SURFACE WATER FLOW HAZARDS AROUND THE EXPLORATORY SHAFT FACILITY

REVIEW OF SAND85-0598

BY:
E. ROVEY, P.E.

March, 1989

PRELIMINARY DRAFT
CENTER TECHNICAL REVIEW
NOT COMPLETED

1.0 RUNOFF RATES AND VOLUME

The probable maximum flood (PMF) is used as the design storm basis for the evaluation by the authors. The basic assumption of the authors, as is a standard in the hydrologic field, is that the PMF is produced by the occurrence of the probable maximum precipitation (PMP).

An evaluation of the adequacy of the PMF as the design event and the results of the PMF study for the ESF site (Bullard, 1986) were made by this reviewer and presented in the review document "Review of Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program", dated April, 1988. The results of the earlier review were that:

- The 3,350 cubic feet per second (cfs) PMF computed for the ESF site was a conservatively high estimate for an extreme thunderstorm of 6 hours duration that was based upon current meterology and hydrologic procedures.

- The risk of a PMF occurring in any 1,000 year interval is 0.1 percent (0.001).

The volume of water which the thunderstorm PMF (the thunderstorm is more severe than the general storm) is predicted to produce, from the 122 acre contributing drainage area, 129 acre-feet. This runoff volume is 91 percent of the total volume of the 13.9 inch PMP. This high percentage of runoff is a conservatively high estimate of the volume of runoff which could occur from such an arid environment as the NTS.

2.0 FLOOD ELEVATIONS

A primary objective of the authors of the reviewed document was to analyze the depth of flow which would occur from the PMF. The flow depth determines the lateral extent of the flood boundary which indicates the potential hazard of the PMF to the ESF.

The authors conducted a hydraulic analysis based upon the existing topographic relief of Coyote Wash with the "working pad" imposed on the area. The pad will provide a working surface around ES-1 and ES-2. The elevation of the collar of the exploratory shafts is approximately 4130 feet mean sea level datum. The hydraulic analysis was based on the Manning's formula for computing velocities applied to 5 cross section on the wash. Sections were located such that individual cross sections were placed at both the ES-1 and ES-2 proposed shafts. Results of the hydraulic analysis are summarized in Figure 3-6 of the report.

The authors reached the conclusion that the maximum water level of the thunderstorm PMF, increased 50 percent to account for possible debris flow, would be 15 feet and 37 feet **below** the 4130 feet pad elevation at the ES-1 and ES-2 cross section. Therefore, the drainage channel, even when modified for the pad geometry, has substantially more capacity than is required by the PMF.

This reviewer conducted an independent hydraulic analysis of the Coyote Wash drainage channel to determine its capacity. This review analysis was performed at six cross sections. The two cross sections a ES-1 and ES-2 were repeated from the authors study. These two cross sections were taken from Figures 3-4 and 3-5. The other four sections were taken from the best available topographic mapping of the channel.

The six cross sections formed the geometric basis for the computer model, HEC-2 Water Surface Profiles (Corps of Engineers, Hydrologic Engineering Center, September 1982). The flow resistance factor of Manning's n = 0.06 was input to the model because this factor was used by the authors.

This reviewer found that the computed peak PMF water level elevations could be replicated (plus or minus 1 foot) from the authors' document at ES-1 and ES-2 if one major restriction was placed on the computer model. That condition was: computed flow was at minimum specific energy, i.e. the flow depth was at critical depth. However, because the channel slope is steep in that reach (6 percent), a computer run was made, all other inputs the same, which analyzed if the flow depths could be less than critical depth. It was found that the depth was less than the critical depth throughout the reach, i.e. the flow was at supercritical condition.

The lower supercritical depths would mean that less of Coyote Wash would be inundated during a PMF but the flooded area would be subjected to higher velocities and more likely to erode. Table 1 is a comparison of the computed velocities at the exploration shaft cross sections.

Table 1. Velocities At ES-1 & ES-2

Exploratory Shaft	Fernandex, et. al. Critical Flow	Current Estimate Supercritical Flow
ES-1	14.1 fps	23.4 fps
ES-2	13.0 fps	20.3 fps

These velocities are computed at the deepest portion the channel and hence would be the highest velocities in the section.

The supercritical flow velocities are significantly greater than for the critical flow conditions. However, there exists some evidence to indicate that supercritical flows are not normally maintained in natural, alluvial channels like Coyote Wash. The erosive action of the water rapidly erodes the slope to a shallower slope, onchannel is widened, etc.

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It is unlikely that the existence of more erosive velocities than previously estimated will jeopardize the performance of the ESF. However, more engineered structures or riprap will need to go into the base of the working pad for the ESF to prevent damage to the pad in the event of a substantial flood.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT: Barr, G.E., 1985, Reduction of the Well Test Data for Test Well USW H-1, Adjacent to Nevada Test Site, Nye County, Nevada: SAND85-0637, Sandia National Laboratories, Albuquerque, New Mexico and Livermore, California, 36 p.

REVIEWER: Williams and Associates, Inc.

DATE REVIEW COMPLETED: November 1985

BRIEF SUMMARY OF DOCUMENT: DATE APPROVED:

The purpose of the report under review is to present an independent analysis of aquifer test data collected by the USGS for well USW H-1. Data reduction for the report under review was conducted with the computer code PUMP (Barr, Miller, and Gonzalez, 1983). A listing of the code used in the report under review is given in Appendix C of the report. The code was used to evaluate the sensitivity of the aquifer test results through changes in hydraulic conductivity and storativity in potential boundary conditions in the vicinity of the well.

The procedure used to evaluate the hydraulic conductivity estimates for well USW H-1 is as follows:

1) Initial values for hydraulic conductivity, storativity, and distance to any hydrogeologic boundary were estimated.

2) Values of hydraulic conductivity and storativity were juggled by trial and error until an approximate fit between the calculated and observed values was found.

3) After a reasonable match between the calculated curves and the actual test data was obtained by juggling the hydraulic conductivity and storativity values, the added effects of potential hydrogeologic boundaries were evaluated.

4) The character of hydrogeologic boundaries (i.e., barrier or recharge) as well as distance from well USW H-1 were juggled

to obtain improved agreement between the calculated curves and the actual test data.

Three pump tests and three recovery tests over the depth intervals of 572 through 688 meters, 687 through 1,829 meters, and 687 through 1,829 meters, and six injections tests over the intervals 687 through through 697 meters, 811 through 1,829 meters, 926 through 1,829 meters, 1,200 through 1,829 meters, 1,407 through 1,829 meters, and 1,621 through 1,829 meters were evaluated by the procedure outlined above.

The report under review notes that the integrated total hydraulic conductivity of the penetrated portion of the saturated zone (687-1,829 meters) obtained by the numerical method (1.67×10^{-7} m/sec) and by Rush and others (1983) (1.16×10^{-7} m/sec) is essentially the same. However, the report notes also that hydraulic conductivity values estimated for individual tests differ from those estimated by Rush and others (1983) by up to an order of magnitude. Storativity values estimated by the numerical method and by Rush and others (1983) differ typically by one order of magnitude. The report under review notes that an upper zone, approximately 100 meters thick, is characterized by relatively high hydraulic conductivities in the range of about 10^{-4} to 10^{-6} m/sec; below this zone, hydraulic conductivity of the volcanic rocks appears to be several orders of magnitude lower.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review does not present any new data or new interpretations of the data collected from test well USW H-1. Therefore, the significance of the report to the NRC waste management program is in the usual sense.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

The report under review claims to provide an independent confirmation of hydraulic conductivity estimates for test well USW H-1. However, because of the nature of the limiting assumptions incorporated into the numerical method (i.e., the same assumptions that are inherent in the theoretical models used by Rush and others (1983) to analyze the test data), it is not surprising that the numerical method would support the estimates of hydraulic conductivity obtained by Rush and others (1983). The major limiting assumption of the numerical method discussed in the report under review and inherent in the theoretical model used by Rush and others (1983) to analyze the test data is that the fractured tuff can be represented by a homogeneous and isotropic porous medium. Another major assumption incorporated into the numerical method is that the packed off intervals of the well were assumed to represent an effective porous medium in a saturated confined aquifer. This assumption requires that deviations of the data plots from the predicted responses, based on the theoretical models, must be due to the effect of hydrogeologic boundary conditions (i.e., barrier boundary or recharge boundary). The numerical method is not capable of evaluating potential effects of leaky-aquifer conditions or the transition from early time to late time in an unconfined aquifer or a double-porosity system.

SUGGESTED FOLLOW-UP ACTIVITY:

No follow-up activity is suggested with respect to the report under review.

REFERENCES CITED:

Rush, F.E., Thordarson, William, and Bruckheimer, Leura, 1983, Geohydrologic and Drill-hole Data for Test Well USWH-1, Adjacent to Nevada Test Site, Nye County, Nevada: USGS Open-file Report 83-141, Denver, 38 p.

Barr, G.E., Miller, W.G., and Gonzalez, D.D., 1983, Interim Report on the Modeling of the Regional Hydraulics of the Rustler Formation: SAND83-0391, Sandia National Laboratories, Albuquerque, New Mexico.

1.0 INTRODUCTION

WWLNUM:	227
DOCUMENT NO.:	SAND85-0854C
TITLE:	"The Effect of Percolation Rate on Water-Travel Time in Deep, Partially Saturated Zones"
AUTHORS:	Peters, R. R., Gauthier, J. H., and Dudley, A. L.
PUBLICATION DATE:	1985
REVIEWER:	Water, Waste & Land, Inc.
DATE REVIEW COMPLETED:	June 27, 1986
SCOPE:	General review of conceptual model used as basis for calculations. Specific review of data used and results obtained. Reviewed in the context of determining important site characterization activities.
KEY WORDS:	Groundwater Travel Times; Percolation Rate; Unsaturated Flux; Dual Porosity; Fracture Flow.
DATE APPROVED:	mgR 7/7/86

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 SUMMARY OF DOCUMENT

The document presents a hydrologic conceptual model of Yucca Mountain. A mathematical model which describes the unsaturated flow mechanisms occurring in the mountain is also presented. Data available for use with the mathematical model are tabulated and results of the flow calculations are provided.

The hydrologic conceptual model presented divides the various geologic units into three basic hydrologic groups:

1. Densely welded tuffs that are highly fractured.
2. Nonwelded, vitric tuffs that have few fractures.
3. Nonwelded, zeolitized tuffs that have few fractures.

The actual hydrologic units used in the one-dimensional calculations are, from youngest to oldest, the welded Tiva Canyon (TCw), the nonwelded Paintbrush Tuff (PTn), the upper, welded Topopah Springs (TSw1), the middle and lower welded Topopah Springs (TSw2-3), and the nonwelded Calico Hills (CHn). The Calico Hills unit is subdivided into vitric (CHnV) and zeolitic (CHnZ) subunits.

The mathematical model used to determine the movement of water in the fractured, rock mass is based on these important assumptions:

1. A unit change in the quantity total saturation times pressure head at a point causes a unit change in the local stress field.
2. Fluid flow can be calculated using Darcy's equation.
3. The pressure heads in the fractures and the matrix are identical in a direction perpendicular to the flow lines.

The total flux flowing through the mountain at any time is then the sum of the flux in the fractures and the flux in the matrix. The water velocity in either the fracture or the matrix is the Darcy flux divided by the area through which the water moves. Both saturation and permeability (and hence flux) are functions of the pressure head. The time required for water to travel across one of the hydrologic units is then the thickness of the unit divided by the velocity of the water in the unit. Two travel times are possible, matrix and fracture. The steady-state module of the TOSPAC computer code was used to determine the one-dimensional movement of water.

The physical properties used in the mathematical model, hydraulic conductivity, porosity, residual saturation, and curve fitting coefficients were based on a variety of sources including reports by Peters et al. (1984), Scott et al. (1983), and Sinnock et al. (1984). Representative properties were assigned to each of the hydrologic units, for both fracture and matrix.

Calculations were performed for six cases, three values of unsaturated flux, 0.1, 0.5, and 4.0 mm/yr, for each of the Calico Hills subunits (CHnv and Chnz). Pressure head distributions, saturation and water velocities are presented as functions of distance above the water table for each of the cases. Travel times from the repository to the water table for each of the cases are listed in the following:

Percolation Rate (mm/yr)	Travel Time Vitric Unit (yrs)	Travel Time Zeolitic Unit (yrs)
0.1	410,000	400,000
0.5	85,000	81,000
4.0	8,400	3

The authors of the report provide the following conclusions:

1. Using current estimates of percolation rate, water movement is confined to the matrix and travel times are on the order of hundreds of thousands of years.

2. Travel times are very sensitive to percolation rate and an increase in percolation rate may initiate fracture flow and reduce travel times significantly.

2.2 SUMMARY OF REVIEW CONCLUSIONS

In general, it is believed that the document is quite useful. The data and results presented allow the reader to quickly grasp the concepts being presented. The method of presenting the various output parameters (pressure head, saturation, etc.) as functions of depth is particularly useful since it allows a rapid qualitative check of the results. These graphs also demonstrate the effects of a layered system very nicely.

As the mathematical model was described in a separate report which has also been reviewed by WWL, we have implicitly assumed that the computational concepts used are appropriate. Therefore, our comments are basically directed at the data used in the calculations. Since the amount of data available is limited, the so called representative values for the parameters are certainly not statistically representative. However, input matrix parameters are based on limited measured values and appear to be reasonable. Input data for the fractures, on the other hand, is based on theoretical concepts (with the possible exceptions of conductivity and porosity) and, therefore, may not be representative. Since the change in water velocity is very sensitive to whether or not fracture flow is occurring, these parameters are probably very important and may have large effects on the overall solution obtained.

In summary, the report is well done and provides valuable insight into the flow phenomena which are believed to be occurring at Yucca Mountain. The additional data collected during site characterization should include measurement of fracture properties to add confidence in the parameter values used as input to the model.

3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The DOE has concluded that evidence does not support a finding that the site is unlikely to meet all of the guidelines. Therefore Yucca Mountain has been chosen for site characterization, to determine if the site is indeed suitable for a repository. Tests will be performed in two shafts and in drifts at the proposed repository depth to determine the geologic and hydrologic properties of the various units. These tests will provide information which can be applied to determine if the Yucca Mountain site can meet regulatory requirements.

Flow of water through the unsaturated zone is a mechanism by which radionuclides could travel from the repository to the accessible environment after closure. The DOE considers this unsaturated zone to be the most significant barrier to waste migration at Yucca Mountain as the total flux of water is limited through this zone. This low flux limits the dissolution rate of the engineered canisters in which the waste is stored and the amount of water which can transport dissolved radionuclides.

The unsaturated zone at Yucca Mountain consists of a number of distinct hydrologic units all of which are fractured to a varying degree. Therefore, the flow phenomena occurring in the unsaturated zone takes place in a dual porosity system. Flow can take place in the matrix, in the fractures, or in both simultaneously. If fracture flow occurs, rapid flow times from the repository to the accessible environment may be possible. The prediction of the effects of flow in the unsaturated zone is critical to evaluation of site performance. The mathematical model presented in this paper provides a mechanism by which data collected during site characterization can be utilized to predict repository performance. In addition, the report provides initial evidence that the Yucca Mountain site will be able to meet regulatory guidelines.

4.0 DETAILED REVIEW (Problems, Deficiencies and Limitations)

The mathematical basis for the model used to estimate travel times is described in a separate report by Klavetter and Peters (1985). Therefore, the following discussion deals primarily with the application of the model and the data utilized rather than the theoretical relevance of the model. A separate review of the development of the mathematical model has also been performed by WWL.

It is assumed that the flow is occurring under steady conditions. Over much of the flow domain the gradient becomes unity under such conditions. While it is likely that the hydrologic units which are above the repository horizon dampen the infiltration pulses which occur at the surface as a result of precipitation events, little evidence has been presented which illustrates that the length of the transient phase of flow is short after a change in pluvial conditions. Due to the extremely tight nature of some of the matrix materials, achieving steady-state conditions between the fracture and matrix subsystems may require long periods of time. This may effect fracture saturation and, therefore, travel times.

4.1 MATRIX PROPERTIES

Matrix properties for each of the hydrologic units were assumed uniform throughout the unit. The values used were assumed to be the representative values described by Peters et al. (1984). These values are based on lab tests performed on core samples taken from two drill holes located on Yucca Mountain (Test Holes G-4 and GU-3). A total of 29 samples from G-4 and 19 samples from GU-3 were tested for saturated matrix conductivity and moisture retention characteristics. Of these samples 39 were from the unsaturated units above the water and 28 were from the Topopah Springs and Calico Hills units which lie between the proposed repository location and the water table.

