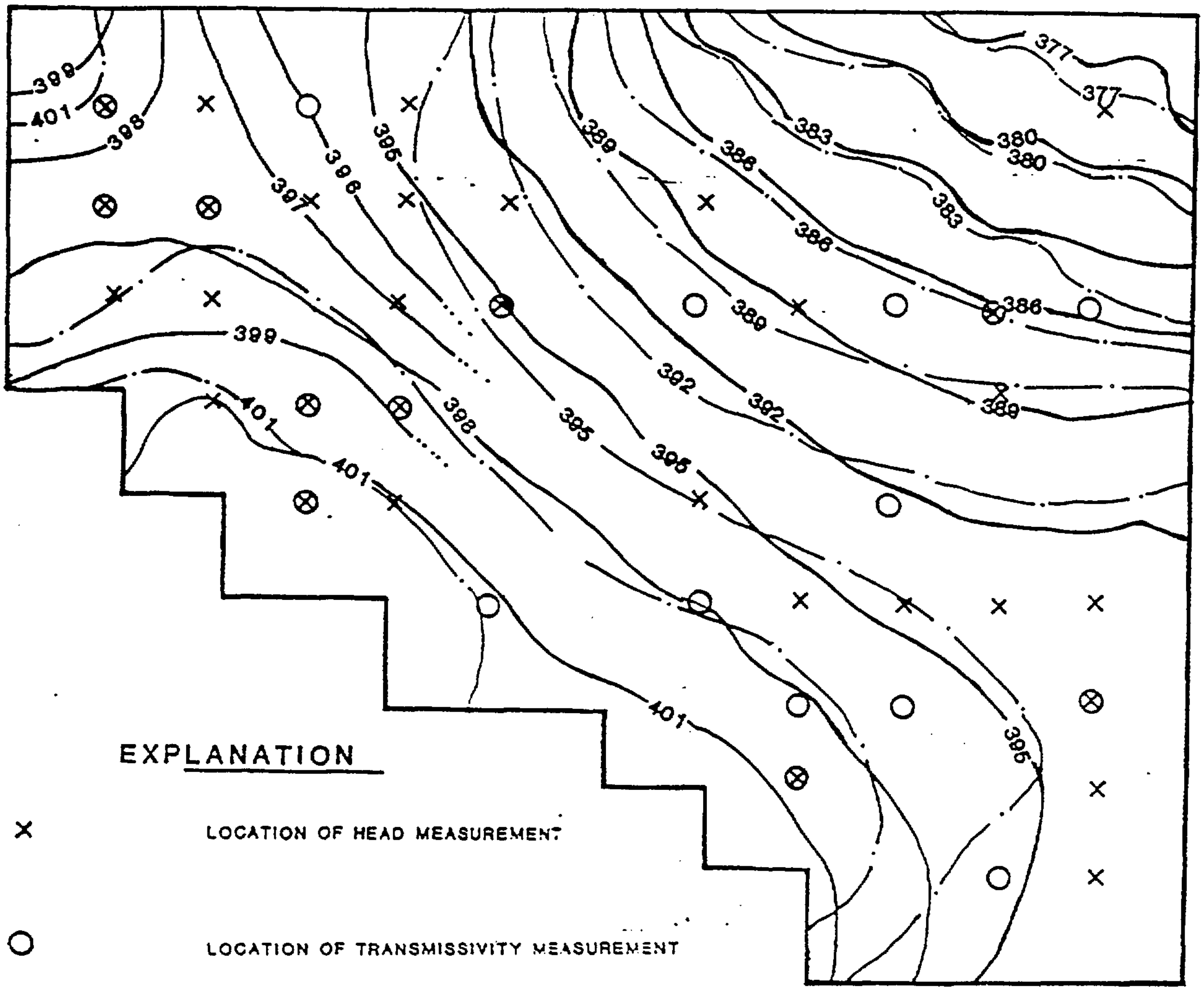
(1) WE USED THE STATE-OF-THE-ART SOLUTION OF THE INVERSE PROBLEM TO ESTIMATE THE PARAMETERS DESCRIBING THE SPATIAL VARIABILITY OF THE TRANSMISSIVITY FIELD USING TRANSMISSIVITY AND HEAD MEASUREMENTS

(2) ONCE THE SPATIAL VARIABILITY HAD BEEN CHARACTERIZED, WE USED THE RECOGNIZED PARAMETERS TO GENERATE HEAD AND TRANSMISSIVITY FIELDS THAT ARE POSSIBLE REALIZATIONS HAVING THE SAME VARIABILITY CHARACTERISTICS AS THE IDENTIFIED FIELD

(3) WE USED DIFFERENT SETS OF HEAD AND TRANSMISSIVITY MEASUREMENTS RANDOMLY PICKED FROM THE GENERATED FIELD AND RE-ESTIMATED FROM THESE MEASUREMENTS THE PARAMETERS THAT DESCRIBE THE SPATIAL FIELD

(4) WE COMPARED THE EXPECTED HEAD FIELD PREDICTED FROM THE DIFFERENT SETS OF MEASUREMENTS CONSIDERED AND THE ORIGINAL HEAD FIELD THAT SHOULD HAVE BEEN RETRIEVED

PREDICTION OF HYDRAULIC HEAD FIELD USING 30 HEAD AND 20 TRANSMISSIVITY MEASUREMENTS



EXPLANATION

× LOCATION OF HEAD MEASUREMENT

○ LOCATION OF TRANSMISSIVITY MEASUREMENT

401 —·—·— HYDRAULIC HEAD TO BE PREDICTED

401 ——— EXPECTED HYDRAULIC HEAD FIELD USING 30 HEAD AND 20 TRANSMISSIVITY MEASUREMENTS

CONTOUR ELEVATION IN FEET (MSL)

N

SCALE

0 5 10 15 MILES

0 5 10 15 20 KILOMETERS

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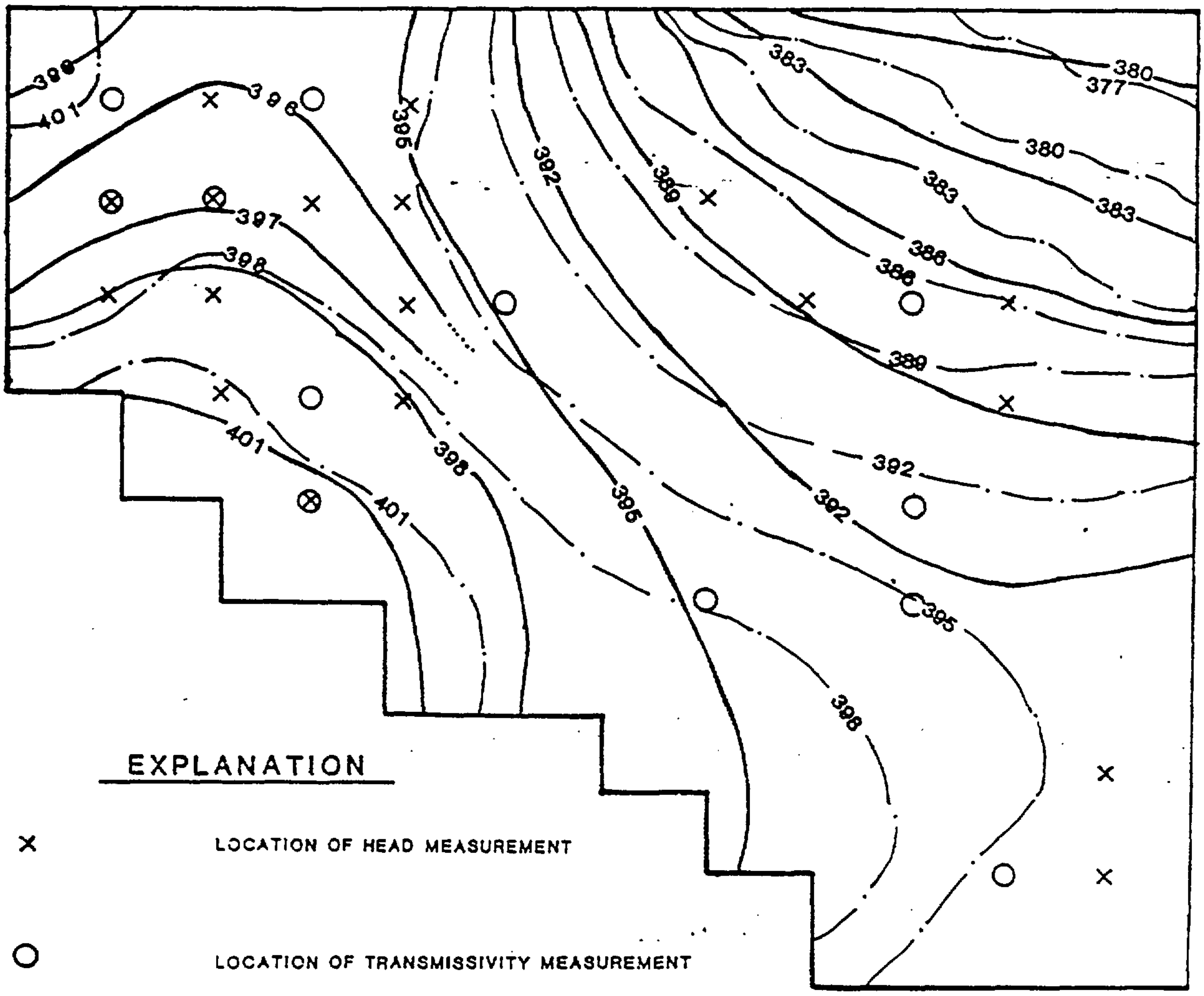
PREDICTION OF HYDRAULIC HEAD FIELD USING 18 HEAD AND 12 TRANSMISSIVITY MEASUREMENTS



EXPLANATION

× LOCATION OF HEAD MEASUREMENT

○ LOCATION OF TRANSMISSIVITY MEASUREMENT

401 —·—·· HYDRAULIC HEAD TO BE PREDICTED

401 ——— EXPECTED HYDRAULIC HEAD FIELD USING 18 HEAD AND 12 TRANSMISSIVITY MEASUREMENTS

CONTOUR ELEVATION IN FEET (MSL)