Using the lab tests results, Peters et al. (1984) attempted to select representative samples for each of the units based on the following criteria (listed in order of decreasing importance):

1. Pressure-Saturation Curve Shape.
2. Saturated Hydraulic Conductivity.
3. Porosity and other bulk properties.

In the original work it was concluded that the TSw3 hydrologic unit (the basal vitrophyre of the Topopah Springs welded unit) could be represented by sample GU3-11 and the TSw2 unit (the Topopah Springs welded unit) could be represented by sample G4-6. In the present work these units are combined (TSw2-3) because the TSw3 unit "is relatively thin (about 15m) and has rock mass hydrologic properties similar to those of TSw2." It might also be added that results of tests have been reported for only four TSw3 samples.

The above discussion is not intended to detract from the work performed and reported in the document under review. It does indicate, however that the representativeness of the parameters used in the calculations is based on judgement rather than statistical considerations. As the authors indicate, the results presented are 'first-cut' and are based on available data and interpretations. It should also be noted that the mathematical model described might be used to determine the sensitivity of the solution to the various parameters. This may be helpful in identifying parameters, which should be emphasized during site characterization.

4.2 FRACTURE PROPERTIES

The representative fracture properties were obtained from Peters et al. (1984) and Scott et al. (1983). Tests reported by Peters et al. (1984) were performed on 5 fractured samples - 2 from unit TSw2, one from unit CHnV and 2 from unit CHnZ. Fracture aperture and conductivity were supposedly based on these results but in most cases it is difficult to correlate values between the two reports. In addition the extremely small samples, cylinders 6 cm in diameter and 8 or 15 cm in length, make the results somewhat questionable at any rate. Each sample had one crack or fracture extending along the long axis of the cylinder. Fracture density for each of the units is taken from Scott et al. (1983). These values were reported for drill hole USW-GU3/G3.

Unsaturated hydraulic properties were not based on measurements but on theoretical considerations. Wang and Narisimhan (1985) provide a statistical approach to developing a pressure-saturation relationship for the fractures. To quote the authors of the paper under review, "Their fracture saturation curve is similar to that of a coarse sand as shown in Freeze and Cherry's text (1979, p. 42)." The same values for the van Genuchten (1978) fitting parameters (S_r, α, and β) are used for the fractures of all units, therefore.

As the above discussion indicates, the representative fracture properties are based on even fewer measured data than the matrix properties. While it is apparent that it may be very difficult to devise tests which can be conducted in a reasonable time on a representative sample of fractured material, it is equally apparent that such tests are necessary to overcome some of the shortcomings noted above.

5.0 RECOMMENDATIONS

It is recommended that the model described in this document be used to analyze the sensitivity of travel time to the various matrix and fracture properties. The viability of vapor transport as a mechanism of significant water movement should also be further investigated. If the percolation rates are indeed as low as believed, vapor movement may be very important.

6.0 REFERENCES

Freeze, R. A., and J. A. Cherry, 1979. "GROUNDWATER," Prentice-Hall, Inc., Englewood Cliffs, NJ.

Klavetter, E. A. and R. R. Peters, 1985. "Fluid Flow in a Fractured Rock Mass," SAND85-0855, Sandia National Laboratories, Albuquerque, New Mexico.

Peters, R. R., E. A. Klavetter, I. J. Hall, S. C. Blair, P. R. Heller, and G. W. Gee, 1984. "Fracture and Matrix Hydrologic Characteristics of Tufaceous Materials from Yucca Mountain, Nye County, Nevada," SAND84-1471, Sandia National Laboratories, Albuquerque, New Mexico.

Scott, R. B., R. W. Spengler, A. R. Lappin, and M. P. Chornack, 1983. "Geologic Character of Tuffs in the Unsaturated Zone at Yucca Mountain, Southern Nevada," in "Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal," edited by J. Mercer, Ann Arbor Science, Ann Arbor, MI.

Sinnock, S., Y. T. Lin, and J. P. Brannen, 1984. "Preliminary Bounds on the Expected Postclosure Performance of the Yucca Mountain Repository Site, Southern Nevada," SAND84-1492, Sandia National Laboratories, Albuquerque, New Mexico.

van Genuchten, R. 1978. "Calculating the Unsaturated Hydraulic Conductivity with a New Closed Form Analytical Model," Water Resources Bulletin, Princeton University Press, Princeton University, Princeton, New Jersey.

Wang, J. S. Y., and T. N. Narasimhan, 1985. "Hydrologic Mechanisms Governing Fluid Flow in Partially Saturated, Fractured, Porous Tuff at Yucca Mountain," SAND84-7202, Sandia National Laboratories, Albuquerque, New Mexico.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: SAND85-0854C

DOCUMENT: The Effect of Percolation Rate on Water Travel Time in Deep, Partially Saturated Zones. R.R. Peters, J.H. Gauthier, and A.L. Dudley, Nevada Nuclear Waste Storage Investigations Project Department, Sandia National Laboratory, Albuquerque, NM.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: May 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report uses a computer code, TOSPAC, along with a conceptual model very similar to that used by Klavetter and Peters (1985). The model does not include the effect of vapor transport but it does treat the effect of compressibilities of the water, of the porous matrix and of the fractures on unsaturated vertical flow.

The code is used to determine the pressure, saturation levels, and velocity distributions for water percolation rates (fluxes) of .1, .5 and 4.0 mm/yr in Yucca Mountain. Two profiles are used: the first is for the Calico Hills vitrified unit; the second is for the Calico Hills zeolitized unit. Calculated travel times from the repository location to the water table are as low as three years for a flux of 4.0 mm/yr in the zeolitized unit and 8400 years for the same flux in the vitric unit. All other travel times are greater than 81,000 years.

This paper presents the most comprehensive treatment of travel times through the unsaturated zone at Yucca Mountain that we have reviewed.

BRIEF SUMMARY OF DOCUMENT:

The authors divide the hydrogeologic units of Yucca Mountain into three groups: 1) densely welded tuffs that are highly fractured,

2) nonwelded vitric tuffs that have few fractures, and 3) nonwelded zeolitized tuffs that have few fractures. The first set of tuffs (first group) has low assumed saturated matrix conductivity (10^{-11} m/s or less) and high assumed saturated fracture conductivity ($\sim 10^{-9}$ m/s). The second group has high assumed saturated matrix conductivity (10^{-6} to 10^{8} m/s) and low assumed saturated fracture conductivity ($<10^{-8}$ m/s). The third group has low assumed saturated matrix conductivity (10^{-11} m/s or less) and higher saturated fracture conductivity ($>10^{-11}$ m/s).

The authors present a brief summary of the various flow rates of water through Yucca Mountain that have been reported in the literature; they also present a short discussion of vapor movement. A mathematical model and a computer program (TOSPAC) are developed and used in the report. The program does not consider vapor transport, but it does treat the effect of compressibility of water and of the rock matrix. The authors assume that Darcy's law is valid and that the pressure heads in the fractures and the matrix are equal in a direction perpendicular to the flow lines. Van Genuchten's (1978) saturation vs. pressure head relationship and Mualem's (1976) conductivity vs. pressure head function are used in the program. The values of physical and hydraulic parameters used in the calculations are from reports by Peters et al. (1984), Scott et al. (1983), and Sinnock et al. (1984). The data in these reports were obtained from samples removed from Yucca Mountain. The equation used in the mathematical model contains terms for the storage of water due to the saturation of the matrix and the fracture systems, and terms representing compressibility of water and dilation of the bulk rock. All these terms are functions of the pressure head in the water. The solution of the equation results in determination of the pressure and saturation level distributions as well as the groundwater velocity and the water flow rate (in the form of travel time) across the hydrogeologic units of Yucca Mountain. The velocity also is a function of the percolation rate and the composition (vitric or zeolitized) of the Calico Hills unit. The various coefficients in the equation are called capacitance coefficients. Curves are presented for the coefficients as functions of pressure head. Composite conductivity curves are presented for the Topopah Springs and the Calico Hills nonvitrified unit. These curves are presented as curves for fracture conductivity, for matrix conductivity and the for the composite conductivity.

Fluxes used in the simulation were .1, .5, and 4 mm/yr. Each of these rates was used with either the vitric or zeolitic portions of the Calico Hills unit. The cases with an infiltration rate of .1 mm/yr assumed water movement only in the matrix throughout the hydrostratigraphic column. The cases with a rate of .5 mm/yr display a relatively small amount of water movement in the fractures of some units. The case with a 4 mm/yr rate reflect considerable water movement in the fractures in the Tiva Canyon and Topopah Spring units. Pressure head vs. distance above the water table are plotted for the six cases studied. These graphs are similar to the analytical solution that can be obtained for unsaturated flow through layered material.

Considerable discussion is presented about the changes of capillary pressure at interfaces and the appearance of nearly discontinuous pressures in the aforementioned graphs. Pressures in this situation are not discontinuous, but regions of very high pressure gradients do occur. Discussion also is presented of possible errors in percolation rates in these regions of large capillary pressure gradients. However, the authors do not elucidate their reasons for concluding that percolation rates are in error in these regions. The error is less than 5% and it could be avoided completely if a finer computational mesh were used. Curves of saturation level vs. distance above the water table for the six cases also are presented. These curves also are similar to those that would be obtained from an analytical solution of unsaturated flow through layered material. The degree of saturation is discontinuous at interfaces between units.

The velocity of water flow through the profile is plotted vs. distance above the water table. These curves indicate that the velocity (2 to 5×10^{-10} m/s) in the Paintbrush Formation at a flux of .1 mm/yr is higher than the velocity for a flux of either .5 or 4 mm/yr. The value presented for a flux of .1 mm/yr is incorrect; the correct value is 6×10^{-11} m/s. This velocity is smaller than that for a flux of 4 mm/yr but is still larger than the velocity for the flux of .5 mm/yr. This apparent contradiction (higher flux and lower velocity) is caused by the degree of saturation in the Paintbrush being higher than that necessary to transmit the specified flux under a potential gradient of 1.0. This value of saturation is only slightly higher than 10% and yet will transmit the specified flux at a potential gradient of less than 1.0.

The authors discuss the groundwater travel time across the various units at Yucca Mountain and state that at a percolation rate of .1 mm/yr the water flow is confined entirely to the matrix in all but one unit. This statement is questionable. It appears that the water would be confined to the matrix in all units at this flow rate because the .1 mm/yr is considerably less than the saturated matrix conductivity of all units. The travel time from the repository to the water table is calculated next for the three specified flow rates using the aforementioned two types of Calico Hills unit; the vitric and the zeolitized. The travel times are as low as three years for the flux rate of 4 mm/yr through the zeolitized unit. The same flux rate through the vitric unit gives a travel time of 8,400 years. The calculations in this report appear to be reasonable with the exception of the one error mentioned above. However, this error applies to a unit above the repository location; consequently the error would not affect the travel time to the accessible environment.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The results of this report show the absolute necessity for determining an accurate value for the percolation rate through Yucca Mountain; the paper demonstrates the high sensitivity of the travel time calculation to the flux rate. This is the most logical analysis conducted to date for the travel time from the repository location to the water table.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The limitation of this report is that the problem of flow velocity was determined for only one value of each physical or hydraulic parameter in each unit. These parameters display considerable variation is most rocks; the flow velocities should be calculated using the extremes of the parameters to determine the effect on calculated travel time. This report, however, is a good first step in the process of determining the minimum travel time.

SUGGESTED FOLLOW-UP ACTIVITIES

A research program should be pursued vigorously to determine the real value of the percolation rate (flux) through Yucca Mountain. Such a program will be absolutely necessary to determine the minimum travel time.

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DOCUMENT #: SAND85-0854C

DOCUMENT: The Effect of Percolation Rate on Water Travel Time in Deep, Partially Saturated Zones. R.R. Peters, J.H. Gauthier, and A.L. Dudley, Nevada Nuclear Waste Storage Investigations Project Department, Sandia National Laboratory, Albuquerque, NM.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: May 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report uses a computer code, TOSPAC, along with a conceptual model very similar to that used by Klavetter and Peters (1985). The model does not include the effect of vapor transport but it does treat the effect of compressibilities of the water, of the porous matrix and of the fractures on unsaturated vertical flow.

The code is used to determine the pressure, saturation levels, and velocity distributions for water percolation rates (fluxes) of .1, .5 and 4.0 mm/yr in Yucca Mountain. Two profiles are used; the first is for the Calico Hills vitrified unit; the second is for the Calico Hills zeolitized unit. Calculated travel times from the repository location to the water table are as low as three years for a flux of 4.0 mm/yr in the zeolitized unit and 8400 years for the same flux in the vitric unit. All other travel times are greater than 81,000 years.

This paper presents the most comprehensive treatment of travel times through the unsaturated zone at Yucca Mountain that we have reviewed.

BRIEF SUMMARY OF DOCUMENT:

The authors divide the hydrogeologic units of Yucca Mountain into three groups: 1) densely welded tuffs that are highly fractured,

2) nonwelded vitric tuffs that have few fractures, and 3) nonwelded zeolitized tuffs that have few fractures. The first set of tuffs (first group) has low assumed saturated matrix conductivity (10^{-11} m/s or less) and high assumed saturated fracture conductivity ($\sim10^{-9}$ m/s). The second group has high assumed saturated matrix conductivity (10^{-6} to 10^{8} m/s) and low assumed saturated fracture conductivity ($<10^{-8}$ m/s). The third group has low assumed saturated matrix conductivity (10^{-11} m/s or less) and higher saturated fracture conductivity ($>10^{-11}$ m/s).

The authors present a brief summary of the various flow rates of water through Yucca Mountain that have been reported in the literature; they also present a short discussion of vapor movement. A mathematical model and a computer program (TOSPAC) are developed and used in the report. The program does not consider vapor transport, but it does treat the effect of compressibility of water and of the rock matrix. The authors assume that Darcy's law is valid and that the pressure heads in the fractures and the matrix are equal in a direction perpendicular to the flow lines. Van Genuchten's (1978) saturation vs. pressure head relationship and Mualem's (1976) conductivity vs. pressure head function are used in the program. The values of physical and hydraulic parameters used in the calculations are from reports by Peters et al. (1984), Scott et al. (1983), and Sinnock et al. (1984). The data in these reports were obtained from samples removed from Yucca Mountain. The equation used in the mathematical model contains terms for the storage of water due to the saturation of the matrix and the fracture systems, and terms representing compressibility of water and dilation of the bulk rock. All these terms are functions of the pressure head in the water. The solution of the equation results in determination of the pressure and saturation level distributions as well as the groundwater velocity and the water flow rate (in the form of travel time) across the hydrogeologic units of Yucca Mountain. The velocity also is a function of the percolation rate and the composition (vitric or zeolitized) of the Calico Hills unit. The various coefficients in the equation are called capacitance coefficients. Curves are presented for the coefficients as functions of pressure head. Composite conductivity curves are presented for the Topopah Springs and the Calico Hills nonvitrified unit. These curves are presented as curves for fracture conductivity, for matrix conductivity and the for the composite conductivity.

Fluxes used in the simulation were .1, .5, and 4 mm/yr. Each of these rates was used with either the vitric or zeolitic portions of the Calico Hills unit. The cases with an infiltration rate of .1 mm/yr assumed water movement only in the matrix throughout the hydrostratigraphic column. The cases with a rate of .5 mm/yr display a relatively small amount of water movement in the fractures of some units. The case with a 4 mm/yr rate reflect considerable water movement in the fractures in the Tiva Canyon and Topopah Spring units. Pressure head vs. distance above the water table are plotted for the six cases studied. These graphs are similar to the analytical solution that can be obtained for unsaturated flow through layered material.

Considerable discussion is presented about the changes of capillary pressure at interfaces and the appearance of nearly discontinuous pressures in the aforementioned graphs. Pressures in this situation are not discontinuous, but regions of very high pressure gradients do occur. Discussion also is presented of possible errors in percolation rates in these regions of large capillary pressure gradients. However, the authors do not elucidate their reasons for concluding that percolation rates are in error in these regions. The error is less than 5% and it could be avoided completely if a finer computational mesh were used. Curves of saturation level vs. distance above the water table for the six cases also are presented. These curves also are similar to those that would be obtained from an analytical solution of unsaturated flow through layered material. The degree of saturation is discontinuous at interfaces between units.

The velocity of water flow through the profile is plotted vs. distance above the water table. These curves indicate that the velocity (2 to 5×10^{-10} m/s) in the Paintbrush Formation at a flux of .1 mm/yr is higher than the velocity for a flux of either .5 or 4 mm/yr. The value presented for a flux of .1 mm/yr is incorrect; the correct value is 6×10^{-11} m/s. This velocity is smaller than that for a flux of 4 mm/yr but is still larger than the velocity for the flux of .5 mm/yr. This apparent contradiction (higher flux and lower velocity) is caused by the degree of saturation in the Paintbrush being higher than that necessary to transmit the specified flux under a potential gradient of 1.0. This value of saturation is only slightly higher than 10% and yet will transmit the specified flux at a potential gradient of less than 1.0.

The authors discuss the groundwater travel time across the various units at Yucca Mountain and state that at a percolation rate of .1 mm/yr the water flow is confined entirely to the matrix in all but one unit. This statement is questionable. It appears that the water would be confined to the matrix in all units at this flow rate because the .1 mm/yr is considerably less than the saturated matrix conductivity of all units. The travel time from the repository to the water table is calculated next for the three specified flow rates using the aforementioned two types of Calico Hills unit; the vitric and the zeolitized. The travel times are as low as three years for the flux rate of 4 mm/yr through the zeolitized unit. The same flux rate through the vitric unit gives a travel time of 8,400 years. The calculations in this report appear to be reasonable with the exception of the one error mentioned above. However, this error applies to a unit above the repository location; consequently the error would not affect the travel time to the accessible environment.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The results of this report show the absolute necessity for determining an accurate value for the percolation rate through Yucca Mountain; the paper demonstrates the high sensitivity of the travel time calculation to the flux rate. This is the most logical analysis conducted to date for the travel time from the repository location to the water table.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The limitation of this report is that the problem of flow velocity was determined for only one value of each physical or hydraulic parameter in each unit. These parameters display considerable variation is most rocks; the flow velocities should be calculated using the extremes of the parameters to determine the effect on calculated travel time. This report, however, is a good first step in the process of determining the minimum travel time.

SUGGESTED FOLLOW-UP ACTIVITIES

A research program should be pursued vigorously to determine the real value of the percolation rate (flux) through Yucca Mountain. Such a program will be absolutely necessary to determine the minimum travel time.

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WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: SAND85-0855

DOCUMENT: Fluid Flow in a Fractured Rock Mass. E.A. Klavetter and R.R. Peters, Nevada Nuclear Waste Storage Investigations Project Department, Sandia National Laboratories, Albuquerque, NM.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: July 15, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

A conceptual model for flow in the matrix and fractures of Yucca Mountain is developed. The authors use the concept of Wang and Narasimhan (1985) that at low moisture contents in the fractures water will flow across the fractures from one matrix block to another. At high moisture content in the fractures flow will occur parallel to the fractures. Using both macroscopic and microscopic analyses, two relationships are developed: 1) for the composite conductivity as a function of pressure and 2) for the storage of water in the matrix and in the fractures as a function of pressure. The two developments are in agreement. This work appears to be the most comprehensive model for downward flow in the unsaturated zone in Yucca Mountain that has been developed at this time.

BRIEF SUMMARY OF DOCUMENT:

In this report a conceptual model is developed for the combined matrix and fracture flow systems in the various units of Yucca Mountain. The authors note that it is possible that some portion of the total flux may be diverted at interfaces between the hydrogeologic units due to the contrast in conductivities, but that calculations and field testing will be required to determine whether water actually is diverted in a situation where a perched water table does not form. The concept of flow in fractures contained within a matrix is based on the work of Wang and Narasimhan (1985). This concept presupposes that at low water contents in the fractures the water will flow across the fractures from one block to the other. If the fractures are filled with water the flow will occur parallel to the fractures. The major points of the conceptual model proposed in the paper may be summarized as follows:

> "1. The fracture conductivity for water movement across the fracture is probably much larger than the adjacent matrix conductivity. Thus flow across the fractures is controlled by the adjacent matrix conductivity and the fracture conductivity across the fracture may be replaced by the matrix conductivity in flow calculations.
>
> 2. The average fracture conductivity for water movement in the plane of the fractures is a highly nonlinear function of fracture saturation or pressure head. If the flux is less than the saturated conductivity of the matrix the water will tend to flow only in the matrix as it moves downward. If the flux is greater than saturated conductivity in the matrix the matrix will saturate and the fractures will carry water also."

Hydrologic Model

The authors review several of the many mathematical models which are available for partially saturated flow in porous media. They then identify two alternatives for modeling situations where water movement occurs in both fractures and the matrix.

> "1. Model the fractures explicitly by zoning them into the calculational mesh as a second region that has much different properties from the properties of the matrix portion.
>
> 2. Rederive the flow equation for an equivalent porous media, taking into account the fact that there are two porosity systems: the matrix porosity system and the fracture porosity system."

Either approach requires a great deal of knowledge about the size and geometry of the fractures. The second option is used in the report under review because of the large size scale problems inherent with a high fracture density in the region being simulated. The equations that describe flow in the equivalent porous media may be developed either from 1) a macroscopic model assuming that the fracture and matrix hydrogeologic properties used are statistically representative of the large volume of rock mass, or 2) a microscopic model using the actual physical structure of the system of interest combined with the fundamental theoretical considerations for fluid flow in pores of a specified geometry. The goal of either of these procedures is to determine relative hydraulic conductivity and degree of saturation values as functions of pressure head. Both of the above approaches are used in the paper under review and both arrive at essentially the same relationships. Both derivations use capillary tube theory in their evaluation of the hydrogeologic variables and therefore are not applicable for systems containing fractures with apertures of the order of many millimeters or larger.

Macroscopic Derivation of Equation for Water Flow:

The equations of flow for the matrix and the fractures are written separately. They may be combined if the pressure distribution in the fractures is the same as in the matrix. This procedure is justified if the flow is nearly steady which is thought to be the case in Yucca Mountain.

The formulation above leads to an analysis of the depth in the formation to which flow would occur in fractures during an episodic pulse of water from the surface. The water injected into the fracture will move quickly into the matrix because of the following two factors:

1) At the front end of the pulse a large pressure head difference exists between the saturated fracture and the partially saturated matrix. This difference may be on the order of 100 m.

2) Because the fracture conductivity is very low (the fracture may be nearly dry), flow in the fracture is retarded and the pulse is diverted into the matrix. Wang and Narasimhan (1985) indicate that the fracture conductivity for flow within the plane of the fracture may be zero until the nearby matrix material is nearly saturated.

The authors later note that episodic pulses of water could penetrate to great depth in regions near large structural features such as fault zones or where the fracture apertures are large enough that capillary tube theory is not applicable. However, we note that such features would have to be in contact with water at near atmospheric pressure.

In summary the authors indicate that water injected into the surface above the main body of the repository is not likely to penetrate the fractures to appreciable depth. The result is nearly steady flow at depth.

The next section of the report discusses the functional relationships between saturation level and pressure head; the same relationship between conductivity and pressure is discussed also. The equation used for saturation level vs. pressure head is from van Genuchten (1978). All matrix property data and most of the fracture data were taken from Peters et al. (1984). The equation that relates conductivity and pressure head is from Mualem (1976). The authors develop a "capacitance" coefficient which combines the effect of all water storage phenomena such as fracture compressibility, matrix saturation, rock bulk compressibility, fracture saturation level, and water compressibility. The water storage due to each of these factors then is computed separately and the sum is termed the capacitance coefficient. The capacitance coefficient is a highly nonlinear function of pressure head.

Curves are presented for hydraulic conductivity as a function of pressure head for the matrix, the fractures and their sum (composite conductivity).

The authors point out that the various terms in the equations are volume averaged values of these parameters.

Microscopic Derivation of Flow Equation

In the microscopic approach the contributions of the matrix pores and the fractures are combined to determine the hydrogeologic parameters. Consequently, the fractures are being treated as large pores. The pore size distribution data for samples of the tuff matrix were obtained from mercury injection tests; they are presented as a graph of pore diameter vs. incremental intrusion volume (the volume of mercury that has moved into the pores). Burdine's (1953) equation was used to calculate the relative hydraulic conductivity from the saturation level vs. pressure data. Relative conductivity-pressure curves calculated with the composite porosity model (macroscopic model) are compared with the relative conductivity curves that are calculated from the pore size distribution data and from the assumed log-normal aperture distribution for the fractures (microscopic model). In most cases the agreement is excellent. The difference between the two developments is that the macroscopic development considered the compressibilities of water, the matrix and the fractures, whereas the microscopic development did not consider these factors. From the comparison of the results, however, it appears that in most cases the differences are insignificant.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

This report includes the most comprehensive development to date for the theory of partially saturated flow through the matrix and fractures in Yucca Mountain. The relationships developed between pressure and relative conductivity should facilitate the use of several different mathematical models for describing the magnitude of flux and the pressure and moisture content distributions in the unsaturated zone in Yucca Mountain.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The limitation of this report is that the work must be continued and the resulting mathematical models must be applied to Yucca Mountain. A portion of this has been done in the report by Peters, Gauthier and Dudley (1985) which we have reviewed recently (Communication Number 60).

SUGGESTED FOLLOW-UP ACTIVITIES

This work must be continued in order to apply the model to Yucca Mountain and to determine the flux rate and the travel time to the accessible environment.

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1.0 INTRODUCTION

WWLNUM:	226
DOCUMENT NO:	SAND85-0855
TITLE:	"Fluid Flow in A Fractured Rock Mass"
AUTHORS:	Klavetter, E. A. and Peters, R. R.
REVIEWER:	Water, Waste & Land, Inc.
DATE REVIEW COMPLETED:	June 27, 1986
SCOPE:	Specific review of mathematical model used to describe flow in the unsaturated zone. Reviewed in the context of application to site modeling.
KEY WORDS:	Mathematical Model; Fracture Flow; Matrix Flow; Dual Porosity; Composite Porosity.
DATE APPROVED:	mgk 7/7/86

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 SUMMARY OF DOCUMENT

The stated purpose of this document is "to discuss, in general terms, (1) the Yucca Mountain site with emphasis on characteristics that affect the hydrologic system, (2) the conceptual hydrologic model, and (3) the mathematical model of flow in the unsaturated zone." The conceptual model of Yucca of Yucca Mountain is based primarily on information from the few test wells drilled within the potential repository block.

2.1.1 Description of Hydrologic Regime

The report considers that the tuff above the water table can be divided into three groups based upon physical properties that affect the hydrology. The three groups are:

1. Densely welded tuffs that are highly fractured.
2. Nonwelded, vitric tuffs that have few fractures.
3. Nonwelded, zeolitized tuffs that have few fractures.

Only a small amount of the annual precipitation infiltrates the surface of the mountain. The authors point out that some of this infiltration may be diverted laterally at unit interfaces, however, further testing must be performed before this diversion is shown to be possible.

2.1.2 Conceptual Model

Within the units, the model for flow is based on capillary bundle theory which states that there is a relationship between pore size and equilibrium head. In applying this theory the authors made several assumptions:

1. The system is changing very slowly with time.
2. The average fracture aperture is 25 micrometers.
3. The matrix average pore diameter is 0.03 micrometers.

As the matrix saturation increases the fracture saturation also increases, however in a highly nonlinear manner. Fracture conductivity does not start to increase from zero until the matrix is nearly saturated. At matrix saturations less than one, flow can occur across the fracture from matrix block to matrix block. The authors summarize the conceptual model of flow in fractures as:

1. Flow across fractures is controlled by the adjacent matrix conductivity. Fracture conductivity across the fracture can be replaced by the matrix conductivity in flow calculations.

2. If flux is less than the saturated conductivity of the matrix, then water will tend to flow only in the matrix. Fractures will carry water only when the matrix is very close to saturation or is saturated.

2.1.3 Mathematical Models

Two derivations are presented for the equation for water flow in a fractured, porous medium. Both derivations use capillary bundle theory to evaluate the hydrologic coefficients. Because the limit of applicability for capillary bundle theory is of the order of millimeters, the models developed in this paper "are not applicable for systems containing fractures with apertures of the order of many millimeters or larger."

2.1.2.1 Fracture Flux and Penetration Depth

The authors review work by several investigators as to the depth that a slug of water can travel in a fracture. The results of the investigations indicated that episodic pulses of water at Yucca Mountain "will not penetrate significant distances into Yucca Mountain if the fracture aperture is less than 100 micrometers". At the front end of the slug, a pressure difference exists between the saturated fracture and the partially saturated matrix. Flow in the fracture is also diverted into the matrix because the fracture conductivity ahead of the water pulse is very low. Thus at depth, the water flux may be a slowly varying function of time and it may be inferred "that the difference in pressure head between fractures and matrix may be small at depth." The difference between the fracture and matrix properties forces the fracture and matrix pressure heads to be nearly identical under conditions of slowly varying flux.

2.1.2.2 Macroscopic Equation for Water Flow

The general fluid continuity equation in a dual-porosity equivalent continuum is presented as:

$$\frac{\partial\,[\rho(S_m n_m + S_f n_f)]}{\partial t} + \nabla \cdot \rho(\bar{q}_m + \bar{q}_f) + \nabla \cdot \rho\,\bar{V}(S_m n_m + S_f n_f) = 0 \tag{1}$$

in which:

ρ = the density of water

S = saturation

n = porosity

$\bar{q}$ = the specific discharge (Darcy flux)

$\bar{V}$ = the deformation velocity of the matrix

t = time

The subscripts m and f indicate matrix and fracture subsystems, respectively.

Assuming that the pressure head, ψ, is the same in both fractures and matrix, using the functional relationships for $S(\psi)$ and $K(\psi)$, substituting and expanding leads to

$$\rho\,\frac{\partial\psi}{\partial t}\left\{\left(n_m\frac{\partial S_m}{\partial\psi} + n_f\frac{\partial S_f}{\partial\psi}\right) + \beta_w'(S_m n_m + S_f n_f) + \right.$$

$$\alpha_{bulk}'\;\frac{(S_m n_m + S_f n_f)}{n_m + n_f}\left(S_m - n_f(S_m - S_f)\right) - \tag{2}$$

$$\left.\frac{\partial n_f}{\partial\sigma'}\;\frac{(S_m n_m + S_f n_f)}{n_m + n_f}\;(S_m - S_f)\right\} = \nabla\cdot\rho(\bar{\bar{K}}_{m,b} + \bar{\bar{K}}_{f,b})\cdot\nabla\,(\psi + z)$$

in which β_w' is the compressibility of water, σ represents effective stress, and the quantity a_{bulk}' is defined in bulk rock properties as:

$$a_{bulk}' = \frac{(1 + \nu)(1 - 2\nu)}{E(1 - \nu)} \tag{3}$$

Coefficients on the left side of equation are referred to as 'capacitance coefficients' and relate to the storage of water as pressure head is varied. The terms on the right side of equation 2 are also very dependent on the pressure head, ψ. At steady state, the left side of equation 2 becomes zero because there is no change in storage with time. Therefore, the equation reduces to:

$$\nabla \cdot [\rho(\bar{\bar{K}}_{m,b} + \bar{\bar{K}}_{f,b}) \cdot \nabla (\psi + z)] = 0 \tag{4}$$

which can be integrated to obtain:

$$-[\bar{\bar{K}}_{m,b} + \bar{\bar{K}}_{f,b}] \cdot \nabla (\psi + z) = \bar{q}_m + \bar{q}_f = \bar{q}_{total} \tag{5}$$

This is the form of equation 2 which is most useful for the calculations which have been performed at Yucca Mountain.

The saturation as a function of pressure head is determined by fitting the van Genuchten (1978) function to the psychrometer data obtained during testing core from wells USW G-4 and USW-GU3. The equation is shown below:

$$S(\psi) = (S_s - S_r) \left[\frac{1}{1 + |\alpha\psi|^{\beta}} \right]^{\lambda} + S_r \tag{6}$$

The equation is valid for pressure head, ψ, values less than zero. For pressure heads greater than zero, the material is saturated. In order to use equations 2 or 5, the hydraulic conductivity as a function of pressure head must also be known. Since no data yet exists from testing for the hydraulic conductivity/pressure head function, the function was developed from theoretical considerations. When the saturation curve fit of van Genuchten is combined with the method of Mualem (1976), the following expression is obtained:

$$K(\psi) = K_s \left[1 + |\alpha\psi|^{\beta} \right]^{-\lambda/2} \left\{ 1 - \left[\frac{|\alpha\psi|^{\beta}}{1 + |\alpha\psi|^{\beta}} \right]^{\lambda} \right\}^{2} \tag{7}$$

2.1.2.3 Microscopic Derivation of the Flow Equation

The basic approach to the microscopic derivation is similar to that taken with the macroscopic derivation, that is the pressure head in the "large fracture pores" and in the small matrix pores are equal along a direction perpendicular to flow. In this approach, the fractures are treated as large pores and "the contributions of the individual matrix pores and fractures for a volume of rock mass are combined to determine the hydrologic parameters for the composite rock material."

The saturation and relative hydraulic conductivity relationships were calculated using available fracture and matrix data. Using capillary bundle theory, the pressure head, ψ, can be related to the individual pore radius, r, by:

$$\psi = \frac{2\,\gamma\,\cos\,\phi}{\rho\,g\,r} \tag{8}$$

where γ is ;the surface tension between solid and fluid, g is acceleration of gravity, and ϕ is the fluid contact angle with solid.