N

SCALE

0 5 10 15 MILES

0 5 10 15 20 KILOMETERS

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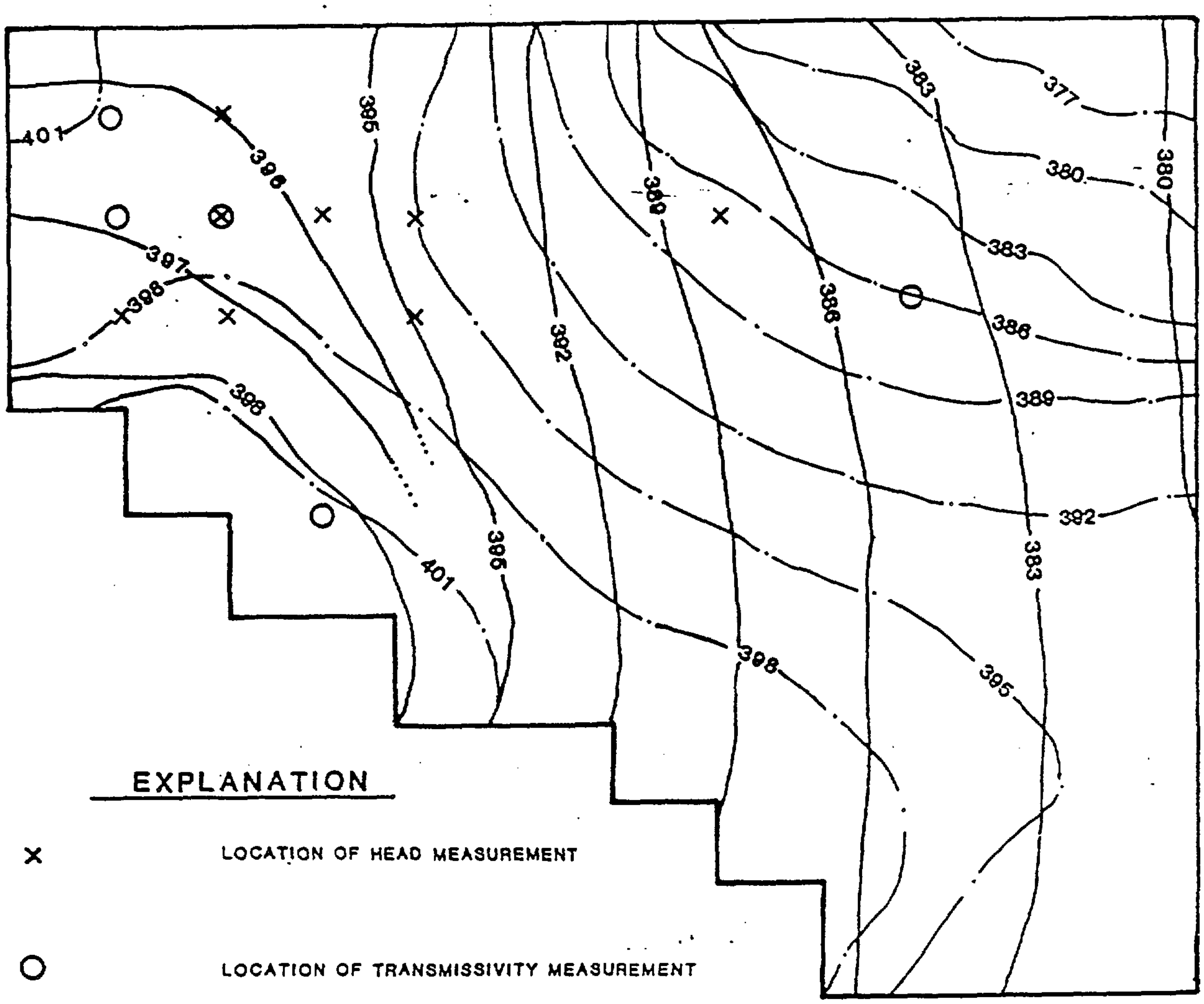
PREDICTION OF HYDRAULIC HEAD FIELD USING 8 HEAD AND 5 TRANSMISSIVITY MEASUREMENTS



EXPLANATION

× LOCATION OF HEAD MEASUREMENT

○ LOCATION OF TRANSMISSIVITY MEASUREMENT

401 —·—·—·· HYDRAULIC HEAD TO BE PREDICTED

401 ——— EXPECTED HYDRAULIC HEAD FIELD USING 8 HEAD AND 5 TRANSMISSIVITY MEASUREMENTS

CONTOUR ELEVATION IN FEET (MSL)

N

SCALE

0 5 10 15 MILES

0 5 10 15 20 KILOMETERS

ENVA

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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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Submitted to:

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Date:

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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 $\bar{n}$ 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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Attachment 16(d)

DRAFT

COMMENTS OF THE

YAKIMA INDIAN NATION

ON THE

DRAFT GENERIC TECHNICAL POSITION

ON GROUNDWATER TRAVEL TIME

JULY 30, 1986

SUBJECT: Comments on "Draft Generic Technical Position on Groundwater Travel Time, by Richard Codell" (NRC 7/86)

DATE: July 30, 1986

EXECUTIVE SUMMARY

This report is a critical review of the NRC paper entitled "Draft Generic Technical Position on Groundwater Travel Time". The purpose of this NRC paper is to provide general guidelines for the relevancy and quality of research affecting the groundwater travel time (GWTT) objective. These research guidelines are important for the evaluation of high-level waste (HLW) repository performance and are not adequately covered by the NRC.

I. INTRODUCTION

One of the NRC performance objectives for HLW repositories, the GWTT objective, is stated as:

" The geologic repository shall be located so that pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1000 years or such other time as may be approved or specified by the Commission." (10 CFR 60.113 (a)(2))

The Disturbed Zone definition (10 CFR 60.2) and GWTT objective were established as part of a multiple barrier approach to HLW isolation. Since groundwater is the most likely means by which significant quantities of radionuclides could escape a HLW repository, transport of radionuclides to the biosphere depends on factors which are directly related to the travel time of groundwater from the repository to the environment.

The following comments point out several problems with and inadequacies of the GWTT analysis and methods described in this NRC technical position paper.

II. REVIEW OF THE NRC TECHNICAL POSITION

1.0 What is Groundwater Travel Time?

Page 4, Equation (1)

Equation (1) should read:

$$T = \int_{D.Z.}^{A.E.} \frac{n_e}{U} ds$$

Page 5, Equation (2)

The material balance and the assumptions that lead to equation (2) cannot be justified when simulating the transport and capture of colloidal particles. Accurate modeling of radioactive and natural colloidal particles in a high-level nuclear waste repository environment would require the inclusion of complex phenomena such as electrical interactions between the particles and the walls of the surrounding rocks. Furthermore, the presence of these interactions may lead to a system which is not in thermodynamic equilibrium. In any case, equation (2) cannot be used as a basis to model colloids and to describe their potential to move faster than the average pore velocity (Avogadro and De Marsily, 1984). When this latter situation occurs, the travel time definition calculated using equation (1) is no longer valid.

Page 5, Paragraph 4

" The immobile phase occupies the fraction $(n - n_e)$ of the rock."

Page 7, Paragraph 3

" This fact tends to support the notion ... groundwater travel time."

Page 9, Paragraph 1

" Groundwater travel time also could be interpreted ... less than 1000 years."

The concept of "immobile water" is ambiguous. As a matter of fact, the dispersion coefficient is supposed to account for the tortuous paths of fluid particles, including the slow ones through zones of low velocity. It is difficult to conceive how one would derive experimentally the various terms of eq. (2), other than n_e and $\underline{D}$, from the equation

$$n(\partial c/\partial t) = n_e \, \mathrm{div}(\underline{D} \text{ grad } C - \underline{U}C)$$

Although in later discussion the influence of adsorption is discarded, the need for future incorporation is noted (p.7, paragraph 3; p.9, paragraph 1). What is not mentioned is the fact that the theory relating travel time to adsorption, decay, etc. has not yet been developed; and the concept has been applied only to relating concentration to adsorption, decay, etc.

Page 6, Equations (5) and (6)

These equations do not follow from equations (3), (4) and (5). The relationship between G and C is missing.

Page 7, Paragraph 2

" Tracer particles considerably larger than molecules will not exhibit the same diffusive behavior as molecular tracers, and will be transported at a speed more typical of the average groundwater seepage velocity."

This argument may not hold true for radiocolloids, which tend to travel in regions of higher than average fluid velocities within the streamflow (Bonano and Beyeler, 1985; Avagadro and De Marsily, 1984).

Page 7, Paragraph 2

" Tracer particles considerably larger than molecules ... groundwater movement is very slow (Blencoe and Grisak, 1984)."

The description of the outcome of the experiment by Cathles in lines 7-13 does not agree with the statement in lines 3 through 7.

Page 7, Paragraph 3

" It should be noted that ... estimated to be 2.7 x 10 $^{-5}$ cm^2/sec."

The distinction between self-diffusion of water molecules and traces is artificial. Tracing is required to detect the self-diffusion of water molecules.

2.3 Groundwater Travel Time Along the Fastest Path

Page 11, Section 2.3

Page 21, Paragraph 6
Page 22, Paragraph 1

"Interpretation of Sparse Data. The temporal and spatial distribution of hydrogeologic field data ... the variance of the hydraulic conductivity (e.g., Neuman and Yakowitz, 1979, Hoeksema and Kitanidis, 1984)."

Page 23, Paragraph 4

" Field data for hydraulic conductivity and porosity ... to apply to these data in this step (Mantoglou and Gelhar, 1985)."

In all of these sections an important source of uncertainty has been ignored, namely the uncertainty manifested in the estimation of the parameters which characterize the probability distribution functions of various properties. In the case of scarce data, this may be a major source. The quantitative evaluation of variances of estimation has been developed in an important series of articles by Hoeksema and Kitanidis (1984), Kitanidis and Lane (1985), and Kitanidis (1986).

A.1 Travel Time Distributions

Page 18, Paragraph 1

The definition of mechanical dispersion applies to pore-scale nonuniformity. The large scale heterogeneities encountered in aquifers can cause solute spreading which may be termed "megadispersion" only under restrictive conditions. These conditions, in essence, require

(i) ergodicity for <u>solute concentration</u> and

(ii) travel distance <u>much larger</u> than the heterogeneity correlation scale (see discussion in Part I of Dagan, 1984).

Page 19, Paragraph 2

> "Stochastic approaches to modeling are at a much less developed state than Monte Carlo techniques, although it is an area of rapid development ... They apparently have not yet been used to calculate directly such spatially integrated properties as GWTT."

The literature on stochastic modeling is much richer than implied here. For comprehensive reviews, see Sposito et al. (1986), Dagan (1985), and Gelhar (1985).