Given a composite pore-size distribution, saturation values as function of pressure head can be determined with equation 8. For the fractures, an average value of 25 micrometers was used for the mean physical aperture. Combining the fracture aperture characteristic length with a composite pore-size distribution for the rock mass, then "saturation values as a function of pressure head and one-dimensional relative hydraulic conductivity values as a function of pressure head were calculated." The relative hydraulic conductivity curve was determined using the method of Burdine (1953):

$$K_{rel} = \frac{n_{total}}{8k_s} \sum_{i=0}^{\gamma\ max} \frac{(S_w - S_{w,r})^2 \quad V(r_i) \quad r_i^2}{(1 - S_{w,r})^2 \quad x^2(r_i)} \tag{9}$$

where: K_{rel} = relative hydraulic conductivity,

n_{total} = porosity,

k_s = intrinsic permeability of the medium,

r_i = pore entry radius,

r_{max} = maximum pore entry radius,

S_w = saturation of the wetting phase,

$S_{w,r}$ = residual saturation of the wetting phase,

$v(r_i)$ = incremental volume fraction, and

$x(r_i)$ = tortuosity factor

The saturation and relative conductivity relationships (Equation 8 and 9) can then be substituted into equation 2 or 5 to describe flow in the fractured, porous media.

2.1.2.4 Results

The total conductivity curves plotted for the three groups of tuff contain "either one or two plateaus of fairly constant conductivity with rapidly changing conductivity in the remaining portions of the curve." Units having low matrix conductivity and relatively high fracture conductivity have two plateaus. The units which show this type of behavior are the TSw2 and the CHnZ. At pressure-head values where the fractures are saturated and at pressure head values where the fractures are at residual saturation and the matrix is nearly salivated, the total conductivity for these units is nearly constant. Units that have relatively low fracture conductivities and high matrix conductivities have a total conductivity curve with a single plateau. For units with this type of curve (PTn), the "total conductivity is essentially that of the matrix over the entire range of pressure head."

When the composite conductivity curves calculated from the macroscopic approach are compared with the conductivity curves calculated from the microscopic approach, the authors describe the comparison as "The curves are not only qualitatively the same, but match quantitatively at most points. The pressure head at which the fracture conductivity becomes significant matches well between the two formulation methods." They conclude that the similarity between the two methods provides confidence in the validity of the 'composite-porosity' assumptions.

2.2 SUMMARY OF REVIEW CONCLUSIONS

The flow regime at Yucca Mountain has been assumed to occur as Darcy flow. The equations which have been developed appear to be valid at this time. The largest difficulty will be obtaining field data to use in the presented theory. Empirically derived equations for standard porous media have been applied directly to the fracture systems. Initial information shows that this is valid, however, field experiments will have to be performed to confirm the theory.

3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The Yucca Mountain site has been chosen by the DOE as one of three possible sites for the storage and deposition of the nation's high level nuclear waste. Site characterization will continue to determine if the site can indeed meet the regulations. Part of the site characterization includes the mining of two shafts in the proposed repository block. Drifts at the proposed repository depth, along with the shafts, will enable testing the geologic and hydrologic properties of the various units. Information from these tests can be applied to determine if the Yucca Mountain site can meet regulatory requirements.

The primary mechanism by which radionuclides could move from the repository to the accessible environment is by the water flowing through the unsaturated zone. The unsaturated zone is considered by the DOE to be the most significant barrier to waste migration at Yucca Mountain. The low flux of water passing through the unsaturated zone would limit the dissolution rate of the canisters and waste emplaced in a potential repository.

Flow in the unsaturated zone could take place in the matrix, fractures, or in both systems for the various hydrologic units which exist at Yucca Mountain. If fracture flow occurs, the transit times from the repository to the accessible environment may be rapid. Therefore, the ability to predict the performance of the unsaturated zone is critical to the evaluation of the site. The theory and mathematical development presented in this paper presents a method by which the repository performance may be modeled. Thus, the report is highly significant to the NRC Waste Management Program.

4.0 DETAILED REVIEW

4.1 DATA

The most apparent problem lies not with the theory or the mathematical development presented in the paper, but with the ability to obtain the necessary data from the site to be able to apply the theory. The control volume necessary to determine the fracture flow characteristics required for the theory may be quite large. To get a statistical valid representation of the physical data at Yucca Mountain may be extremely difficult. Certainly, the fracture aperture distribution, fracture frequency, and fracture flow characteristics will need to be determined from in situ testing. The theory presented in the reviewed paper is assumed to be correct at this point in time. Only when additional field data is available will it be possible to fully check the theory as to its correctness for predicting flow velocities in the unsaturated zone. It does not appear that all of the necessary data to perform calculations based on the equations for the microscopic approach are given in the report. Therefore, it is not possible to check the calculations as presented in the graphs of the report.

4.2 FUNCTIONAL RELATIONSHIPS FOR MATRIX FLOW

To obtain the flow relationships, the authors made several assumptions about the flow regime occurring in the unsaturated zone. The first, that Darcy's law holds, is an assumption which has been made by other DOE investigators working on the site. Because of the extremely low permeabilities of the matrix in some of the units (less than 1 mm/yr), the functional relationship between pressure head and permeability has not been tested in the laboratory. The theory presented is the only way to determine the function. Actual data from cores taken from Yucca Mountain has been obtained for the saturation/pressure head relationship and a good fit of the data was possible using the van Genuchten (1978) function. However, the permeability/pressure head relationship was developed using the method of Mualem (1976). The method of Mualem was developed primarily for use with unsaturated and unconsolidated soils for use in agriculture. Unlike the saturation/pressure head relationships measured in the laboratory, the permeability/pressure head relationship has not been measured for the tuff at Yucca Mountain and the method of Mualem has been extended to these tight consolidated materials.

4.3 FUNCTIONAL RELATIONSHIPS FOR FRACTURE FLOW

The second assumption is that the saturation-conductivity/pressure head curves initially developed for porous media can be applied to the fracture system. Again field testing will have to be done to prove if this approach is valid. The authors have used saturated hydraulic conductivities for the fractures based on tests of core containing one fracture parallel to the axis of the core. It has not been shown that the permeability results from the core tests are similar to actual fracture permeabilities in Yucca Mountain. Boundary effects in the core during water injection may alter the measured fracture permeability. The permeability/pressure head and saturation/pressure head relationship for the fracture unsaturated properties was based on the van Genuchten function combined with the method of Mualem. The coefficients for the fracture permeability function were base on the Freeze and Cherry sand curve (Peters et al, 1985). It has not been shown that the coefficients for a porous media like sand can be applied to a fracture system.

5.0 RECOMMENDATIONS

It is recommended that the model presented in this document be used to analyze the flow phenomena occurring within Yucca Mountain. The model can give insight as to the important data which needs to be determined during site characterization. The importance of vapor transport of radionuclides at the site should be further investigated. Vapor movement may be important if the percolation rates are as low as currently thought.

6.0 REFERENCES

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Center for Nuclear Waste Regulatory Analyses

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April 29, 1988

Dr. Philip S. Justus
Technical Review Branch
Division of High-Level Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
1 White Flint North 5H6
11555 Rockville Pike
Rockville, MD 20852

Dear Dr. Justus:

RE: Technical Direction #4 for the Geologic Setting Program Element of Contract NRC-02-88-005.

Included with this letter is a review of SAND 84-1895 report by J. A. Fernandez and others entitled: "Technical Basis For Performance Goals, Design Requirements, and Material Recommendations For The NNWSI Repository Sealing Program." This review includes the information requested in Technical Direction #4 which was issued by you on March 24, 1988, and the subsequent modification of the Technical Direction issued on April 18, 1988. Also included with this letter is the letter of April 28, 1988, from Mark J. Logsdon of Nuclear Waste Consultants, Inc. which was included with the transmittal of the review to the Center. Nuclear Waste Consultants, Inc. conducted the review as a Subtask 4.1 activity of Contract NRC-02-88-005.

Concerns on the performance of Exploratory Shaft One (ES-1) with respect to potential flooding were expressed in the six issues for which focused review and analyses were requested in the April 18, 1988, modification of Technical Direction #4. The primary emphasis of SAND 84-1895 is not directed to these issues. Furthermore, it contains analyses based on the original location of ES-1 which was in a portion of the valley where alluvium is present above the tuff bedrock. A more applicable document which contains more current information, including the relocated proposed site of ES-1, is the Draft SAND 85-0598. The analyses presented in the report for Technical Direction #4, were done in cognizance of Draft SAND 85-0598.

In this regard, please note that calculations of water inflow into ES-1 presented in SAND 84-1895 incorporated flow from surficial alluvium ("valley fill"). The relocated proposed site for ES-1 is at the valley margin with little or no surficial alluvium or colluvium present on the tuff. Calculations of water flow into the relocated proposed ES-1 incorporating flow through a surficial layer of alluvial sediments will be conservative (in terms of repository performance criteria).

Based on the discussion of Issue 3 on pages 20 and 21 of the review by Nuclear Waste Consultants, Inc. the Center believes greater confidence in evaluating the susceptibility of ES-1 to surface water flooding can be obtained. It is recommended that information needs noted on pages 20 and 21 of the review be fulfilled.

If you have questions about the document review or the cover letter please contact me.

Respectfully submitted,

J L Russell

John L. Russell, Ph.D.
Manager, Geologic Setting Program Element

JLR/lf

Enclosure

cc: Fred Ross

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April 28, 1988

Center for Nuclear Waste Regulatory Analyses
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Attn: Dr. John Russell

Re: CNWRA Subcontract No. 19363 - Review of Fernandez et al. (1987)

Dear Dr. Russell:

This letter transmits to CNWRA by Federal Express the document review by Nuclear Waste Consultants (NWC) of Fernandez et al., 1987, "Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program: SAND84-1895". The document review was prepared by Mr. T. Sniff and Dr. D. McWhorter (Water, Waste, and Land) and Mssrs. E. Rovey and M. Logsdon (NWC) under Task Directive 5 from CNWRA to Nuclear Waste Consultants. Technical and management reviews were performed by Mssrs. A. Brown and M. Logsdon and Ms. B. Basse of NWC. The final review incorporates the comments and suggestions made on the draft of April 26, 1988 by Dr. J. Russell of CNWRA.

As you know, the technical direction by the NRC Staff for the review has changed during the task. The document review presented incorporates detailed and independent analyses for the specific concerns on which that the NRC Staff directed comment. In general, these matters relate primarily to the performance of the Exploratory Shaft with respect to potential flooding. NWC understands that this matter is of currently critical interest to the NRC Staff because of discussions between the NRC and DOE on the NNWSI Consultation Draft Site Characterization Plan. However, NWC notes that Fernandez et al. (1987) is only peripherally directed at this issue. The Fernandez et al. (1987) document is a major programmatic document that is part of the NNWSI Advanced Conceptual Design program, and as such is intended primarily to address the sealing of the geologic repository after permanent closure. Because the specific, written technical direction (including that related to schedule) from the NRC Staff did not contemplate independent reanalysis of the DOE conclusions related to shaft or repository backfilling, we have not, at this time, performed such an independent technical analysis. Based on the available hydrologic information and preliminary conceptual models of flow and transport in variably saturated fractured tuff, we consider that the argument presented by Fernandez et al. (1987) is reasonable at this time and as a basis for further investigations and refinements of the design. However, we emphasize that this is a preliminary conclusion based on the limited review of these matters conducted to date. We recommend that the NRC Staff consider the extent to which detailed technical review, including independent reanalyses in selected areas, of additional matters in Fernandez et al. (1987) is needed at this time.

Based on our review of the matters of particular concern to the NRC Staff at this time, our review concludes:

- o The analysis of flooding based on the revised data of (Bullard, 1986b) and SAND85-0598 is a very conservative approach to estimating peak discharges.
- o The probability of one PMF in 1000 years (assuming the ANSI/ANS 2.8-1981 requirement of an exceedance frequency of not greater than 1E-6) would be less than or equal to 0.1%.
- o Based on steady-state flow analyses, under the unlikely events of extreme flooding conditions, the inflow to the shaft is close to the outflow from the shaft. If the new location of ES-1 were above the alluvium (i.e., on the TCw outcrop), the flooding of the shaft by unanticipated events would be extremely improbable.
- o NWC considers that the performance goal with respect to airborne transport, specifically of C-14 and I-129, has been improperly determined by DOE. The DOE technical basis would likely comply with the cumulative release requirements (40 CFR 191 and 10 CFR 60.112), but would likely not be consistent with the NRC requirement for controlled release from the Engineered Barrier System.

If you have any questions about the document review or this cover letter, please contact me immediately.

Respectfully submitted,
NUCLEAR WASTE CONSULTANTS, INC.

Mark J. Logsdon

Mark J. Logsdon
Vice President

Att: Document Review of "Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program", by Fernandez et al., September, 1987. SAND84-1895.

DRAFT

U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

REVIEW OF
"TECHNICAL BASIS FOR PERFORMANCE GOALS,
DESIGN REQUIREMENTS, AND MATERIAL
RECOMMENDATIONS FOR THE NNWSI REPOSITORY
SEALING PROGRAM

BY J.A. FERNANDEZ ET AL.

SAND 84-1895

By
Nuclear Waste Consultants, Inc.

DRAFT

APRIL, 1988

1.0 INTRODUCTION

WWLNUM: 321

DOCUMENT NO.: SAND84-1395

TITLE: "Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program"

AUTHORS: Fernandez, J. A., Kelsall, P. C., Case, J. B., and Meyer, D.

PUBLICATION DATE: September, 1987

REVIEWERS: Thomas L. Sniff, David B. McWhorter, Water, Waste and Land, Inc., and Mark Logsdon, Ed Rovey, Nuclear Waste Consultants

DATE REVIEW COMPLETED:

SCOPE: The surface water and groundwater sections of the report were reviewed to determine the adequacy of the technical basis for NNWSI repository sealing performance goals and design requirements. Chapter 3 was reviewed to evaluate the adequacy and conservativeness of the methodology used to develop the hydrologic goal for the sealing system. Chapter 4 was reviewed to determine if the methodology and modeling of water flow into the shafts and underground facility was valid. The conclusions about the need for sealing presented in Chapter 5 were reviewed to determine if they were reasonably conservative.

The reviews of Chapters 3 and 4 focused on the following issues:

1. The estimation of the probable maximum flood with a discussion of uncertainty or confidence interval.
2. The estimation of total hydrograph (volume) with a discussion of uncertainty or confidence interval.
3. The estimation of the elevation (depth) peak discharge of the PMF at the location of Exploratory Shaft (ES-1). The flood routing method used to estimate the flow depth for determination of the peak discharge elevation.

In addition, the Sandia estimation of recharge volume into the Exploratory Shaft (ES-1) was evaluated. Finally, the drainage rate from the bottom of the ES was evaluated.

KEY WORDS: Capillary Barrier, Conceptual Model, Exploratory Shaft, Faults, Ground Water Movement, Hydrograph, Moisture Characteristic Curves, Perched Water, Probable Maximum Flood, Probable Maximum Precipitation, Radionuclide Transport, Runoff, Vapor Transport, Waste Dissolution, Water Surface Elevation

DATE APPROVED:

2.0 SUMMARY OF DOCUMENT

The report by Fernandez et al. (1987) presents the design requirements and recommends materials to be used in the NNWSI Repository Sealing Program. Minimum desired performance goals (specific values of how well the sealing subsystem must perform its function) were computed to establish the need for sealing. Water flows for anticipated and unanticipated conditions were determined and compared to these performance goals. Ultimate design requirements for sealing were based on this comparison.

As defined in the report, sealing is the permanent closure of the underground facility, shafts, ramps, and boreholes. Backfill and all seals or plugs in the underground facility are part of the repository engineered barriers subsystem of the Yucca Mountain Mined Geologic Disposal System (YMMGDS). Shaft and borehole seals are considered separately from sealing components located within the underground facility.

The quantitative criteria given in 10 CFR 60, Section 60.113.ii were used to develop the performance goals for the engineered barrier subsystem and the shaft and borehole seal subsystem (shaft portion only). The qualitative design criteria given in Section 60.134.(a) and (b) were used in developing the performance goals for the shaft and borehole seals subsystem (borehole portion only).

Two key issues were presented as being pertinent to sealing. Key Issue 1 asks the question: "Will the mined geologic disposal system at Yucca Mountain isolate the radioactive waste from the accessible environment after closure in accordance with the requirements set forth in 40 CFR Part 191, 10 CFR Part 60, and 10 CFR Part 960?" The corresponding design issue (1.12) asks the question "Have the characteristics and configurations of the shaft and borehole seals been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.134, and (b) provide information to support resolution of the performance issues?"

Key Issue 4, the second issue, asks the question "Will mined geologic disposal system construction, operation (including retrieval), closure, and decommissioning be feasible at Yucca Mountain on the basis of reasonable available technology, and will the associated costs be reasonable in accordance with the requirements set forth in 10 CFR Part 960?" Associated with this key issue is Design Issue 4.4; "Are the repository construction, operation, closure, and decommissioning technologies adequately established to support resolution of the performance issue?"

The approach used in the report to establish the design requirements for the engineered, sealing components was as follows:

1. The hydrologic performance goals were selected for the sealing subsystem. Hydrologic performance goals refer to the allowable amount of water that could enter the waste disposal areas.

2. The expected rather than the allowable amount of water that could enter the waste disposal area and contact the waste was computed.

3. The need for sealing was assessed.

As a basis for the calculations, a reference conceptual model of the Yucca Mountain site is given in Chapter 2. This model considers water infiltrating from the surface may be impeded by permeability contrasts and capillary barriers between the welded and nonwelded units. Because of the combined effects of low average rainfall and permeability and capillary barriers, the model assumed the flux through most of the Topopah Spring Member (TSw) was probably restricted to about 0.1 mm/year. Higher infiltration rates could occur through fault or fracture zones. These faults could possibly provide flow paths through the permeability and capillary barriers.

The reference waste description used in this report is a mixture of 650 MTU of WVHLW, 7,350 MTU of DHLW, and 62,000 MTU of spent fuel. The number of canisters to be disposed of in the repository is estimated to be about 42,200. The current repository is designed as one inclined level at about the 305-m depth in the exploratory shafts. Two alternative canister emplacement modes were considered, vertical and horizontal. The repository design incorporates six openings to the subsurface facilities, including four vertical shafts and two inclined ramps.

2.1 Performance Goals for the Sealing Subsystem

The hydrologic performance goals represent the allowable amount of water that could enter the waste disposal areas and apply to the engineered barrier subsystem and the shaft and borehole seals subsystem (shaft portion only). Fernandez et al. (1987) presented what they considered to be a conservative radionuclide release model. This radionuclide release model provided a link between the performance objective of the repository and the design basis for sealing designs.

The failure rates of the waste packages and fuel rods were considered to compute the radionuclide releases. Fuel rods consist of a stack of uranium dioxide pellets (matrix) encapsulated within a helium environment in a Zircaloy tube or cladding. The radionuclide releases were assumed to occur from the matrix and, for select radionuclides, from the cladding and the gap/grain boundaries. The majority of the radionuclides (90%) are located within the uranium dioxide matrix.

Fernandez et al. (1987) assumed that radionuclide releases from the matrix were directly proportional to the volume of water that contacts the waste. Releases of radionuclides from gap/grain boundaries were computed by making assumptions on the percentage of their inventory in nonmatrix locations. The release of the radionuclides to the environment outside the waste package is controlled by the failure behavior of the waste package and the fuel rods. The following assumptions were made to compute the release of radionuclides contained within the matrix:

1. Congruent matrix dissolution
2. Each radionuclide is uniformly distributed within the matrix.
3. The uranium dissolution rate is determined by its solubility coupled with the quantity of water.
4. Water will only contact the matrix within a fuel rod after both the fuel rod and the waste package have failed.

For the radionuclides which exist outside the matrix, the release mechanism is primarily dependant upon the failure of the waste package. The following assumptions were made for the failure of the waste package:

1. No canisters fail during the first 300 years following emplacement.
2. At the end of 1300 years, all of the canisters have failed. The failure rate is linear at a rate of 0.1% per year.
3. All of the fuel rods will have failed by 2300 years after closure of the repository.
4. Failed waste packages and fuel rods are uniformly distributed throughout the repository.

Fernandez et al. (1987) do not expect the failure rates of the waste package and the fuel rods to be as high as assumed and therefore consider the failure rate assumptions to be conservative.

Using these listed assumptions, two factors were developed, a matrix and an immediate release factor. The matrix release factor (MRF) represents the portion of the matrix that is available for dissolution. The immediate release factor (IRF) is the portion of the total inventory that fails in any given year. This factor is applied to those radionuclides that exist in some portion outside the matrix and can be released easily once the fuel rods are breached. The MRF's value can range from the IRF value at year 301 to 1 at year 2300 after closure.

The computer code SPARTAN was used to compute radionuclide releases from the matrix. SPARTAN assumes congruent leaching; therefore the release of individual radionuclides is controlled by the dissolution of the uranium matrix. The amount of water contacting the waste package is considered to be directly proportional to the annual release of any radionuclide. Under this assumption, an amount of water can be computed which represents the maximum amount of water that can contact the waste form and not violate the EPA and NRC criteria. The results were then coupled with the assumed release rates of those radionuclides located in nonmatrix locations.

Fernandez et al. (1987) stated that the variable which would most significantly change the hydrologic performance goals was the amount of Carbon-14 that could be instantaneously released once the waste package fails. A number of possible variations can exist dealing with the location of the radionuclides and the portion of those radionuclides which can be immediately released. However, one set of hydrologic performance goals was used. This set of hydrologic performance goals was taken from the SPARTAN analysis and gave the lowest value of the maximum allowable goal for any specific radionuclide for the design basis performance goals (proposed volume of water that can enter the waste disposal areas each year). The design-basis-performance goals for the sealing subsystem range from 1,180 cubic meters per year at 300 years to 136,000 for the period from 1,000 to 10,000 years.

Release to the accessible environment can also occur through air transport. Air transport and air flow out of the repository can be induced by convection caused as the temperature of the repository rises because of waste decay. Fernandez et al. (1987) concluded that the radionuclides which can possibly enter the repository in a gaseous state are Carbon-14 and Iodine-129. The total inventories of these radionuclides which can be released from the waste packages under the release model are 4 Ci and 0.2 Ci, respectively. Fernandez et al. (1987) adopted the basis that the requirements given in 10 CFR 60.134 are satisfied if the radionuclide releases of C-14 and I-129 as a gas out of the shaft is restricted to one percent of the allowable release limit for each radionuclide. This equates to 1 Ci released for each radionuclide. For the C-14, no more than 25% of the total air flow should exit form the shafts. This was the performance goal for air flow out of shafts.

The primary conclusions reached from the air flow calculations that were performed in Appendix C were:

1. Total air flow rates are dependent on the air conductivity of the shaft fill and the undamaged tuff.

2. Little reduction in air flow rate is achieved by backfilling drifts. Filling shafts and ramps is most effective in reducing the air flow rate.

3. When the air conductivity of the overlying tuff rock is high, varying the air conductivity of the shaft fill does not affect the total flow rate over a broad range of shaft fill air conductivities.

4. The presence of a modified permeability zone around the shaft and ramp excavations does not significantly affect the flow rates out of the shafts.

Boreholes are an additional pathway which exists for radionuclide release from the repository to the water table. Water which drains through the repository floor may be come perched, flow down dip, and enter a borehole which penetrates through the stratigraphic contact to the water table. However, if unsaturated conditions exist around the borehole, the borehole would act as a capillary barrier.

The performance goals and requirements for the borehole seals were developed from the NRC 10 CFR 60 requirement. Fernandez et al. (1987) considered this requirement was satisfied if the potential for vertical flow through boreholes is only one percent or less of the potential for vertical flow through the entire rock mass over which lateral flow along stratigraphic contacts is assumed to occur.

2.2 Estimates of Water Flow into Shafts and the Underground Facility

Both anticipated and unanticipated conditions were postulated for water flow into shafts and the underground facility. Fernandez et al. (1987) used engineering judgment in defining the conditions that were evaluated (as hydrologic data were limited). Anticipated hydrologic conditions included (1) matrix flow over the entire repository area, (2) annual, limited, and localized fracture flow, and (3) limited, surface flow into shafts. Unanticipated hydrologic conditions included (1) continuous fracture and matrix flows over the entire repository area and (2) extensive surface flow into shafts from major flooding events.

Water was considered to flow into repository shafts by two mechanisms; surface runoff or ground water. Surface runoff and subsequent flow into the upper portion of a shaft was assumed to be potentially limited by a number of mechanisms. Fernandez et al. (1987) concluded that ground-water inflow to a shaft will be insignificant provided unsaturated conditions prevail. Higher inflows to a shaft could occur if perched water conditions developed in the vicinity of a shaft. Higher inflows could also occur if a shaft was intersected by a high-permeability fault or fracture zone.

For the evaluation of the surface runoff, three scenarios were selected to represent the anticipated and unanticipated flows to the shaft. These scenarios are:

1. Large debris slide downstream from the shaft location, or erosion of alluvium around the shaft (The location of the shafts have been changed since this report was issued).

2. Subsidence adjacent to the shaft or settlement within the shaft resulting in inward collapse of the upper part of the shaft and formation of a depression.

3. Periodic sheet flow over shaft entry points for the anticipated water flow condition.

The amount of inflow into the shaft which can occur from the rock matrix was analyzed by Fernandez and Freshley in 1984. Matrix flow around a shaft was determined using TRUST, a computer program for variably saturated flow. These calculations were performed assuming isothermal, unsaturated conditions. One of the conclusions of this study was that when sand was used as shaft fill the calculated matrix inflow to the shaft was about four orders of magnitude less than when clay was used as shaft fill. Therefore, according to this study, sand was better for use as shaft fill than clay.

The inflow into the shaft under perched water (saturated matrix and fractures) conditions was also analyzed, albeit on a qualitative basis. Fernandez et al. (1987) describe that under certain conditions higher inflows into a shaft could occur if local saturation would develop in the vicinity of a shaft. However, they conclude that there is no evidence that perched water exists at Yucca Mountain. Finally, the authors conclude that inflow into shafts would not occur from a fault as no significant faults were found near the ES-1 shaft location in borehole USW G-4.

Fernandez et al. (1987) made estimates of water flow into the shafts under anticipated conditions. The expected method of water entering the shafts is to occur from periodic sheet flow over the shaft entry points. Therefore, the water flow into the shafts is controlled only by the duration and frequency of the surface flooding events. In their analysis, they assumed the duration of flow is approximately one hour (which corresponds to the duration of a probable thunderstorm). Another assumed conservative assumption was that runoff would occur if precipitation were greater than 1.3 cm. On the average, thunderstorms having a precipitation greater than 1.3 cm occur 4 times per year on the NTS. Therefore the authors assumed that infiltration into the shaft fill occurs four times during the year and the duration for each event is one hour. Fernandez et al. (1987) used the Green and Ampt approach (Hillel, 1971, p. 140-143) to compute the amount of water entering the shaft based on the above infiltration events.

2.3 Assessment of the Need for Sealing

Fernandez et al. (1987) concluded that for anticipated conditions water entering the shafts and ramps will not enter the waste emplacement areas. Only the water directly entering the emplacement drifts (for vertical emplacement) or the emplacement boreholes (for horizontal emplacement) could contact waste. For the unanticipated events, the water inflows did not exceed the maximum-hydrologic-performance goals computed for the selected radionuclides. However, the potential inflow from the probable maximum flood would exceed the storage capacity for both vertical and horizontal emplacement.

Fernandez et al. (1987) concluded that such an event would theoretically occur infrequently during the lifetime of the repository. They concluded that "given the current understanding of the site, that sealing is not necessary." They also concluded that the shafts do clearly provide preferential pathways for water movement into the repository althougn, as described above, the amount of water will be small except for extreme events. Therefore, sealing measures are proposed to provide additional assurance that repository performance objectives would be met when extreme conditions occur. Sealing would also address the 10 CFR 60 guidelines that some measures should be taken so that the penetrations would not act as preferential pathways for ground water movement.

3.0 GENERAL REVIEW COMMENTS

Comments from the review of the report of a general nature are identified in this section. These comments are separate from those specifically requested by the NRC staff which are covered in section 4.0 of the review. The following general comments are referenced by page number in the Fernandez report.

Comment 3.1
page 2-10 The flux through most of the Topopah Spring Member is probably restricted to about 0.1 mm/year.

The value for the flux in the unsaturated zone is as yet unknown. The current values being utilized by the DOE are not based on direct measurements, and, at less than 2% of precipitation, are low by accepted world-wide standards (WWL Technical Report #7, 1988).

Comment 3.2
page 2-10 If the faults cut across stratigraphic boundaries and are highly conductive throughout, they may provide flow paths through the permeability and capillary barriers. It is estimated that such zones could be recharged directly from the surface or by subsurface water perched above a capillary or permeability barrier at a maximum rate of 0.5 mm/yr.

It is not clear that the flux along a fault would be limited to 0.5 mm/yr. If the faults cut across the stratigraphic boundaries and are recharged directly from the surface, then it seems reasonable to assume the flux would not be limited by the matrix (from which the 0.5 mm/yr is assumed by the reviewers to be derived).

Comment 3.3

page 4-3 Table 4-1 lists flood values of peak rate and runoff volumes for the four shaft locations. At the Exploratory Shafts location, the 1-hour Thunderstorm PMF is calculated to have a peak discharge of 22 cu.m/sec (750 cfs) and contain 55,000 cu.m (45 ac.ft.) of volume.

These thunderstorm characteristics in the vicinity of the Exploratory Shafts are based upon a Probable Maximum Thunderstorm (PMTR)of 7 inches in one hour. The source of this data is from Design of Small Dams, U. S. Bureau of Reclamation, 1974. The 7 inch PMTR is 30 per cent smaller than a more updated value of 10.1 inches as prepared by Bullard (1986b) for the NNWSI site. The underestimated PMTR results in a probable maximum flood (PMF) estimation that is substantially less than regional flood envelope curve developed by the U. S. Geological Survey and other PMF estimates in the region as shown in Figure 1.

There is an explanation of the derivation of Figure 1 and further discussion regarding it in Section 5.0 of this review. The underestimation of the thunderstorm PMF is apparent when comparing the calculated PMF peak flow rate to the estimated 500-year flow of 24 cu.m/sec (850 cfs) for the Exploratory Shafts location. The 500-year peak was estimated by Squires and Young (1984) based upon a regression analysis of observed peaks in the region. Few hydrologists will agree on a recurrence interval for a PMF, or even if the concept of a recurrence interval is appropriate for a PMF. However, when there is general discussion of some a recurrence interval for a PMF, it is normally in the interval of once in 10,000 to once in 1,000,000 years. If a PMF has this low probability of occurrence (1×10^{-4} to 1×10^{-6} in any given year), it certainly would have a discharge rate substantially greater than the 500-year flood.

The updated estimates of the PMF peak flow rates and volumes, as developed by Bullard (1986b), are the current values used in the "Analyses to Evaluate the Effect of Exploratory Shafts on Repository Performance at Yucca Mountain," SAND85-0598, draft dated March, 1988 by J. A. Fernandez, T. E. Hinkebein, and J. B. Case. It is assumed for purposes of this review that present considerations of peak flow and volume are based upon these revised estimates made by Bullard (1986b).

Comment 3.4
p. 3-20 ...(Fernandez et al.(1987)) adopt the position...that the requirements given in 10 CFR 60.134 are satisfied if the radionuclide releases of C-14 and I-129 as a gas out of the shaft is restricted to one pecent of the allowable release limit for each radionuclide. Because the allowable release limit is 100 Ci/1000 MTHM, the performance goal would be 1 Ci released for each radionuclide.

While a 1 Ci total cumulative release of C-14 or I-129 would meet the 40 CFR 191 and (by reference) 10 CFR 60.112 requirements, such a release would not necessarily meet the 10 CFR 60.113(a)(ii)(B) release rate restrictions. Based on an initial C-14 inventory of 750 Ci/1000 MTHM at 10 years out-of-reactor and a half-life of 5730 years (converted from data in NUREG/CR-3235, p. 17), the inventory at year 1050 (i.e., 1000 years after permanent closure) would be 660 Ci. For I-129, the inventory at year 1050 would be 32 Ci. Therefore, the 1 Ci release would be 1.5 E-3 of the C-14 inventory and 3 E-2 of the I-129 inventory. To meet the 1 E-5/year NRC release requirement, the release from the engineered barrier system (EBS) via air would have to occur over 150 years for C-14 or 3000 years for I-129. Even if the EBS were backfilled with material equivalent to the backfill of the shaft (whichis not currently contemplated), the design-basis air conductivities (3 E-4 m/min (sic)) do not seem consistent with the required controlled release rates. The rate of release of C-14 and I-129 has not been addressed by Fernandez et al. (1987), as is required by 10 CFR 60.113 (a)(ii)(B), and the reviewers consider that the performance goals are at least incomplete and perhaps seriously flawed as a result.

Comment 3.5
p. 3-23/3-24 (Fernandez et al. (1987)) adopt the position that this (10 CFR 60.134) requirement is satisfied if the potential for vertical flow through boreholes is only one percent of less of the potential for vertical flow through the entire rock mass...

No quantitative basis for this position with respect to repository performance is offered by Fernandez et al. (1987). As far as can be determined from the text, the position is entirely arbitrary, and it is not possible to determine independently if this is a "conservative" or even reasonable assumption.

Comment 3.6
page 4-4 If the settlement were 15 m, equivalent to 3.4% over 451 m depth, the area affected would be about 11 m in diameter, assuming an angle of draw of 45 degrees. The volume created within the depression would be about 160 cubic meters.

A quick calculation indicates that the volume of the right circular cone (which is what the depression would seem to be) would be 475 cubic meters. This discrepancy needs to be evaluated.

Comment 3.7
page 4-5 There is no conclusive evidence that perched water currently exists at Yucca Mountain.

Perched water has been shown to exist at borehole USW UZ-1 (WWL, 1986). Whether the water is naturally perched or was perched due to drilling activities is not known. However, it has been shown that water can be perched, even in the fractured, welded Topopah Springs unit.