A.3.1 Treatment of Uncertainties in Site Characterization

Page 22, Paragraph 2

> " Computer codes should be verified with analytical solutions, validated with real field data, and compared or benchmarked with other similar computer codes (Silling, 1983)."

The validation of computer codes by comparison with analytical solutions is highly desirable. Such comparison is not possible at present for GWTT because, to the best of our knowledge, there are no analytical solutions available for GWTT in two- or three-dimensional flows.

A.4 Estimating GWTT from Deterministic Models with Randomly-Generated Input

Page 23, Paragraph 1

> " This solution generally is accomplished ... then counting their arrival times as they reach the accessible environment."

The computation of travel time by these techniques may be plagued by large discretization errors due to the need to numerically differentiate the head in order to derive the velocity, to integrate along the velocity vectors in order to determine the trajectories, and to integrate along trajectories in order to calculate time (eq. 1). A better streamfunction technique (Frind and Matanga, 1985) developed for two-dimensional, steady flow, is not mentioned.

A.4.1 Treatment of Spatial Variability

Page 23, Paragraph 3

> " This method has been applied to 2-dimensional steady state, saturated flow models for equivalent porous media (e.g., Delhomme, 1979, Clifton and Neuman, 1982), but it could be adapted to three dimensions (Mantoglou and Gelhar, 1985). The procedure is outlined below for the 2-dimensional, steady state case (Clifton, 1984)".

This paragraph gives the misleading impression that Delhomme (1979) and Clifton and Neuman (1982) have employed conditional simulations of GWTT. These papers do not deal with transport. Similarly, it is not true that Clifton (1984) has carried out conditional simulations of GWTT, as implied by the NRC (p.24, lines 10-12), and the conclusion regarding the considerable reduction of the variance is unproven, if not gratuitous. The subject of the effect of conductivity conditioning upon transport has been addressed for a particular case, using numerical methods, by Smith and Schwartz (1980), and the combined effect of conditioning of both conductivity and head has been discussed in a general manner by Dagan (1984, Part 2).

Page 24, Paragraph 1

> " Two widely-used procedures for generating these random fields ... otherwise, the parameter fields are "unconditional"".

In addition to these methods, the ready-made generation of multi-variate normal variables is available in most computer libraries.

A.5 Simplified Analysis

Page 24 (bottom line)
Page 25, Paragraph 1

> " If the medium is assumed to be spatially uniform (i.e., infinite spatial covariance), then it must be assumed that all variations of the parameters are caused by measurement error."

There is no real need for the correlation scale to be infinite. It is sufficient for it to be large compared to the distance traveled by particles from the disturbed zone to the compliance surface. Furthermore, the variations of parameters cannot be attributed only to measurement errors, but also to interpretation, modeling, etc. and spatial variability at large scale.

III. CONCLUSIONS AND RECOMMENDATIONS

Some important issues in addition to those mentioned above, are not discussed in the draft. Here are a few such issues:

(1) Does the cummulative probability distribution function for groundwater travel time represent uncertainty, as is the case for a single particle, or does it represent the actual partition of travel times of a large number of particles simultaneously released from the boundary of the disturbed zone, as is assumed in diffusion or dispersion theories? The answer to this question is intimately related to ergodicity of transport, which in turn is related to the scale of the initial zone of release, correlation scale and travel distance (for a discussion concerning concentration see Dagan, 1984 Part 1). This is an important topic which requires serious consideration and investigation in order to adequately address the question of simultaneous release of a number of particles in each realization. It should also be noted that, whereas uncertainty can be reduced by increasing the quantity and improving the quality of

measurements and by subsequent conditioning, the dispersive effect of spatial variability cannot be diminished this way.

(2) The fact that Monte-Carlo techniques have not yet been applied to complex three-dimensional flows (except, Warren and Price, 1961) is not mentioned. Furthermore, the inclusion of three-dimensional effects in a two-dimensional scheme by introducing a diffusive (dispersive) term in the computation of the travel time, is not considered. The Monte-Carlo simulations used by Clifton (1984) and advocated in the draft are not able to account for these effects.

(3) The Monte-Carlo and numerical scheme referred to in the draft GTP (i.e., Clifton, 1984) is not able to account for random velocity fluctuations whose correlation scale is smaller or comparable to the grid scale (so called subgrid diffusion). These fluctuations cause uncertainty in GWTT and they will show up as a dispersive term in a concentration formulation.

(4) Little is said about the uncertainty associated with boundary conditions for the flow field, i.e., the selection of the boundaries of the domain to be modeled in Monte-Carlo simulations and of the appropriate boundary conditions.

In conclusion, it is believed that this document, rather than attempting to define criteria of GWTT only, emphasizes too heavily a particular technique applied in the last few years. This may lead to the impression that this technique is flawless and furthermore, that it is the one preferred by NRC. From the above critical comments, it is clear that further scientific developments and improvements are needed to adequately address the NRC GWTT performance objective.

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CENTENNIAL JUNE 9, 1955

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EWA INC

Mr. John J. Linehan, Acting Chief
Repository Projects Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Mail Stop 623-SS
Washington, D. C. 20555

Dear Mr. Linehan:

A review of the NRC "Draft Generic Technical Position on Groundwater Travel Time" has been completed by the Yakima Indian Nation. Attached please find a copy of our comments.

Your attention to this matter is greatly appreciated. If you have any questions, please do not hesitate to contact me.

Sincerely,

YAKIMA INDIAN NATION

Russell Jim

Russell Jim, Manager
Nuclear Waste Program

Enclosures

RJ/skC

Attachment 16(e)

DRAFT

EVALUATION OF DOE ANALYSIS OF GROUNDWATER TRAVEL TIME HANFORD SITE

By:

A. M. Djerrari
G. Dagan
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EWA, Inc.

Submitted to:

YAKIMA NATION

Date:

July, 1986

To: Yakima File, Task: 2.e.3 and 2.h.5.c

From A.M. Djerrari, G. Dagan, V.V. Nguyen and G.V. Abi-Ghanem/EWA, Inc.

Subject Evaluation of DOE Analysis of Groundwater Travel Time, Hanford Site.

Date: July 29, 1986

EXECUTIVE SUMMARY

The U.S Nuclear Regulatory Commission (NRC) has established performance criteria for the qualification of a high-level nuclear waste repository. One of these criteria is referred to as the pre-waste-emplacement groundwater travel time objective. To study the compliance of DOE to meet the NRC objective (i.e.; groundwater travel time (GWTT) exceeding 1,000 yrs), Clifton and Arnett (1984) and Clifton (1984) carried out Monte Carlo simulations using a two-dimensional model. This report reviews the two studies cited previously with respect to the overall method of estimation of the GWTT distribution. It is found that i) the domain in which the groundwater flow problem is solved influences the GWTT distribution, which makes the resulting outcome uncertain, and ii) the GWTT distribution, as derived by the DOE, does not account for uncertainties in the statistical parameter estimates.

The possible range of GWTT exceedance probability for 1,000 yrs has been derived analytically. Due to the scarcity of the available data representing the transmissivity field heterogeneity, the exceedance probability for 1,000 years can be any value between 75% and 99%. Hence, no conclusion on the compliance with the NRC regulation can be made at this time. Several recommendations to improve future numerical simulations are presented. These numerical improvements, however, can not be a substitute for the field effort needed to gain a better knowledge of the field heterogeneity.

I. INTRODUCTION

The objective of the Basalt Waste Isolation Project (BWIP) is to locate, test and construct a deep geologic repository for the terminal storage of high-level nuclear waste at Hanford, Washington. Among the criteria used by BWIP to assess the long term performance of a repository is the predicted groundwater travel time to the accessible environment. Over the past few years, a number of preliminary numerical modeling studies have evaluated potential groundwater flowpaths and travel time estimates (DEA, DOE 1984). These studies presented a broad range of travel time estimates. The variance in estimates has been attributed to measurement and model uncertainties. Since modeling was always carried out in a deterministic way in the previous studies, stochastic modeling was considered to be an appropriate technique for calculating groundwater travel times (DEA, DOE 1984). Stochastic modeling was performed in two studies by Clifton and Arnett (1984) and Clifton (1984). This report will review the overall approach used by these authors. The method for evaluating the groundwater travel time distribution is presented in the first section. The DOE/BWIP approach is evaluated and its limitations discussed in the second section, while the third section contains conclusions and recommendations.

II. GROUNDWATER TRAVEL TIME DISTRIBUTION: APPROACH AND RESULTS

A. Summary of the General Approach

The technique proposed for generation of random variables is the Monte Carlo technique. The quantities generated by this technique are subsequently used in the groundwater flow and groundwater travel time equations. The stochastic quantities under consideration are i) transmissivities, ii) effective thickness and/or iii) boundary conditions through the hydraulic head gradient. Monte Carlo analysis produces a series of groundwater travel time realizations that are used to construct probability distribution of the groundwater travel time.

1. Governing equations

Assuming steady state conditions and a heterogeneous porous medium with no internal sources or sinks, the groundwater flow system is described by the following equation,

$$\nabla .(T \quad h) = 0 \qquad (1)$$

subject to prescribed head and flux boundary conditions, using the following notations

∇ = the two-dimensional vector diferential operator,

T = transmissivity (L^2/T),

h = hydraulic head (L).

Groundwater travel times are calculated using the solution of equation (1) and the following relationship,

$$T_i = \int_L \frac{dL}{|\underline{q}_s|} \qquad (2)$$

where

T_i = ground-water travel time (T)

$|\underline{q}_s|$ = magnitude of the seepage velocity vector (L/T)

dL = curvilinear elemental length along the direction of $\underline{q}_s$ (L)

The seepage velocity vector is given by

$$\underline{q}_s = - T \nabla h /(b x n_e) \qquad (3)$$

where

b = aquifer thickness (L),

n_e = effective porosity (dimensionless).

The quantity be ($=bxn_e$) is called "effective thickness" and represents the area of pore space available to flow, in a vertical cross section of an aquifer of unit width and thickness b. To determine ground-water travel time using equation (2), a transmissivity field and boundary conditions are specified and used to solve equation (1). The numerical solution of equation (1) is accomplished by means of either a finite element (Clifton and Arnett, 1984) or a finite difference technique (Clifton 1984). Both techniques lead to a matrix equation of the general form:

$$\underline{\underline{A}}\,(\underline{T})\;\underline{h} = \underline{b}_c \qquad (4)$$

where

$\underline{\underline{A}}\,(\underline{T})$ = square matrix of order N,

$\underline{h}$ = N-dimensional vector of hydraulic head,

N = number of node points used to represent the flow domain,

$\underline{T}$ = N-dimensional vector of transmissivities,

$\underline{b}_c$ = vector of known constants incorporating boundary conditions,

Each zone of the flow domain is assigned a unique transmissivity. Hence, the number of zones considered characterizes the degree of heterogeneity of the system. When solving for the travel time, in the context of the stochastic approach, transmissivity, effective thickness and boundary conditions are viewed as random variables having specific probability distributions. The generated realizations of the input parameters are constrained by the prescribed statistics of the field. By accounting for the uncertainty of the input parameters and boundary conditions, the statistics of the groundwater travel time are obtained.

2. Random field generation technique

Equation (4) is regarded as a stochastic matrix equation which depends on the random input paramaters (T and be) and/or boundary conditions. The discretized form of equation (3) is also regarded as a stochastic equation with random input parameters for T and be. The GWTT probability distribution is determined using a Monte Carlo technique which involves repeatedly solving equations (2), (3) and (4) for the input parameters, subject to prescribed distributions. The technique used to generate values of the transmissivity at each node of the computational grid is underlain by the following assumptions: i) $Y = \log T$ is a random stationary space function, ii) Y is normal, i.e. T is lognormal, iii) Y, hence T, is completely defined, in a statistical sense, by its mean $m_Y = \log T_g$, where T_g is the geometric mean, and its two-point isotropic autocovariance C(r), where r is the distance between the two points, and iv) consequently, the values of Y at the grid nodes constitute a multivariate normal vector Y of mean m_Y and covariance matrix $C(r_{ij})$, (i,j=1,..,N), where r_{ij} is the distance between two nodes.

The generation of the random values of a multivariate normal vector is a routine procedure. Clifton and Arnett (1984) use an unconditional probability distribution of $\bar{Y}$ and assume a spherical covariance function,

$$C(r) = \begin{cases} C_0 - C_0[\,1.5\, r/s_0 - 0.5\, (r/s_0)^3\,] & \text{for } r < s_0 \\ 0 & \text{for } r > s_0 \end{cases}$$

where C_0 is the variance of Y.

Hence, the entire statistical structure of Y (and T) is given in terms of three parameters: m_Y, C_0 and the correlation range s_0. Clifton and Arnett (1984) assume that these parameters are known in a deterministic manner. m_Y and C_0 have been derived by linear regression on measurements of T at 13 locations in the Hanford site area, whereas the range s_0 has been given a few arbitrarily selected values.

To implement the stochastic method for GWTT estimation, additional parameters remain to be fixed. These are parameters used to solve the deterministic flow problem (e.g., geometry of the flow domain, type of boundary condition and size of numerical mesh).

B. Numerical Results

In the two reports (Clifton and Arnett, 1984 and Clifton, 1984), the DOE method of evaluation is applied to a particular set of input parameters (Reference Case).

1. Reference case

a. model input

In the Reference Case, the domain under study is a rectangle with dimensions 20 km by 10 km. Impermeable boundary conditions are set along the two longer dimensions. Constant head boundaries are set along the shorter dimensions so that the regional hydraulic head gradient is 10^{-3}. Effective thickness is deterministically set at a uniform value of 0.04 m. Figure 1 shows the flow domain and deterministic input as defined for the Reference

Case. The log-transmissivity is the only input parameter considered to be uncertain. The unbiased estimate of mean log-transmissivity required by the unconditional estimator is the logarithm of the geometric mean of the available data in Grande Ronde flow top (e.g., $\log_{10}(0.153\ m^2/day)$). The variance is 3.35 and the correlation range chosen is 5 km. The numerical grid is defined by 1 km x 1 km square domains.

b. results

With the above unconditional estimates of mean log-transmissivity and unconditional covariance matrix, the MNG was used to construct a suite of 600 random log-transmissivity fields in Clifton and Arnett (1984) and a suite of 10,000 random log-transmissivity fields in Clifton (1984). A finite element computer code, the MAGNUM-MC, was used by Clifton and Arnett (1984) while Clifton (1984) used a finite difference code, the PORMC. Clifton and Arnett (1984) found a GWTT distribution with a median of 17,000 yrs and standard deviation of $\log_{10}$(GWTT) of 0.71 while Clifton (1984), solving the same Reference Case, found for these two paramaters values of 21,500 yrs and 0.81, respectively.

The discrepancy between the two GWTT statistics in these studies raises several questions. The differences may have resulted from the fact that 600 simulations were not sufficient to converge toward a stable travel time distribution even though the authors assumed that the transmissivity field had been adequately sampled. The difference may have also resulted from the use of two different codes, as suspected by Clifton (1984). In that case, further investigations must be carried out to determine which code provides reliable results.

Several problems that arise on the median travel time become more crucial at the tail of the probability distribution. For example, it can be seen from Clifton (1984) (see Figure 2) that the median travel time does not stabilize even after 6,000 simulations. This problem would be more amplified in the tail of the GWTT distribution and a greater number of realizations would be needed to accurately assess the probability exceedance of 1,000 yrs. As a matter of fact, the number of Monte Carlo realizations utilized in order to depict the tail is probably small. As pointed out by Nguyen (1985), presentation of the GWTT probability distribution as a smoothed curve may be imprecise near the tail, which is the zone of interest. The investigators should provide an enlargement graph of the tail of the GWTT empirical distribution derived from the Monte Carlo analysis. A separate assessment of the interval of confidence, similar to that of Figure 2, should be provided for the tail region.

2. Sensitivity analysis to regional hydraulic head gradient and effective thickness

Clifton and Arnett (1984) present a sensitivity analysis of the GWTT distribution to uncertainty on regional hydraulic head gradient (G) and effective thickness (be). Uniform probability distributions were assumed to describe G and be. The ranges chosen were 10^{-4} to 10^{-3} for G and 10^{-3} to 10^{-1} for be. To demonstrate the progressive effect of additional parameter variability, two cases were considered:

Case 2: Stochastic transmissivity, regional hydraulic head gradient values and deterministic effective thickness.

Case 3: Stochastic values for transmissivity, regional hydraulic head gradient and effective thickness.

The GWTT distributions for these two cases were compared with those of the Reference Case. The median and log-travel time standard deviation are 86,000 yrs and 0.77 for case 2 and 81,000 yrs and 0.96 for case 3. In these two cases, the authors did not expand on the procedure used. The results are stated without any discussion. The number of Monte Carlo realizations is not given and the generation technique is not described. The only description of a generation technique in the case of a stochastic modeling of G and be is given in Clifton et al.(1983). The authors pointed out that a multivariate normal generator is used to construct a random field of a vector Y, where Y can be either log-transmissivity, effective thickness or regional head gradient. In the development, the vector Y is assumed to be normally distributed. However, if the same normal distribution was used for generating (be) and (G) in Case 2 and 3, its applicability to uniformly distributed variables had to be proved.

III. EVALUATION OF THE DOE APPROACH

A. Comments on the Method of Evaluation of GWTT Statistics

In this section, the DOE approach is evaluated. Their method relies on two assumptions: i) a Cohassett flow top that provides the fastest pathway to the accessible environment, ii) a GWTT probability distribution, derived from Monte Carlo simulations carried out in a numerical domain representing a restricted area of the formation, that is adequate to assess the actual occurrence of travel time in the Cohassett flow top. These two assumptions will be subsequently discussed.

1. Fastest probable pathway to the accessible environment

In the DOE's GWTT studies, the most likely pathway for radionuclide transport is assumed to go through the Cohassett flow overlying the preferred candidate horizon. This assumption has been substantiated by computations carried out by Clifton and Arnett (1984).

Clifton and Arnett (1984) computed the steady state groundwater velocity field in the Grande Ronde and the Wanapum formations. An overall vertical gradient of 2×10^{-3} was assigned to the Grande Ronde Basalt while a vertical gradient of 10^{-3} was assigned to the Wanapum. The computations were performed using the finite element computer code MAGNUM-MC. Four values for the ratio of the dense interior vertical conductivity to the flow top horizontal conductivity were considered (1.5×10^{-6}, 5×10^{-6}, 5×10^{-5} and 5×10^{-4}) in 4 successive simulations. It was found that i) a ratio of 5×10^{-5} or less is not sufficient to induce upward flow beyond the overlying Cohassett candidate horizon within the 10 km horizontal distance, ii) a conductivity ratio of 5×10^{-4} is sufficient to induce upward flow within the 10 km lateral distance. The authors concluded that the fastest pathway must be provided by the overlying flow top, since the travel time must be greater when an upward movement is induced.

In their simulations, the authors have only taken into account the effect of vertical hydraulic gradient. The actual post-closure conditions encountered in the repository are far removed from the isothermal conditions implicitly assumed by Clifton and Arnett (1984). A proper analysis of the post-closure natural barrier performance should account for the coupled thermo-hydrological processes. This problem may be of importance since the accessible environment lies only 250 m above the repository at a downgradient distance of 2 km (DEA, DOE 1984) (see Figure 3).

2. Method of evaluation of the GWTT probability distribution

The overall method of estimating GWTT statistics using stochastic modeling has been described in the previous section. As was pointed out, several parameters must be chosen. Parameters that describe the geostatistical transmissivity field must be identified. Flow domain geometry and boundary conditions must be prescribed in order to simulate the actual groundwater flow in the field.

The statistics of the travel time, obtained by considering the ensemble of travel times calculated in the various Monte Carlo simulations and its interpretation, depend on whether i) the ergodic hypothesis is obeyed, ii) the GWTT probability distribution derived from simulation over the restricted domain adopted in computations is close to the one derived for the actual domain, and iii) the identified statistics of the transmissivity (i.e., geometric mean, variance and correlation range) reflect accurately enough the transmissivity field heterogeneity.

These three aspects and their treatment in the forementioned DOE reports are discussed below.

a. <u>ergodicity</u>

Ergodicity for a stationary random function implies that all states of the ensemble are encountered in each realization (Beran, 1968). Whether this requirement is obeyed or not depends on the particular random function of concern. Starting with the transmissivity and the dependent velocity field, ergodicity prevails if the extent of the simulated domain is larger by factors of ten than the spatial correlation range. Since the range was selected to be 5 km, and the simulated area is a rectangle with dimensions 10 km by 20 km, it is quite improbable that ergodicity applied to these fields.