4.0 SPECIFIC HYDROGEOLOGIC REVIEW COMMENTS

The hydrogeologic review comments are listed in order of the chapters which were specifically reviewed; Chapters 3, 4, and 5. The comments are directed at determining if the SAND84-1395 report has presented a conservative approach to develop the hydrologic goal for the sealing system. For the purposes of this review, an approach is considered to be "conservative" if it produces a result that, when applied to a quantitative analysis against the requirements of 40 CFR 191 or 10 CFR 60 would:

- Underestimate mean-time-to-failure or failure rates for containment in waste packages (10 CFR 60.113(a)(ii)(A));
- Overestimate cumulative releases of radionuclides to the accessible environment (40 CFR 191;10 CFR 60.112);
- Overestimate release rates of any radionuclide from the engineered barrier system (10 CFR 60.113(a)(ii)(B));
- Understate the confidence in the likely performance of borehole and shaft seals (10 CFR 60.134) or in the ability to meet the retrievability requirement (10 CFR 60.111(b)).

4.1 Review Comments on Chapter 3 - Performance Goals for the Sealing Subsystem

Chapter 3 was reviewed to evaluate the adequacy and conservativeness of the methodology used to develop the hydrologic goals for the sealing system. These goals represent the allowable amount of water that could enter the waste disposal areas and apply to the engineered barrier subsystem and the shaft and borehole seals subsystem (shaft portion only).

The approach used by Fernandez et al. (1987) was to compute the volume of water required to release radionuclides in amounts equal to the annual release rate established by the NRC. Fernandez et al. (1987) state that "these performance goals are preliminary and subject to change." Two radionuclide release models were used to determine the annual release rate. Model one assumed a constant rate of failure of the waste packages beginning 300 years following closure of the repository and release of radionuclides outside of the uranium dioxide matrix. Model two assumed all of the radionuclides were located in the matrix and all waste packages have failed 300 years after closure.

The assumptions on the waste package and fuel rods failure rates seem to be conservative based on currently available data and models. The sensitivity analysis performed by the authors indicated that the variable that would most significantly change the hydrologic performance goals is the amount of Carbon-14 that could be instantaneously released once the waste package fails. As more data becomes available on the specific characteristics of the waste that will be emplaced, the assumptions used in this report should be updated and re-evaluated.

4.2 Review Comments on Chapter 4 - Estimates of Water Flow into Shafts and the Underground Facility

The following assumptions were used in the development of estimates for water flow into and out of the shafts, drifts, and ramp floors.

Assumption Used in Report:
The shaft sump should act as a drain such that none of the surface water or ground water entering the shaft would flow into the repository through the shaft station. To calculate the flow out of the shaft it was assumed that the rock was isotropic and homogeneous and could be modeled as a continuum with an equivalent, porous-medium, hydraulic conductivity.

Comment 4.2.1:
The Topopah Springs welded unit is highly fractured, with a matrix having an extremely low hydraulic conductivity. Fernandez et al. (1987) considered that it was reasonable to consider the TSw unit as a continuum. However, particles or precipitates could form on the matrix faces and fractures of the TSw and CHn unit at the bottom of the shaft. The permeability of these formations could be significantly reduced by this mechanism. This scenario was not considered by the authors.

Assumption Used in Report:
The ground-water inflows to a shaft from the rock matrix was calculated using the Trust computer program and ambient thermal conditions. The matrix was assumed to be homogeneous and isotropic for each hydrogeologic unit. This analysis was used to determine the amount of inflow when either sand or clay was used as the shaft fill.

Comment 4.2.2:
Two problems could exist using this assumption:

1. The hydrogeological units along the shafts are obviously not homogeneous and isotropic. The effect that porosity and permeability contrasts within a hydrogeologic unit will have on the flow of ground water is not yet known for the Yucca Mountain Site. It may be possible that areas of matrix saturation or near saturation can form within the Topopah Springs welded unit due to heterogeneities (e.g., as at USW UZ-1). If this saturated matrix is near the shaft, the water may preferentially flow in the sand, rather than be inhibited by the sand. The water saturation of the matrix can be less than 1 and this still could possibly occur (Fernandez and Fresnley, 1984).

2. The calculations were performed under isothermal conditions although the analyses cover the performance period of maximum thermal effects.

Heat from the decaying waste packages may form large potential and water content changes in the rock volume surrounding the repository. This may in turn cause saturation changes in the matrix surrounding the shafts and alter the amount of flow into the shafts from the matrix. It is not yet known what the effect of heat will be on the flow regime of the TSw unit.

Assumption Used in Report:
The hydrogeologic unit(s) below each shaft are free draining. Fernandez et al. (1987) have assumed that waters draining from the shafts is free to travel to the water table.

Comment 4.2.3:
Perched water has been located in the TSw unit at the USW UZ-1 borehole. Therefore, the possibility exists that percned water could exist or could form beneath a shaft. If this is true, then the amount of water which could drain from a shaft could be limited.

Assumption Used in Report:
In the calculation of the air flow out of the repository (Appendix C), the air conductivities of the nonwelded and welded tuffs were calculated from the saturated hydraulic conductivities for these units.

Comment 4.2.4:
The bulk hydraulic conductivities of the Paintbrush Tuff nonwelded and the Tiva Canyon and Topopah Springs welded hydrogeologic units were determined in wells located a distance away from the Yucca Mountain site. Therefore, an assumption has already been made that the hydraulic conductivity of these units is the same in the unsaturated zone at Yucca Mountain as at the location tested. A further extrapolation must be made in deriving the air conductivity from the saturated hydraulic conductivity. An assumption must be made that the intrinsic permeability of the rock mass is equivalent to the intrinsic air conductivity of the rock mass. There are certain flow situations where this is not true in a single porosity rock (Klinkenburg effect). Therefore, it is not known how conservative the air conductivity values used by Fernandez et al. (1987) are in the calculations of air flow in the repository. As site characterization at Yucca Mountain progresses, air conductivity values for the various units will be determined. The values used in this report should be compared with those determined during testing to evaluate the conservativeness of the air flow calculations.

Assumption Used in Report:
The air conductivity of the rock used in calculations for Mechanism 3 was determined by assuming flow in series through welded and nonwelded tuff units. This method was used to determine an equivalent conductivity of strata in series, namely the TCw, PTn, and the TSw units.

Comment 4.2.5
The use of an equivalent conductivity assumes that the only flow paths for air

from the repository are vertically upward through the TSw, PTn, and TCw units. The vertical flow-in-series calculation is dominated by the low air conductivty value used for PTn. However, heated air from the relatively hot waste-disposal areas could also flow directly from the repository to the surface through TSw unit outcrops in the Solitario Canyon on the west side of Yucca Mountain, without flowing through the PTn and TCw units. This flow mechanism does not appear to have been addressed by Fernandez et al (1987).

4.3 Review Comments on Chapter 5 - Assessment of the Need for Sealing

Based on the given assumptions in the report, the conclusions reached in Chapter 5 are appropriate. Sealing measures are proposed to provide additional assurance that repository performance objectives would be met when extreme conditions occur. The assumptions used to reach these conclusions will need to be evaluated periodically as the site characterization process begins to provide additional data. Even before new data are available, the reviewers consider that DOE will need to reassess the performance goals for airborne transport of C-14 and I-129 in light of the questions raised in Section 3 about compliance with the NRC's requirement for controlled release rates from the EBS.

5.0 REQUESTED ANALYSIS

A memorandum dated April 14, 1988 to John L. Russell, Center for Nuclear Waste Regulatory Analyses, from Philip S. Justus, Nuclear Regulatory Commission, provides a modified Technical Direction #4 to the CNWRA and is the basis of this portion of the analysis. Section 5.0 focuses on issues related specifically to Exploratory Shaft 1 (ES-1), though the total number of shafts providing access to the repository is four along with two ramps. The proposed location of both exploratory shafts was moved in April, 1987, to a proposed position northeast of the location defined in the EA of the site. This relocation has not materially affected the size of the surface water drainage basin which could contribute flow past the location. For purposes of this review, it has been assumed that the drainage area and basin characteristics have not changed from the SAND 84-1895 analyses. ES-1 is presently the shaft opening closest to the Coyote Wash channel.

ISSUES 1 & 2 Review the estimation of the probable maximum flood peak (NRC Issue 1) and total hydrograph volume (NRC Issue 2) with a discussion of uncertainity or confidence interval.

Issues 1 and 2 of the NRC Staff's April 14, 1988, Modified Direction No. 4 are considered together since they both relate to the probable maximum flood (PMF) in the vicinity of ES-1. The use of the PMF as the surface hydrologic event criterion stems from the application the American Nuclear Society's design basis flooding (ANSI/ANS 2.8-1981) at the surface facility locations of the NNWSI site. ANSI/ANS 2.8-1981 sets forth some guidelines for applying consistent standards to evaluate flooding potential from a maximum storm.

The PMF is the flood assumed to result from the occurrence of the probable maximum precipitation (PMP). The PMP is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year (WMO, 1973). The values derived as PMP under this definition are subject to change as knowledge of the physics of atmospheric processes increases. The operational methodologies of estimating PMP provide an upper envelope of probable amounts of precipitation. If sufficient precipitation records are available, it is possible to estimate PMP from a statistical approach. However, from a practical standpoint, there is seldom sufficient data, so a statistical PMP is not recommended as a procedure (WMO, 1973, Hansen, et al., 1984).

There are two known, relevant PMP studies (USBR, 1974, Hansen, et al. 1984) that apply to the location of the NNWSI site. Both studies were considered in the SAND 84-1895 report. PMP values are used as input to a hydrologic model that uses measured or synthetic responses of runoff to unit values of rainfall (unitgraphs). The USBR (1974) work was used to estimate the one hour thunderstorm PMF which will generate the highest peak flow rates in the vicinity of ES-1. The PMF, as derived from Hansen, et al. (1984), with a duration longer than one hour will result in a greater volume of runoff than the one hour thunderstorm PMF.

The report SAND85-0598 is the current, more uptodate evaluation of the exploratory shaft. The surface hydrologic estimates in that evaluation use only the PMF calculations performed by Bullard (1986b). Bullard found that the local storm (thunderstorm) estimates by Hansen, et al. (1984) controlled both the peak flow rate and the runoff volume for the exploratory shaft. The peak runoff rate and volume at the exploratory shaft used in SAND85-0598 are 3350 cubic feet per second (cfs) and 129 acre-feet, respectively. These are the PMF estimates developed by Bullard (1986b) for a six hour local storm of 13.9 inches with a maximum one hour precipitation of 10.1 inches.

One of the elements of Issues 1 and 2 is the uncertainity or confidence interval relating to the PMF estimation. There is definitely a great amount of uncertainity in the PMF estimation, but it is difficult to quantify. Confidence intervals (CI) are a way of identifying the uncertainity in an estimate but require that basic statistics of an estimate be known. Since the PMP, and hence the probable maximum flood, has not been developed by a statistical approach, there are no statistics, such as the standard error of estimate, to develop a confidence interval. However, since the PMP is an "envelope" approach to setting an upper bound on possible events, it is possible to compare the "envelope" values derived from the PMP to actual, recorded occurrences. If the PMP is truly the upper bound of a precipitation value, then no actual occurrences should exceed it.

Figure 1 is a graphical presentation of some extreme floods that have been observed in the western United States areas that are hydrologically similar to the NNWSI area. Details about each flood are given in Table 1. The figure also contains the regional maximum curve as originally developed by Crippen and Bue (1977) and used by Squires and Young (1984) in their evaluation of flood potential for the NNWSI area. Subsequent to these two studies, Bullard (1986a) computed PMF based upon appropriate PMPs at many locations in the United States that had experienced very large historical floods. Some of the locations Bullard evaluated were the same ones used in the Crippen and Bue and Squires and Young studies. These computed PMFs are also plotted in Figure 1. Conclusions regarding PMFs in the region are as follows. The USGS regional maximum curve (Crippen and Bue, 1977) was developed to "envelope" the observed major floods shown in Figure 1 for the drainage basin sizes ranging from 0.22 to 25 square miles. Subsequently calculated PMFs by Bullard (1986a) for some of the same basins as observed major floods show that the PMFs all plot on or slightly below the USGS envelope curve with the exception of the Eldorado Canyon flood (NV2). The calculated PMF is 110,700 cfs while the envelope curve is about 108,000 cfs for the Eldorado Canyon site. All computed PMFs are larger than the observed flood peaks, which gives a degree of credibility to the concept of the PMF being at or near the upper bound of physically realistic floods. Figure 1 shows two estimates of the PMF peak flow rate for the exploratory shaft site. The original peak flow of 750 cfs (SAND84-1895) based upon the one hour thunderstorm from the USBR (1974) source is significantly under the envelope curve of maximum regional floods. However, the subsequent estimate by Bullard (1986b) of PMF peak flow of 3350 cfs at the exploratory shaft and used in the SAND85-0598 document plots well above the envelope curve of Figure 1. This gives a degree of confidence that the currently used PMF at ES-1 is a conservatively high estimate of the probable maximum flood.

A method of evaluating the impact of uncertainty in the PMF estimation is to consider the effects of shifts in PMP estimates for the site. The source of Bullard's (1986b) one-hour thunderstorm of 10.1 inches was reviewed. This reviewer determined that the largest potential one-hour thunderstorm for the western United States from Bullard's Plate 11 transposed to the site yielded 12.3 inches in the maximum hour. Using Bullard's unit hydrographs for the ES-1 site, the PMF peak was determined to increase to 4100 cfs for this location. This is a 22 per cent increase over the 3350 cfs PMF of SAND85-0598. Based upon Bullard's (1986b) same assumptions of infiltration and losses, the PMF volume would also be about 22 per cent greater than that used in SAND85-0598. This increased PMF was considered in the range of flood elevations computed in SAND 85-0598. Further discussion of water surface elevations is considered under Issue 3.

Another means of evaluating the impact of the PMF on the repository is to review the risk of such an event occurring within a specified time frame. Section 3.1.1.2 of SAND84-1895 indicates that time interval of years 301 to 1300 after closure is important for the assumptions stated related to complete contaimnment through year 300 and to assumed complete failure of all waste packages at year 1,300. The occurrence of a PMF during this interval could be important because the waste material has not yet decayed to llower level. It is possible to assess the liklihood of the PMF occurring within this 1,000 year interval if the following assumptions are made.

1. The binomial distribution can be used to estimate the liklihood of a flood with annual exceedance frequency within an specified time interval (U.S Water Resources Council, 1977).

2. The annual exceedence frequncy of the PMF is exactly known.

Assumption 2 is the most difficult to assess, since the PMF has previously been defined as the upper bound of flood potential rather than a specified frequency. If the requirement of ANSI/ANS 2.8-1981 is used that a PMF series should have an annual occurrence probability of not greater than one in one million, then one can make the estimation of risk.

The binomial distribution is used to estimate risk as

$$\text{Risk} = \frac{N!}{I!\,(N-I)!} \quad P^{I}\,(1-P)^{N-I}$$

where P = annual exceedence probability of flood of interest (10^{-6})
I = number of floods exceeding the magnitude (1)
N = years in the interval (1000)

For the occurrence of one PMF in a 1000 years assuming the PMF has an annual exceedence probability of 0.000001 has a risk of 0.1 per cent (.001). The risk of a PMF in even a one thousand year interval is small.

ISSUE 3 Review the estimation of the elevation (depth) of peak discharge of the PMF at the Exploratory Shaft (ES-1). Explain the flood routing method used to estimate the flow depth for determination of the peak discharge elevation.

Water surface elevations in the vicinity of the relocated exploratory shafts were calculated at eight locations on Coyote Wash based upon existing topography (SAND85-0598, Section 3.2.4, pg. 3-39). The basis of the topographic information is not stated. The figure used to depict the area shows 5 ft contours. The accuracy of the topographic data is important for evaluation of the potential impacts of flooding on ES-1. The method of flood routing the peak flow is not explicitly stated in that section. However, the section references Squires and Youngs (1984) previous work at the NNWSI site. The method applied in the original work indicates that the Manning formula of

$$Q = (1.49/n)\ A\ R^{.667}\ S^{.5}$$

where
- Q = the discharge, in cubic feet per second
- n = the Mannings roughness coefficient (dimensionless)
- A = the cross sectional area, in square feet
- R = the hydraulic radius (area/wetted perimeter), feet
- S = the slope of the energy grade line, in units of ft./ft.

was used to estimate the water surface elevation. For the specified peak PMF flow, and assuming the slope of the energy grade line is equivalent to the slope of the channel at the cross section, the Mannings formula can be solved for the term $A\ R^{.667}$, known as the conveyance. Detailed cross sectional geomentry can be used to estimate the conveyance factor required to pass the specified PMF peak. Section 3.2.4 indicates that a Mannings roughness coefficient of 0.06 was used at all cross sections. The roughness coefficient is higher than the range of 0.030 to 0.055 that Squires and Young used. The higher roughness coefficient will give a higher water surface elevation for a specified discharge.