Even if the velocity field is stationary and ergodic, ergodicity is not necessarily obeyed by transport, i.e., concentration and travel time. For ergodicity to be obeyed, both input zone and compliance surface must have dimensions normal to the flow direction much larger than the concentration scale, or the travel distance has to be very large compared to the correlation scale to permit dispersion to ensure spreading over a large area (these conditions are discussed in Dagan, 1984). In terms of travel time, ergodicity would imply that the probability distribution obtained for a particle in an ensemble of realizations is close to the one derived for a large number of particles traced from the input zone in each realization.

The effect of non-ergodicity upon the interpretation of the GWTT distribution curve, P(t), obtained from Monte Carlo simulation, is quite dramatic. In the first extreme case of an integral scale of the transmissivity and velocity much smaller than the input and output zones, P(t) can be interpreted as a deterministic curve representing with certainty the relative number of solute particles launched at t=0 which have crossed the compliance surface at time t. In the opposite non-ergodic case, P(t) is a measure of uncertainty and represents the probability for all particles launched at t=0 to cross the compliance surface at time t. These two different interpretations may have a quite different impact upon the decision making process.

This important point of principle is discussed only briefly and superficially in the DOE reports. From the above discussion, it is clear that for a correlation range of 5 km, even if the repository were assumed to leak over its entire area (i.e., 1.6 km by 3.35 km), ergodicity would not have been obeyed. Since simulations were carried out for a single particle in each realization, ergodicity could not be verified empirically along the lines discussed above. It is therefore quite probable that the GWTT probability distribution, P(t), derived in DOE reports, should be viewed as representing uncertainty. This is generally the interpretation adopted by Clifton (1984), although in Clifton and Arnett (1984, pp 25 lines 1-17) it is claimed that the

GWTT probability distribution could be representative of the actual spatial distribution of GWTT.

b. influence of domain boundary

There are at least two approaches to selecting boundaries and boundary conditions in Monte Carlo simulations. The first is the case in which the layout of the boundaries and the conditions satisfied by head on them is known, and they are modeled accordingly. In the second case, in which the flow domain is of an extent which is large compared to the correlation scale and conditions of average uniform flow prevail, one may model only part of the formation with the belief that the results are insensitive to the size selected for the domain. In the latter case, the GWTT probability distribution would have been insensitive to the size of the formation, which was selected to be 10 km by 20km, for the condition of no flow through lateral boundaries. This is apparently not the case and the point is illustrated in Figure 4 (reproducing Fig. 25 in Clifton,1984) which shows the large impact of the domain width upon travel time distributions and particularly upon median time. Thus, this problem cannot be regarded as settled.

c. impact of variance of transmissivity statistical parameters

In any identification procedure, only estimates of the various parameters are obtained and those estimates are subject to uncertainty (This point has been discussed in the present context e.g., by Hoeksema and Kitanidis, 1984). This is particularly true in the case in which data are scarce or missing. On the 42 transmissivities compiled by Strait et al.(1984), 34 were given with a range of uncertainty of one order of magnitude when the transmissivities are expressed in ft^2/s, 3 were given by a deterministic value and 5 were given by a maximum or a minimum value. The geometric mean and the standard deviation are assumed to be deterministic by Clifton and Arnett (1984) and Clifton

(1984), but given the original data, the estimates of these quantities are subject to uncertainties. While the authors recognized this uncertainty for the case of the regional hydraulic head gradient, G, and the effective thickness, be, they did not consider it for the estimates of the log-transmissivity distribution. This inconsistency has already been pointed out by Nguyen (1985). Incorporating the estimation variance of all parameters simultaneously is bound to lead to larger variance of GWTT estimates. Some calculations along these lines will be carried out in the next section.

B. Analytical Assessment of the GWTT Probability Distribution

The GWTT probability distribution can be derived analytically for two particular values of the correlation range. The two curves obtained may suggest a bounding range for the probability of occurrence of the shortest travel times. The analytical derivation accounts for the uncertainty of the estimate of the transmissivity geometric mean as well as for the uncertainty of the hydraulic head gradient and the effective thickness. The two cases under study are mentioned by Clifton (1984), without considering uncertainty of the transmissivity geometric mean.

1. Small integral scale

The first case considered is of a transmissivity integral scale much smaller than the distance to the accessible environment. In this limit case, spatial variability does not affect the trajectories (except for a small dispersive effect), which become almost straight. The travel time t is then given by

$$t = \frac{L}{G} \frac{be}{T_g} \qquad (5)$$

where

T_g = transmissivity geometric mean,

be = effective thickness,

L = distance to the accessible environment (10 km),

G = regional hydraulic head gradient.

Unlike Clifton (1984), we shall follow the lines indicated by Nguyen (1985), namely, not only be and G, but also T_g is regarded as a random variable. Following Clifton and Arnett (1984), be and G are assigned uniform distributions, i.e.,

$$f(be) = 1 /(be_M - be_m) \quad (\text{ for } be_m < be < be_M) \qquad (6)$$
$$f(be) = 0 \quad (\text{ for } be < be_m \text{ or } be > be_M)$$

$$f(G) = 1 /(G_M - G_m) \quad (\text{ for } G_m < G < G_M) \qquad (7)$$
$$f(G) = 0 \quad (\text{ for } G < G_m \text{ or } G > G_M)$$

where be_M, be_m and G_M, G_m are the upper and lower values of the possible range for be and G respectively. Following Nguyen (1985), T_g is assumed to be log-normal. The distribution of $Y = \text{Ln } T_g$ is normal with mean m_Y and standard deviation σ_Y i.e.,

$$f(Y) = \frac{1}{\sqrt{2\pi}\,\sigma_Y} \exp\left[-(Y-m_Y)^2 / 2 \sigma_Y^2 \right] \qquad (8)$$

Under these conditions, the probability that the GWTT is smaller than t is given by the general formula

$$P(t) = \int_{be_m}^{be_M} f(be) \int_{G_m}^{G_M} f(G) \int_{A}^{\infty} f(Y)\, dY\, dG\, dbe \qquad (9)$$

where A = Ln(Lbe / Gt) and Ln stands for the natural logarithm.

Integration over Y using equation (8) yields

$$\int f(Y)\, dY = 1/2 \text{ erfc } \left(\frac{A - m_Y}{\sqrt{2}\, \sigma_Y}\right)$$

Using the auxilary formula (Abramowitz et al., 1972, p 304)

$$\int \exp(ax) \text{ erfc}[b(x+c)]\, dx = \frac{1}{a} \exp(ax) \text{ erfc}[b(x+c)]$$

$$+ \frac{1}{a} \exp((a/2b)^2 - ac) \text{ erf}[b(x+c) - a/2b] \qquad (10)$$

(where erf and erfc stand for the error function and the complementary error function), the integration over (G) and (be) can be carried out in a closed form. With f(be) and f(G) given by (6) and (7), P(t) results in the following closed form

$$P(t) = \frac{F(G_M, be_M) - F(G_m, be_M) - F(G_M, be_m) + F(G_m, be_m)}{(G_M - G_m)(be_M - be_m)} \qquad (11)$$

The function F(G,be) is given by the following relationship,

$$F(G,be) = \frac{be\ G}{2} [\text{erfc}(\text{Ln}(B/\sqrt{2}\, \sigma_Y)) + \frac{B}{2} \exp(\sigma_Y^2/2) \text{ erf}(\text{Ln}(B/\sqrt{2}\, \sigma_Y) + \sigma_Y/2)$$

$$- \frac{1}{2B} \exp(\sigma_Y^2/2) \text{ erfc}[\text{Ln}(B/\sqrt{2}\, \sigma_Y) - \sigma_Y/ 2] \qquad (12)$$

where $B = L\ be / (t\ G\ T_g)$

Using equations (18) and (19), P(t) can be plotted, the pertinent data being:

$$b_m = 10^{-3}\text{m}\ ,\ b_M = 10^{-1}\text{m},$$
$$G_m = 10^{-4}\ ,\ G_M = 10^{-3}, \qquad (13)$$

m_Y = Ln(0.153 m^2/day),

L = 10 km,

and σ_Y is given the value suggested by Nguyen (1985),

$$\sigma_Y = \mathrm{Ln}(10)\ \sigma_{\log T} \ / \ (N)^{1/2} \qquad (14)$$
$$= .65$$

where $\sigma^2_{\log T}$ is the variance of the base 10 log-transmissivity found by Clifton and Arnett (1984) (i.e., 3.35) and N the number of observations (i.e., 42). It should be mentioned that (14) is not conservative since it implies that the measurements of T are independent.

2. Large integral scale

The second extreme case is the one in which the integral scale I is much larger than the distance L. The transmissivity may then be assumed to be constant in the zone between the input and the compliance surface, and the GWTT is given again by equation (5). Since the variance of T_g (14) is much smaller than that of T and we neglect it, the cumulative probability distribution, P(t), is then given by the same equations (11) and (12) in which σ_Y is now replaced by the one derived by Clifton and Arnett (1984), i.e.,

$$\sigma_Y = (\mathrm{Ln}\ 10)\ (3.35)^{1/2} \qquad (15)$$
$$= 4.21$$

The probability distributions, P(t), for the limit cases are presented in Figure (5). An enlargement of the tail is shown on Figure (6). The tail of the curve depicting P(t) for a finite integral scale presumably falls between these two curves for the shortest travel times. Because the actual value of the integral scale is unknown, the probability of GWTT exceeding 1,000 yrs may fall between 93% and 73%. For the value of the integral scale chosen by Clifton and Arnett (1984), the results are closer to the upper limit.

3. Sensitivity to be and G distribution

The actual distribution of the effective thickness and the regional hydraulic head gradient are actually unknown. A different assumption on the distribution may lead to a different uncertainty range on the 1000 yrs probability of exceedance. To investigate such an effect, lognormal distributions, besides the uniform ones, were considered for be and G.

Equation (5) of the GWTT still holds for the two extreme cases. By taking the logarithm of each side of equation (5), we obtain

$$Ln(t) = Ln(L) + Ln(be) - Ln(G) - Ln(T_g)$$

With the normal distribution assumed for Ln(be), Ln(G) and $Ln(T_g)$, Ln(t) as a sum of three independent normal variables, has a normal distribution of mean

$$\langle Ln(t)\rangle = \langle Ln(L)\rangle + \langle Ln(be)\rangle - \langle Ln(G)\rangle - \langle Ln(T_g)\rangle \quad (16)$$

and variance,

$$\sigma^2_{Ln(t)} = \sigma^2_{Ln(be)} + \sigma^2_{Ln(G)} + \sigma^2_{Ln(T\ )} \quad (17)$$

For the purpose of comparison, the mean and standard deviation of the variables be and G are assumed to be equal to the ones derived from a uniform distribution, i.e.,

$$\begin{aligned} \langle X\rangle &= (X_M + X_m)/2 \\ X^2 &= (X_M^3 - X_m^3)/(3*(X_M - X_m)) - (\langle X\rangle)^2/4 \end{aligned} \quad (18)$$

where

X stands for either G or be

X_M, X_m are the upper and lower values of the possible range of G or be.

The mean and the standard deviation of Ln(be) and Ln(G) are then derived using the relationships that exist between the two first moments of a variable (X) and its logarithm (Z=Ln(X)) i.e.,

$$\langle Z \rangle = \mathrm{Ln}\left[\langle X \rangle / (1 + C_v^2)^{1/2} \right] \qquad (19)$$
$$\sigma_Z = \left[\mathrm{Ln}(1 + C_v^2) \right]^{1/2}$$

where

$$C_v = \sigma_X / \langle X \rangle$$

With the set of data considered already and described by the relations (13), (14) and (15), the lognormal distribution leads to a probability of a GWTT exceeding 1,000 yrs ranging from 99.8% to 74%. The comparison between these values and the ones obtained previously shows that the range of uncertainty on the probability of exceedance of the 1,000 yrs is not very sensitive to the distribution of the hydraulic gradient and the effective thickness (see Figure 5 and 6). Based on actual knowledge of the transmissivity field, the uncertainty range on the exceedance probability of 1,000 yrs cannot presumably be narrowed more than the 25% range found above. Hence, at this preliminary stage, the only conclusion that can be reached is that experiments to better characterize the pertinent parameters to the GWTT problem (e.g; transmissivity field, effective thickness..) are needed to reduce the present uncertainty on the exceedance probality for 1,000 yrs.

IV. CONCLUSIONS AND RECOMMENDATIONS

The DOE method of evaluating the GWTT distribution, presented by Clifton and Arnett (1984) and Clifton (1984), has been reviewed in this report. Several question marks have been raised. Different computer codes used to solve the groundwater flow problem for the same case yield different groundwater travel time distributions. The GWTT distribution derived by carrying out Monte Carlo simulations in a relatively small numerical domain is influenced by the domain size and the arbitrary choice of the impervious boundaries that confines the groundwater flow. The overall method of determining the GWTT distribution does not provide complete results, since the uncertainty of statistical parameters describing the transmissivity field has to be taken into account. The choice of a value for the integral scale has a large influence upon the results, and the particular value selected by the DOE is questionable. Analytical groundwater travel time distributions were derived for two extreme cases. These cases provide the upper and lower limit for the GWTT exceedance probability for 1,000 yrs. The results show that no justifiable conclusion on compliance with the GWTT objective can be made.

A few possible improvements to the numerical simulations developed by Clifton and Arnett (1984) and Clifton (1984) are suggested. These can lead to both increased accuracy and savings in computer time. They are mainly concerned with i) an improved simulated domain, ii) an increase in accuracy on the GWTT distribution tail area and iii) a better representativeness of the GWTT distribution obtained by simultaneously tracking a few particles.

The selection of the flow domain as a rectangle of restricted area bounded by two lines of constant head and two impervious boundaries may lead to different results from those obtained for a larger domain. To save computer time, simulations may be carried out in an extended domain in which the central zone is spatially variable and its transmissivity is simulated numerically, while the embedding matrix has a constant transmissivity equal to the geometric mean (see Figure 7).

Since we are interested mainly in the exceedance probability for 1,000 yrs, which corresponds to the tail of the GWTT distribution, the detailed calculation of travel time beyond a certain value (say, 2,000 yrs), is wasteful. It is suggested that the number of realizations of transmissivity field be increased to a very large number. The realizations in which transmissivities in the zone between the input and the compliance surface are sufficiently high should be separated from the rest of the realizations. The groundwater flow problem should be solved mainly for these latter realizations and for a sufficiently large number of times to ensure an accurate representation of the GWTT distribution tail zone. In order to improve the interpretation of the GWTT distribution, it is suggested that a cloud of particles on a line be followed in each realization.

All of these improvements can lead to a more precise travel time distribution only if the pertinent parameters entering the GWTT problem are accurately assessed. Better estimates of the statistical parameters describing the heterogeneous transmissivity field and the effective thickness remain, however, the key to any improvement.

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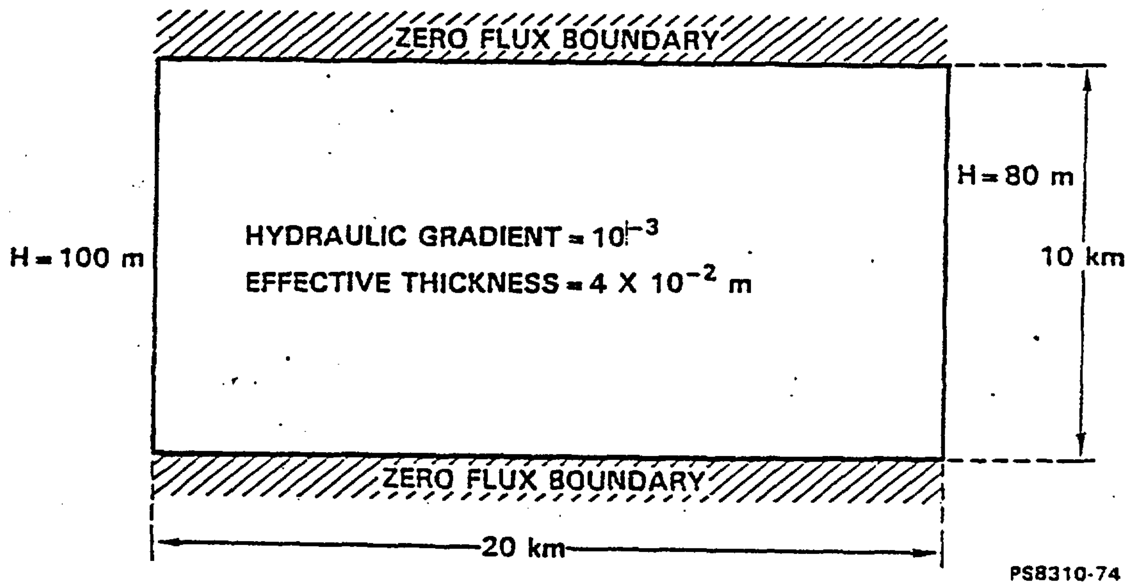
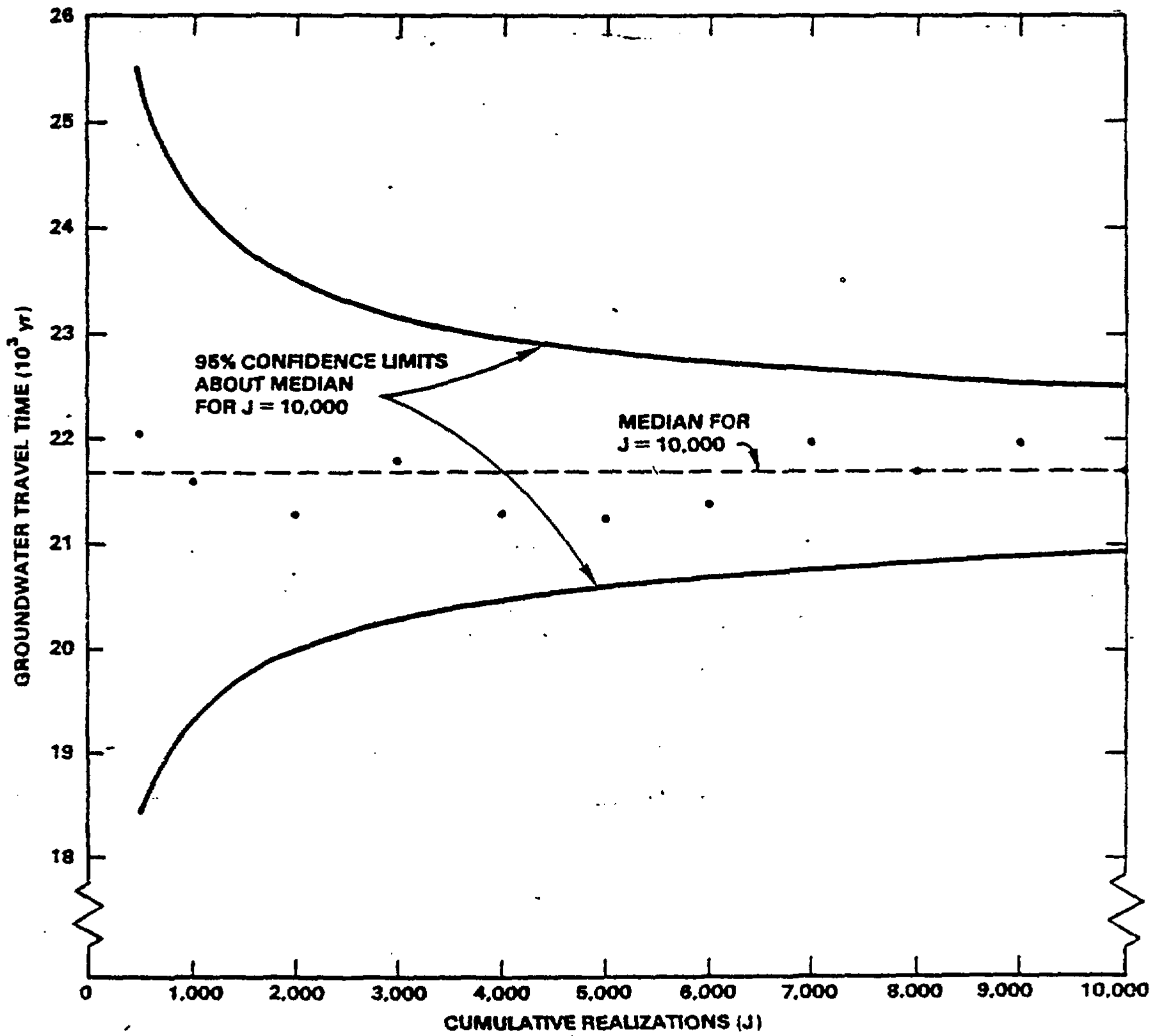


Model Domain and Deterministic Inputs For the Pre-Waste-Emplacement Stochastic Groundwater Travel Time Analysis

(ADAPTED FROM CLIFTON ET AL., 1984)



(ADAPTED FROM CLIFTON, 1984)

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Median Groundwater Travel Time 95% Confidence Interval, Reference Case Analysis.