The flow of 3350 cfs was used as the peak PMF flow rate. In order to account for the unknown impact that debris could have on computing the water surface elevation, the peak flow was increased by a factor of 1.5 (5030 cfs). The floodplain, i.e. potential area of PMF inundation, was plotted in Figure 3-17 for both the calculated peak and the 1.5 times peak flow rate.

Further detail is needed in the SAND85-0598 document to ascertain whether this was the actual procedure used. Details of each cross section should be presented. This could be done in the form of tables or charts and may be appropriate for an appendix. An alternative to the procedure of Squires and Young would be to use a computer model of water surface elevation to start at a known or assumed elevation away from the exploratory shaft location and iterate successively from one cross section to the adjacent cross section. This type of model can be used to show the impact of nearby topography, if any, on the computed water surface elevation. Justification for using an arbitrary factor to account for debris should be given. An analysis of the impacts of debris flow flooding should be made. Debris problems in the region are not a hypothetical problem. The Draft Site Characterization Plan for the site (Section 3.2.1) identified debris flows as significant geomorphic process. Also the Eldorado Canyon flood (NV2 on Figure 1) included serious damage from the associated debris flood.

ISSUES 4, 5, AND 6 Evaluate the Sandia esimation of recharge volume in the Exploratory Saft (ES-1). If a single event (PMF) estimate, extend the estimate to an estimate for one year assuming a single PMF event and a conservative estimate or a sequence of other events for a year period (Issue 4). Assume a twofold increase in annual rainfall and repeat the evaluations 1-4 (Issue 5). Evaluate the drainage rate from the bottom of the ES (Issue 6).

The requested Issue 4 review work pertains to the estimates of water flow into shafts under unanticipated conditions (Section 4.1.5) of the SAND84-1895 report. Fernandez et al. (1987) made the following assumptions to determine the flow into shafts:

1. All of the waters from selected, major flood events are restricted in the alluvial basins adjacent to each shaft. This allows all of the water from the flood event to be available for drainage into the shafts.

2. The total amount of the flow into the shaft was controlled by several types of flow, as well as the geometry used in the model.

3. The shaft fill below the alluvium/Tiva Canyon contact had a saturated hydraulic conductivity of .01 cm/s.

4. The shaft liner was ignored, which yielded a higher flow rate through the shaft and was thus a conservative assumption.

5. The modified permeability zone (MPZ) extended out one radius from the shaft wall. The hydraulic conductivity of the MPZ was considered to be either 20 or 60 times greater than the undisturbed, hydraulic conductivity of the TCw unit.

6. Three flow phases were considered, an initial desaturation phase, a steady-state phase, and a final desaturation phase.

7. Four types of flow were considered for each flow phase. These flow types were: (1) unconfined radial flow under the Dupuit flow assumption, (2) alluvial flow, (3) Tiva Canyon flow, and (4) flow through the MPZ and the shaft fill.

Since the release of the SAND84-1895 report, the ES-1 location has been changed. To extend the estimate for recharge performed by Fernandez et al. (1987), a single PMF event and the yearly rainfall were used as to estimate the volume of water available for recharge into ES-1. It was assumed that the runoff area (120 acres) for ES-1 received six inches of precipitation per year. This volume of water was then added to the single PMF (5,610,000 cubic feet) for a yearly water volume of 8,220,000 cubic feet.

Assumption 1 of Fernandez et al. (1987) was the water from the flood events would be available for flow into ES-1 as storage in the alluvium. This assumption will also be used in the extended analysis. The amount of alluvium required for storage of the volume of water (8,220,000 cubic feet) would be (assuming 30% porosity, which may be more porosity than is actually available) about 27,400,000 cubic feet. If the thickness of the alluvium is 9.1 m (based on depth of alluvium at USW G-4) then approximately 21 acres of alluvial material are required to store the water.

One extreme of flow of water into the shaft occurs when the shaft fill and the TCw unit have equal hydraulic conductivities (see Figure 2). The total flow into the shaft is then proportional to the ratio of the area of the shaft to the area of the alluvium. It was assumed the radius of ES-1 was 1.83 meters at the surface. The volume of water which would enter the shaft under these conditions and assumptions was calculated at 1,015 cubic feet.

The other extreme for flow of water into the shaft occurs if the TCw unit is considered impervious and the shaft is the only drain point for the water stored in the alluvium. The following assumptions were used to determine the flow rate into the shaft:

1. The shaft was considered to be instantaneously saturated.

2. Darcian steady state flow was valid, and a unit hydraulic gradient existed.

3. The shaft ~~hydraulic~~ conductivity was assumed to be .01 cm/s.

4. The shaft radius at the surface was 1.83 meters.

A steady state flow rate was determined at 2.23 cubic feet per minute. This value should be a conservative flow rate into ES-1 for the flooding event. At this flow rate, it would take about 2560 days for the water in the alluvium from the extreme flood event to drain into the shaft.

Issue number 6 of the requested review stated "Evaluate the drainage of the ES." The Nasberg-Terletskata equation for drainage in an unlined shaft (U.S. Bureau of Reclamation, 1977) is conservative and was considered appropriate.

$$Q = \frac{K\,H^2}{0.423} \quad \frac{1}{\mathrm{Log}\,(2H/r)}$$

where: Q = flow rate
K = saturated, effective hydraulic conductivity of fractured tuff
H = total head in shaft
r = shaft radius

The unlined sump at ES-1 was assumed to be 140 meters deep and have a radius of 2.2 meters. The conductivity of the Topopah Springs welded and Calico Hills nonwelded units surrounding the sump was assumed to be 5 E-8 m/s, which represents the low range of DOE estimates of bulk saturated hydraulic conductivities. Applying these values to the Nasberg-Terletskata equation yielded a flow rate out of the shaft of 2.33 cubic feet per minute.

Because the estimated flow rates are based on steady state conditions, the increase of the single PMF event with a two fold increase in annual rainfall would not change the rate of flow into or out of the shaft. Only the amount of time required to drain the alluvium would change with the new volume. The calculated drainage rate is, of course, based on the parametric values assumed. As discussed in Sections 4.2.1 and 4.2.3 above, drainage would be inhibited if clogging of matrix and (particularly) fractures occured at the bottom of the sump or if perched water existed below the sump. On the other hand, the calculation does not take any credit for enhanced permeability in the MPZ or for saturated hydraulic conductivities above the low-range value of 5 E-8 m/s. Thus, the potential uncertainties are at least qualitatively off-setting, and it would probably be fruitless speculation to attempt to assess their impacts without real data that can be obtained during Site Characterization.

The conclusions from the very simplified analysis indicate that under extreme conditions, the inflow into the shaft is close to the outflow from the shaft. This relation depends on the actual hydraulic conductivities of the formations and the height of the unlined sump. However, if the new location of ES-1 is above the alluvium and is located on the TCw outcrop, the probability of flooding the shaft by an unanticipated event becomes extremely remote.

6.0 CONCLUSIONS

The general approach which the authors utilized in developing the technical basis for developing seal designs for the NNWSI program appears valid as an initial attempt. As the authors state in their report, the geohydrologic data forming the basis for their report are preliminary. Therefore the technical basis for sealing designs may change as additional site information is acquired through site characterization activities. Based on the available data this report provides a good basis for further investigations into the NNWSI Repository Sealing Program. These further investigations should address the comments from sections three and four of this review.

Specific data which ultimately will be needed will include site-specific hydraulic parameters for detailed assessment of the performence of shaft sealing and hydraulic, geologic (including geomorphic) and topographic data sufficient to assess detailed flood routing near theshafts and ramps for the full range of feasible flooding scenarios, including, but not necessarily limited to debris flows.

Table 1. Observed Peak Flows and PMFs at Selected Western Sites

Site ID in Fig. 1	Location & Date	Drainage Area (sq.mi.)	cubic ft/sec Observed Peak (cfs/sq.mi)	PMF * (cfs/sq.mi)
AZ1	Bronco Crk nr Wikieup, AZ(8/18/71)	19.0	73,500 (3,870)	- -
CA1	Arch Crk nr Earp, CA (8/19/71)	1.52	7,160 (4,710)	- -
CA2	Indian Wells Canyon nr Inyakern, CA (10/6/45)	16.6	50,000 (3,010)	78,800 (4,750)
NV1	Lahonton Resvr. trib. 3 nr Silver Springs, NV (7/20/71)	.22	1,680 (7,640)	- -
NV2	Eldorado Canyon at L. Mohave, NV(9/14/74)	22.8	76,000 (3,300)	110,700 (4,860)
NM1	El Rancho Arroyo nr Pojoaque, NM (8/22/52)	6.7	44,000 (6,570)	50,200 (7,490)
UT1	Little Pinto Crk trib. nr Old Irontown, UT (8/11/64)	.30	2,630 (8,770)	2,990 (9,970)
ES-1	Exploratory Shaft 1, NNWSI site	.19	- -	3,350 (17,630)

* from Bullard, 1986b

Figure 1. PMFs and Regional Floods.

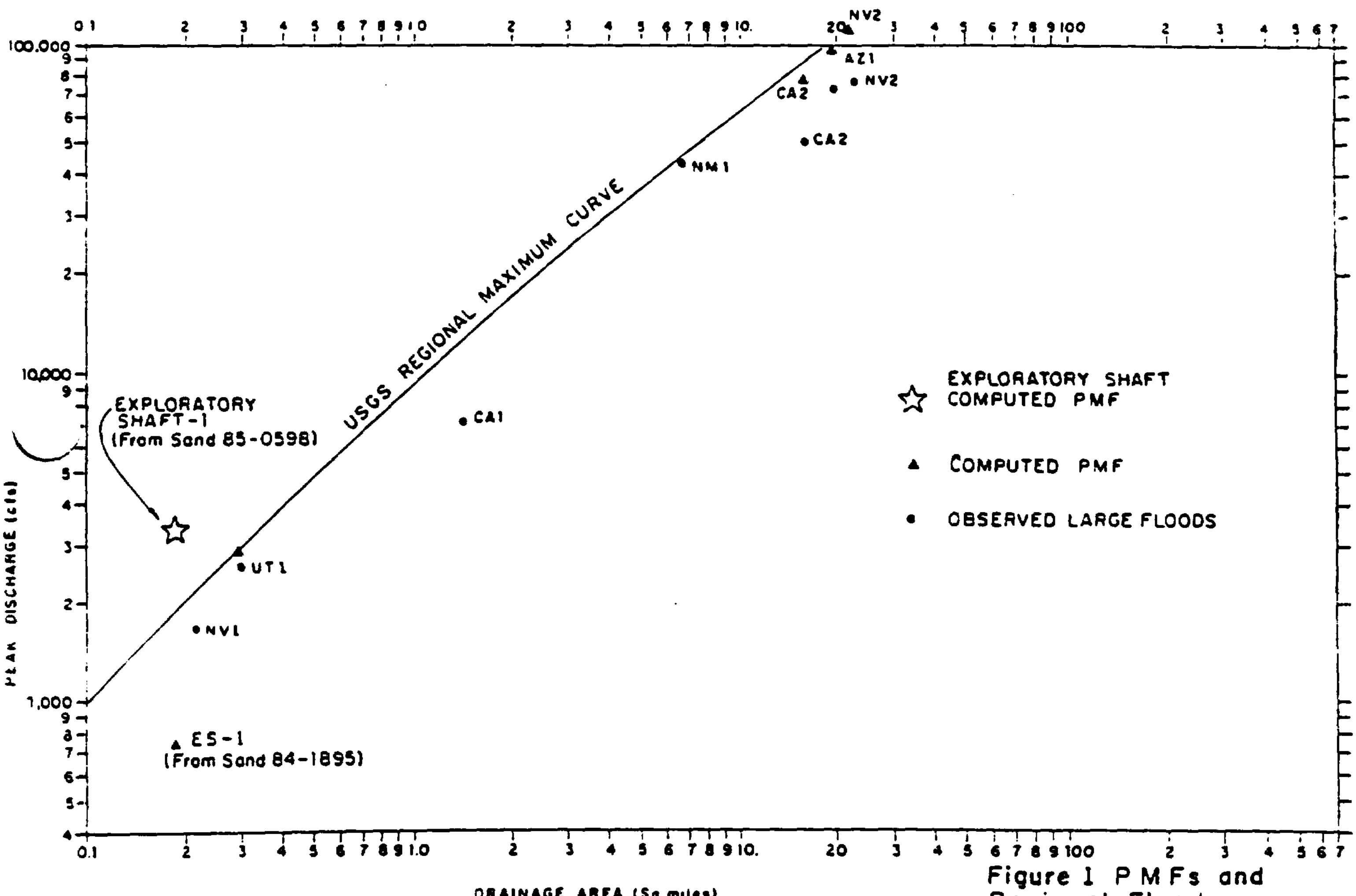
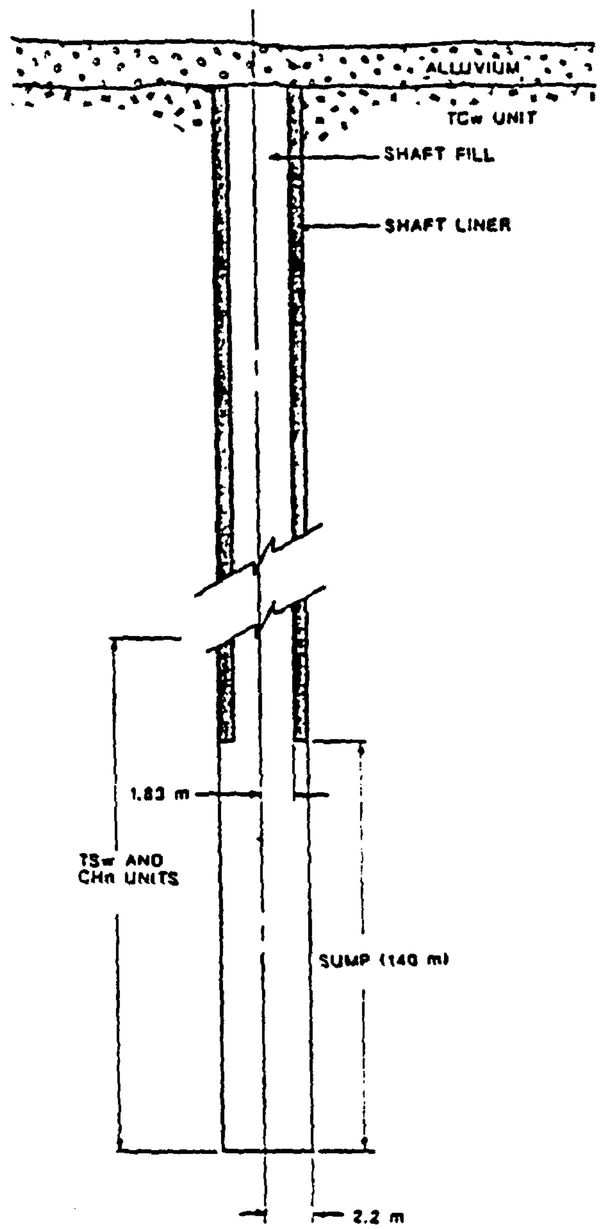


Figure 1 PMFs and Regional Floods

NUCLEAR WASTE CONSULTANTS INC.

Figure 2. ES-1 Schematic.



Water, Waste & Land, Inc.	FIGURE 2 ES-1 SCHEMATIC	Date: 4/27/88 Project: 004

7.0 REFERENCES

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WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: SAND85-2701

DOCUMENT: Sinnock, Scott, Lin, Y.T., Tierney, M.S., and others, 1986, Preliminary Estimates of Groundwater Travel Time and Radionuclide Transport at the Yucca Mountain Repository Site.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: November 14, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams/sl

The report under review constitutes the primary support document for travel time estimates presented in the Final Environmental Assessment. The report is concerned with improvements to methods for the calculation of distributions of groundwater travel time through the unsaturated zone of Yucca Mountain, Nevada. Travel times were calculated for the region between the disturbed zone and the water table. The region was divided horizontally into elements 250 ft square. Several different vertical dimensions of elements were used to investigate the effect of possible vertical correlation of element materials. Hydraulic property values for each element were selected randomly from assumed distributions, and groundwater travel times (realizations) were calculated for each input configuration. These realizations were then assembled to estimate a cumulative distribution curve for travel times. Horizontal correlation lengths were discussed, but they were not used in the development of the travel times. The authors also mention the possible correlation between material properties but assume that such properties are independent random variables.

A section on radionuclide movement also is included. This analysis is consistent with the travel times determined previously in the report. It is concluded that the possible movement of radionuclides to the accessible environment is well within EPA standards.

BRIEF SUMMARY OF DOCUMENT:

The purpose of the report under review was to document the analysis of groundwater travel time and radionuclide transport in support of the Environmental Assessment document of the Nevada Nuclear Storage Investigations Project. The report contains updated versions of the probabilistic methods for estimating the distribution of groundwater travel time and radionuclide transport.