2

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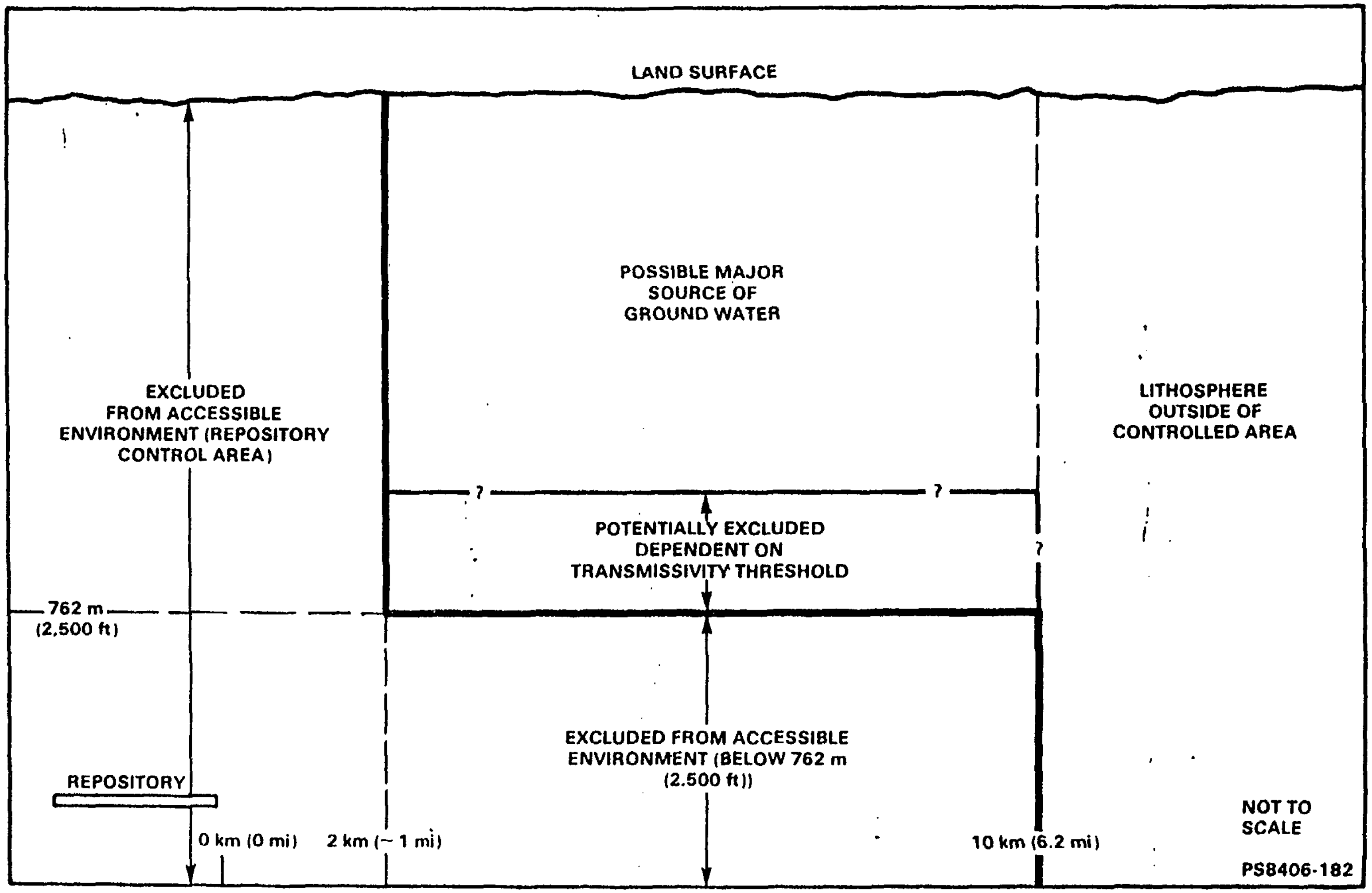
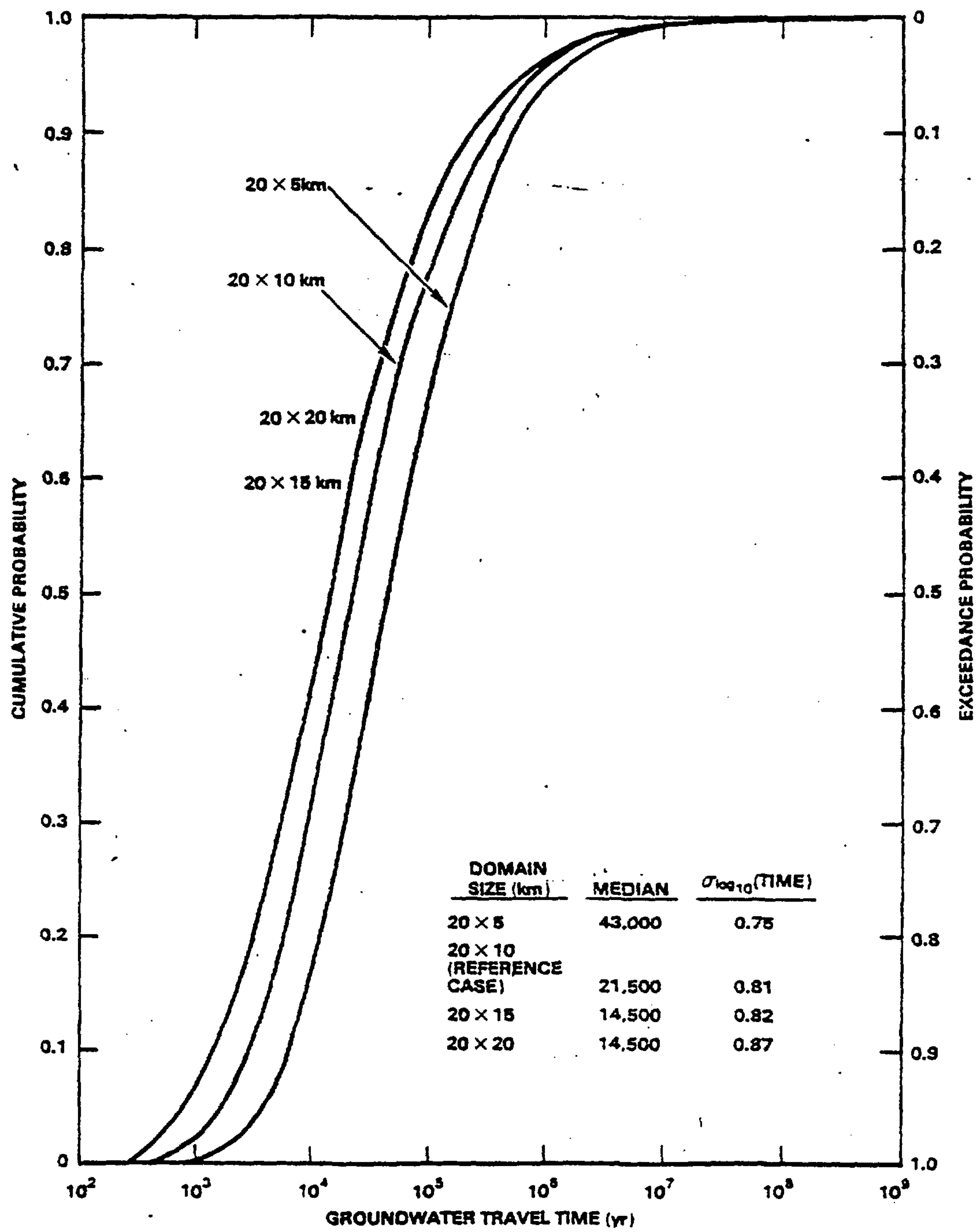


(ADAPTED FROM DOE, DEA, 1984)

Definition of accessible environment boundary.

3



(ADAPTED FROM FIGURE 25 OF CLIFTON, 1984)

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Distribution of Groundwater Travel Times from Models with Different Domain Widths.

4

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GROUND WATER TRAVEL TIME DISTRIBUTION

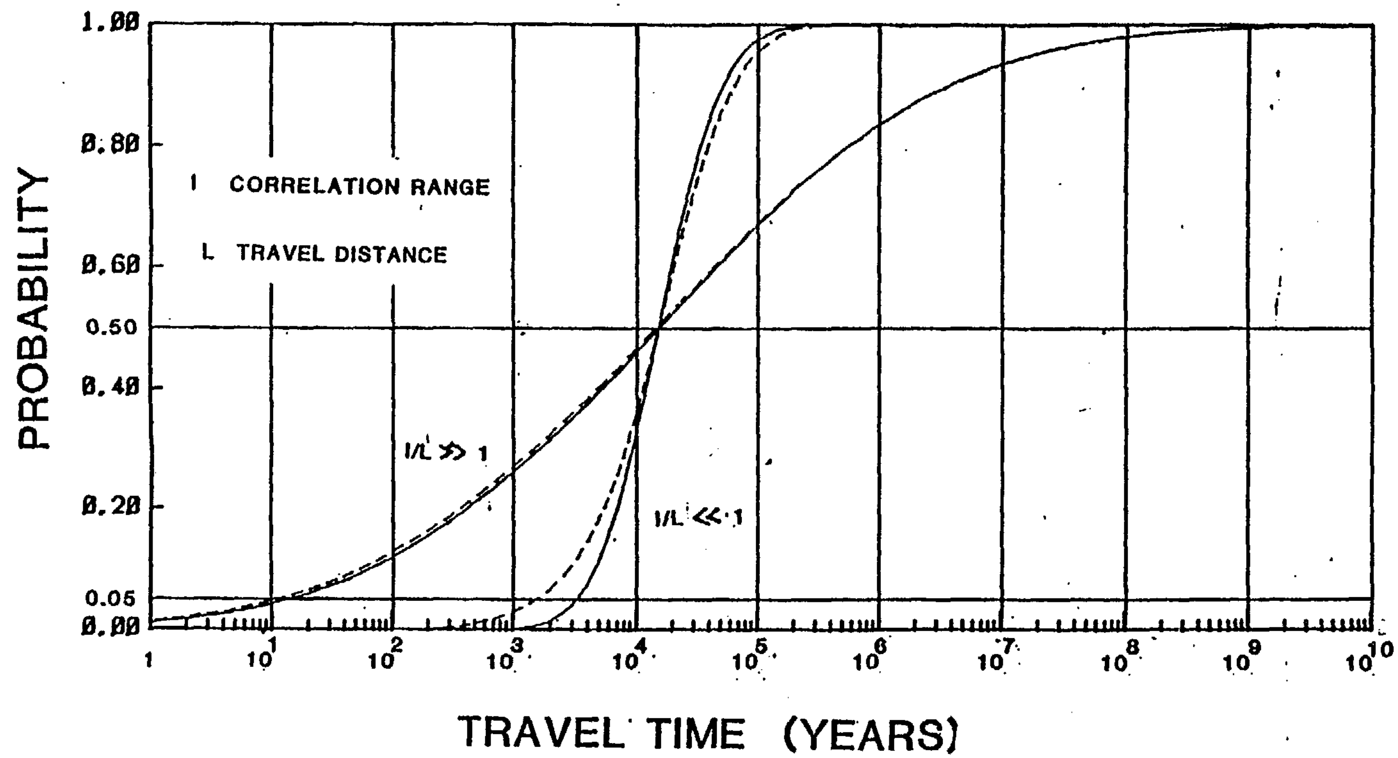
T, B_{NE}, G LOGNORMAL DISTRIBUTION

MEDIAN TRAVEL TIME **16000 YRS**

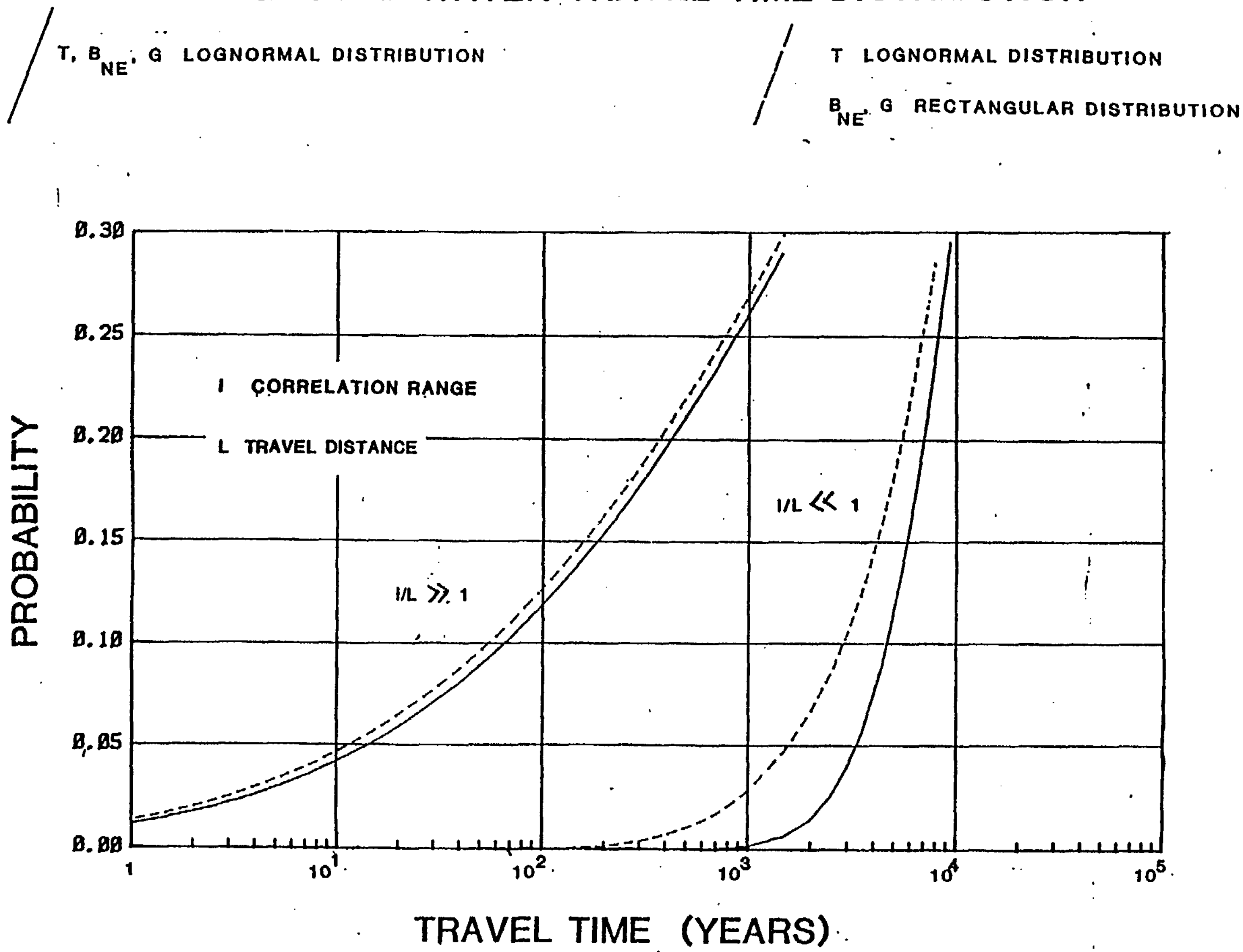
T LOGNORMAL DISTRIBUTION

B_{NE}, G RECTANGULAR DISTRIBUTION

MEDIAN TRAVEL TIME **16000 YRS**



GROUND WATER TRAVEL TIME DISTRIBUTION



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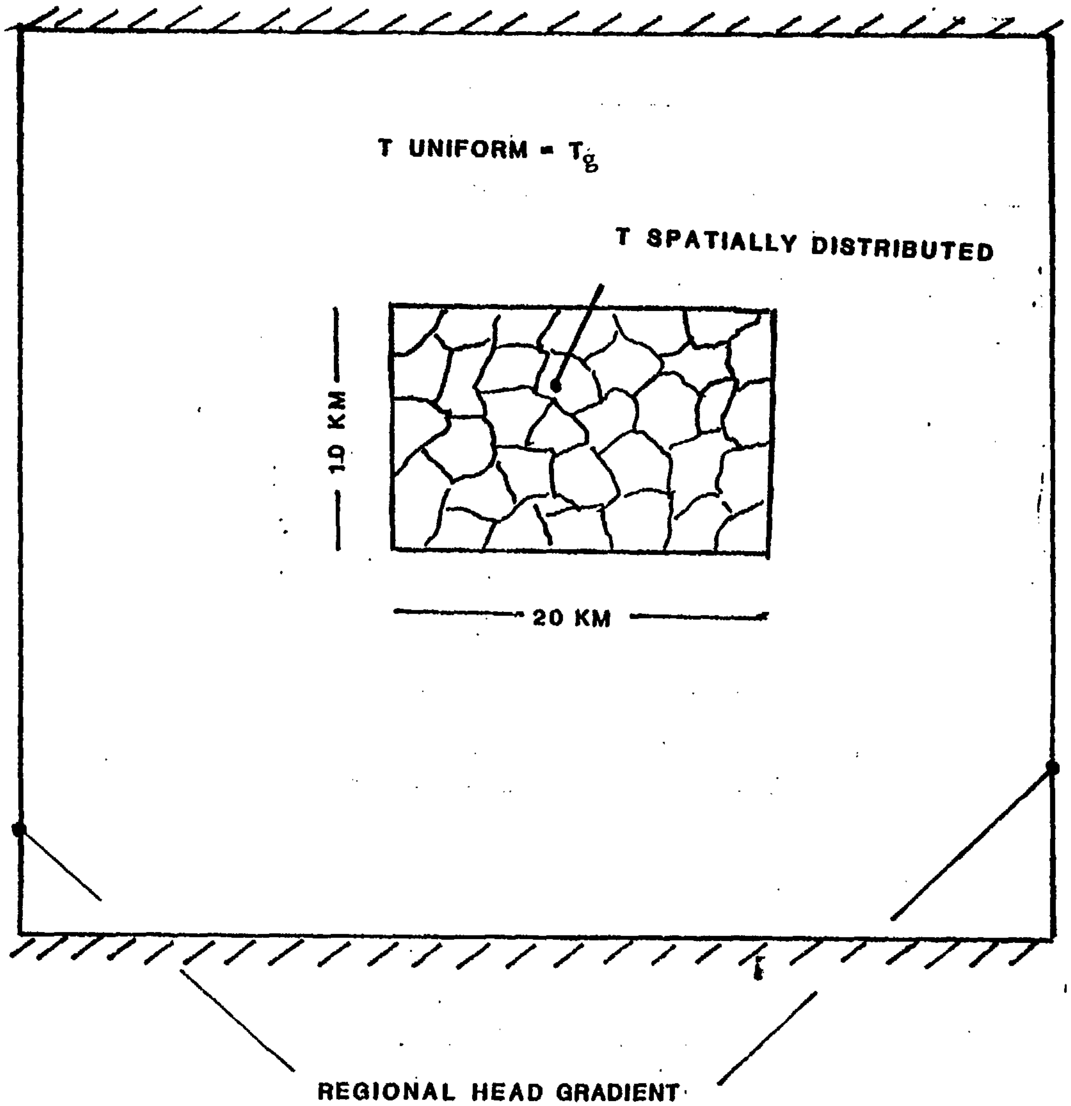
IMPROVED SIMULATION DOMAIN

7



ESTABLISHED BY THE
TREATY OF JUNE 9, 1855
CENTENNIAL JUNE 9, 1955

CONFEDERATED TRIBES AND BANDS
Yakima Indian Nation

GENERAL COUNCIL
TRIBAL COUNCIL

POST OFFICE BOX 151
TOPPENISH, WASHINGTON 98948

August 4, 1986

Mr. O.L. Olson, Project Manager
Basalt Waste Isolation Project Office
Department of Energy
Richland Operations Office
P.O. Box 550
Richland, WA 99352

Dear Mr. Olson:

In regard to the review of the BWIP hydrogeology works, our technical consultants have submitted to our office the enclosed report on DOE Analysis of Groundwater Travel Time.

Because the groundwater travel time is an important indicator of the geologic suitability of the Hanford Site, I hope you shall consider these comments and let us know of your response to our concerns.

If you have any questions, please do not hesitate to contact me.

Sincerely,

YAKIMA INDIAN NATION

Russell Jim, Manager
Nuclear Waste Program

Enclosures

RJ/skC