This report focuses only on the downward percolation of water through the unsaturated zone. The conceptual model used is slightly different than that which has been presented previously; no horizontal flow occurs along contacts between units. For downward flow the Darcy equation is assumed to be valid with a hydraulic gradient of one. The actual velocity of downward flow is equal to the specific discharge divided by the effective porosity. It is assumed that any infiltration pulses are damped by the matrix pores so that essentially steady flow occurs through the Topopah Spring unit and underlying units.

For unsaturated conditions the velocity is determined by dividing the specific discharge by the effective porosity and the degree of saturation. The degree of saturation, however, may be related to capillary pressure, hydraulic conductivity and discharge by using the Brooks-Corey relationship (Brooks and Corey, 1966). The authors develop an expression for the velocity in the pores in terms of specific discharge, effective porosity, saturated conductivity, and a pore size distribution index. This development is correct. A correlation length is introduced to relate the hydraulic properties of one block of material to those of adjacent blocks. This correlation length ultimately will have to be determined experimentally; however, no discussion as to how this may be done is presented. It seems very likely that there will need to be some correlation between the properties of adjacent blocks.

The information which the authors state is needed for use of their approach includes:

1) Thickness of each hydrogeologic unit along the assumed vertical flow paths between the disturbed zone and the water table.

2) Effective matrix porosity and fracture porosity.

3) Saturated matrix hydraulic conductivity.

4) The Brooks-Corey exponent for relative conductivity.

5) Percolation flux between the disturbed zone and the water table.

In addition, Williams and Associates, Inc. believes that the correlation length also will be necessary.

The entire repository volume was divided into a horizontal grid with grid points every 250 feet. Because the actual problem is three-dimensional, isopach contour maps are presented which give the total thickness of each of the units of interest. The total thickness used in the simulation is from the repository level down through the Calico Hills unit to the water table. Effective porosity for the various units was calculated from bulk porosity and residual saturation data. The bulk porosity data were obtained from the NNWSI tuff data base which includes data from four drill holes. The means and standard deviations of the available porosity values were calculated for each hydrogeologic unit. The residual saturation values were obtained from Peters et al. (1984) for samples from drill holes USW G-4 and USW GU-3. Saturated matrix hydraulic conductivity data also were obtained from the tuff data base and Peters et al. (1984). Conductivity values were assumed to follow a lognormal distribution for each hydrogeologic unit. Histograms of the logarithms of the available measured values and the theoretical normal distribution curves derived from the calculated means of standard deviation are presented in the report. The Brooks-Corey parameter epsilon (ε) was obtained from effective saturation-capillary pressure data by standard procedures. Epsilon is treated as a constant for each hydrogeologic unit by averaging the various sample values. Values of percolation flux of one millimeter per year (mm/yr), 0.5 mm/yr and 0.1 mm/yr are used in this report. The authors state that according to available information a steady vertical flux of less than 0.5 mm/yr probably occurs beneath the potential underground facilities in the matrix of the Topopah Spring welded unit (Montazer et al., 1985; Wilson, 1985; Sinnock et al., 1985). This value has been questioned by Williams and Associates, Inc. and NRC staff in the FEA review comments.

The calculation model for groundwater travel time consists of the various horizontal elements, each of which is divided into tens of elements in the vertical direction. The physical properties of each element are selected on a random basis from the appropriate distributions. The time of travel through each element is calculated and these are summed to calculate the travel time through the entire column. The authors used varying thicknesses for the calculation elements in the column to simulate the effect of varying vertical correlation lengths. One ft, 50 ft and 150 ft thick slabs were used. The entire unit thickness was used as a bounding case. Use of the entire unit thickness would give a very conservative value of travel time since it is unlikely that many water bearing fractures penetrate the entire thickness of any of the rock units. It is assumed that 10 feet is the baseline representation of the vertical correlation length. No data are available to indicate whether 10 feet is more realistic than 15 or 50 feet. A weakness of the described model is that no opportunity exists for flow from one column to another. In the actual physical case it seems likely that there may be horizontal flow into other columns when the flow in one column encounters a particularly low permeability layer (saturated matric conductivity less than the flux). Williams and Associates, Inc. believes that there should be some correlation length in the horizontal direction and an allowance for flow from one column into an adjacent column. If this actually occurs, the assumption of uniformly distributed flux in the horizontal direction would not be valid.

In the operation of the calculational model one realization of total travel time consists of one set of "sampled" values from permeability and porosity distributions for each of the variables, and the calculation of travel time through a complete column. The distribution of total travel time is constructed from an ensemble of realizations of the travel time for all columns extending from the disturbed zone to the water table. Therefore the population of all travel times is obtained by direct simulation using the Monte Carlo method.

Whether the flux in a particular element occurs through fractures or not is determined by whether the flux value is less than 95% of the saturated matrix conductivity. If the flux is greater than 95%, it is assumed that flow occurs in the fractures.

In the selection of physical parameters for each element it is assumed that the matrix porosity is independent of the hydraulic conductivity. This assumption is very questionable. The porosity and saturated hydraulic conductivity data from Peters et al. (1984) were plotted as shown in figure 1. It is clear that these are not independent variables. In fact, for the data from GU-3 it appears that there is a strong linear relationship between the log of saturated conductivity, and porosity. In the report under review no justification for the value of 0.95 as the cutoff between flow in the fractures and flow in the matrix is presented. It may have been advisable to use various values of this coefficient to determine the sensitivity of travel time to this arbitrary value.

The results of the simulation process are presented in the form of contour maps showing the spatial distribution of travel times. histograms showing the number of flow paths in the calculational model, curves of cumulative distribution functions, and tables of means of standard deviations of sets of travel time values. Probably the most significant presentation of these data is the cumulative distribution curves which show the effect of using

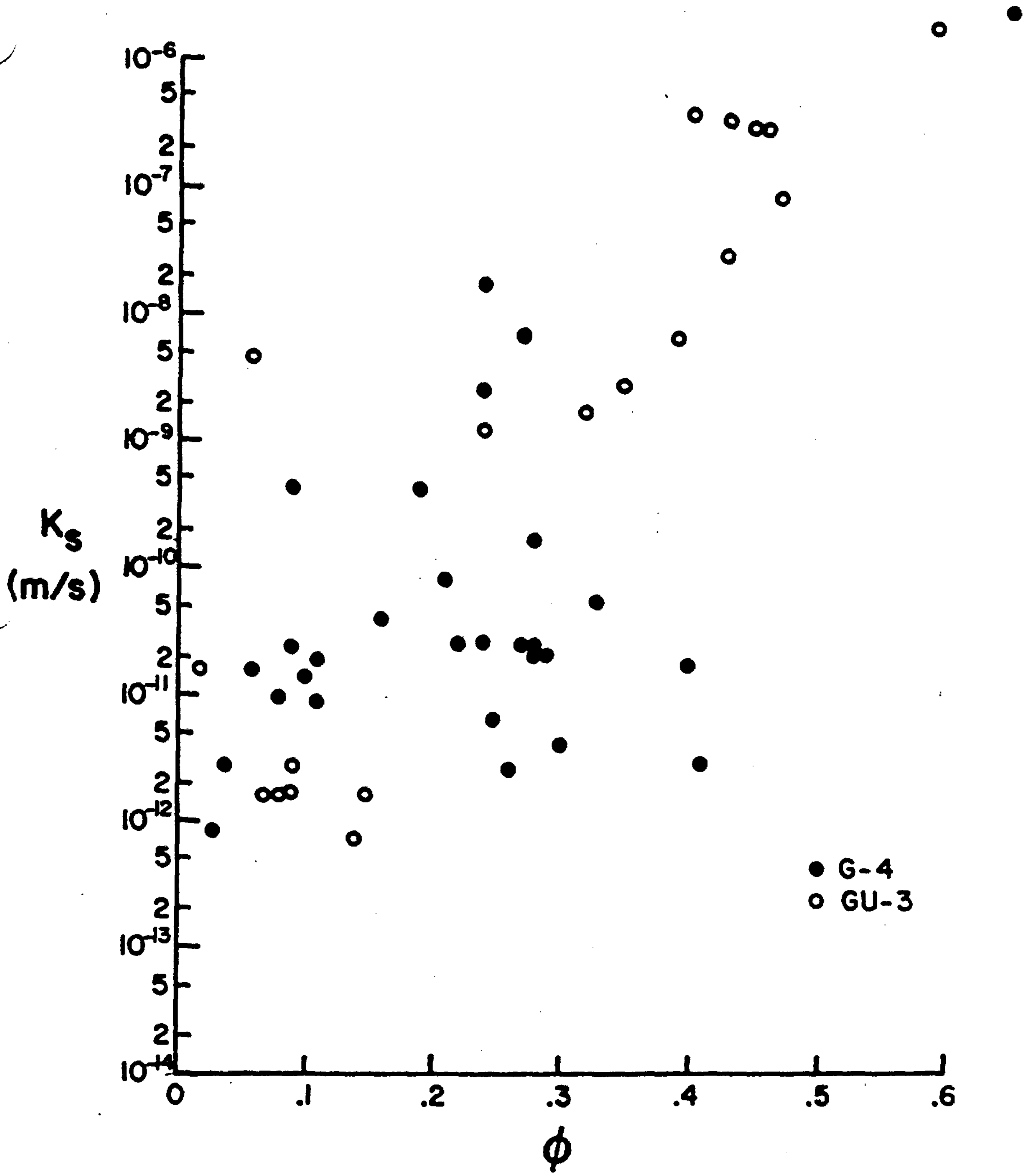

Figure 1. Plot of hydraulic conductivity versus porosity for samples from boreholes G-4 and GU-3.

mean values of effective porosity and hydraulic conductivity as opposed to using several realizations and selections from the distributions of porosity and hydraulic conductivity.

In all cases the travel times are larger than 16,000 years. These series of data are for a flux of 0.5 mm/yr. The results show that the average travel time increases in the southwesterly direction from a minimum of less than 25,000 years along the eastern edge to a maximum of about 70,000 years in the southwest corner. This increase is due to an increase in thickness of the unsaturated rock mass. The authors state that the results suggest strongly that the requirements of a one thousand year groundwater travel time from the disturbed zone to the accessible environment can be met solely by flow time within several of the individual hydrogeologic units of the unsaturated zone beneath the disturbed zone at Yucca Mountain. In addition, the total travel times through the unsaturated zone may be sufficient to demonstrate compliance with EPA requirements with regard to the control of radionuclide releases for 10,000 years.

The vertical correlation length of 10 feet was investigated by changing the thickness of the elements from one foot up to the entire unit thickness. The cumulative distribution curve in the case of the entire unit thickness shows a groundwater travel time of less than 1,000 years in some realizations. In such a case it is possible to have a column which has fracture flow through the entire depth which will result in a short travel time. If the elements are of smaller thickness it is very unlikely that there would be fracture flow through the entire profile.

When flux was varied from 0.1 to 0.5 to 1 mm/yr the minimum travel time still was greater than 1,000 years. The authors indicate that travel time distribution is very sensitive to the magnitude of flux, and that uncertainty will be reduced by flux measurements made during site characterization activities.

The range of variability of saturated matrix hydraulic conductivity within each unit was examined by varying the standard deviations of the natural log of the baseline conductivity values. The travel times are quite sensitive to variations in the saturated matrix hydraulic conductivity, although not as sensitive as to the mean value of flux. However, it is important to obtain a good estimate of saturated matrix hydraulic conductivity for each hydrogeologic unit. The effective matrix porosity within each unit has less effect on travel time than the variations of other parameters because the matrix porosities have relatively small standard deviations. The authors state that "porosity is likely to be closely correlated with parameters that are more difficult to measure, such as hydraulic conductivity. From this perspective the spatial distribution of porosity values should be included in the site characterization activities." The authors of the document recognize that porosity probably iscorrelated closely with hydraulic conductivity. Yet, the authors assumed in previous sections that they were completely independent.

In summary, the authors make the following conclusions:

1. The travel times will exceed 1,000 years with a very high level of probability and are likely to exceed 10,000 years as well.

2) The travel time distribution is most sensitive to flux correlation lengths and spatial variations of saturated matrix hydraulic conductivity.

3) Potential lateral flow and concentration of flux down fault zones need to be investigated before the cumulative distribution function can be interpreted as representative for the fastest paths of likely radionuclide travel.

4) In most cases hydraulic data are insufficient for performing geostatistical analyses.

The next section of this report is concerned with radionuclide transport from the waste emplacement area to the water table. The analysis is performed for a single canister which contains 3.33 metric tons of heavy metal in the form of spent fuel rods or pellets. The underground facilities will be capable of containing about 21,000 canisters. The disposal horizon has an effective area of 510 hectares (1260 acres). Calculations are carried out with time t=0 representing the time at closure. At some later time $t=t_c$, a breach in the canister could occur allowing water to come into contact with the spent fuel pellets. Water in the partially saturated rock will not flow into the space between the borehole and the canister unless suction is exerted in the space or local hydraulic conductivity allows ponding of sufficient water near the space to cause positive pressure at the face of the borehole.

In the analysis it is assumed that the canister is breached and water moves through the canister at a rate equal to the percolation flux at the repository level times an 'effective water intercept area' for the canister. As the spent fuel matrix is dissolved, radionuclides embedded in the matrix will become available for conversion to a liquid phase. The solubility limits of the radionuclide bearing compound will determine the actual rate at which the matrix dissolves. This analysis leads to an upper bound approximation of the mass release rate from a canister as well as the fractional release for a particular nuclide in terms of parts per year.

Finally, an equation is developed for the time dependent concentration of the radionuclide at the underground facility.

The transport of radionuclides between the underground facilities and the water table is considered next. The continuity equation for transport is presented first. It is assumed then that the flow is one dimensional and steady, and the percolation flux is constant along a vertical path. The equation does not include the effect of dispersion nor molecular diffusion. The authors believe that molecular diffusion is relatively small compared with the rates of mass transport by advection, and dispersion is considered with the new independent variable of travel time. Travel time is introduced as an integral of the moisture content divided by the flux and multiplied by a retardation coefficient. The result is an expression relating the cumulative discharge of a particular radionuclide to time since closure and a transport time. The transport equation presented is valid for radionuclides that have single member decay chains. Some of these are C^{14}, I^{29} and possibly Tc^{99}. Radionuclides such as cesium and strontium also could be handled by this equation but retardation factors are very large. The authors believe that such radionuclides are effectively immobile and would not be transported to the water table within a realistic time scale. At flux rates of 0.5 mm/yr the transport time for uranium would be more than 100,000 years and could be ignored easily. These factors suggest that there is justification for avoiding the complications of including multi-member decay chains in the formulation of a transport equation. The authors include dispersion in the transport problem. The cumulative discharge is a function of two variables, that is, time which is a free parameter and transport time which is a random variable of distribution as determined by flux and the distribution of hydrologic properties throughout the rock column. The expected cumulative discharge through each single column is calculated. Many of the parameters which are included in these equations could be functions of the coordinates of the particular column. The cumulative discharge for all the columns is simply the sum of each column. The time of travel through each column is considered to be an independent random variable. This is justified only if the characteristic size of each of the (m) columns is no smaller than the spatial correlation length in the horizontal direction. The report notes several times that the distance over which relevant rock hydrologic properties are correlated is unknown.

Many of the equations in this report are missing brackets, integral signs, and summation signs, which complicates the review process. The authors note that although the equations were developed for the expected total cumulative release it was not possible to use these equations in the development of the environmental assessment. The method that was used for the environmental assessment was to assume that the water travel time distribution for the entire repository could be approximated by a normal distribution with the mean and variance equal to the sample mean and sample variance obtained from the numerical simulation of ground water travel time. The expression then was multiplied by the repository area and the normal probability density function; the product was integrated over all values of travel time to obtain an expression that is identical to the analytical development in the report under review. A table of the estimates of cumulative releases to the water table for C^{14}, I^{129} and Tc^{99} is presented. The error introduced by the above approximation has not been estimated carefully; however, it is discussed in the report. The authors conclude that use of the normal approximation was conservative for the 10,000 year time scale. This is shown by a plot of the cumulative distribution frequency curves using both the empirical equation and the normal distribution. These curves indicate that cumulative releases of all nuclides during 100,000 years may have been underestimated by an amount that is unknown but probably is insignificant.

The major assumptions behind the determination of travel time are:

1) Water travels vertically downward through the unsaturated zone below the disturbed zone

2) Quasi-steady flow conditions prevail between the disturbed zone and the water table.

3) Water flows through the porous matrix unless it is diverted into fracture where percolation flux exceeds the saturated matrix hydraulic conductivity.

The authors state that "all of the flow parameters are assumed to be statistically independent quantities on the basis of the present model because available hydrologic data are insufficient for determining the degree of correlation." It should be pointed out that sufficient permeability and porosity data to allow correlation exist from at least one borehole. These data are presented in figure 1; it appears that the data for GU-3 are well correlated, while those for G-4 may be nearly random. Possible correlations should be determined and introduced into the present model. Other factors that should be investigated are the horizontal correlation length and the possibility of flow from one column to an adjacent column due to variability in the permeability of the matrix.

The calculations for cumulative releases to the water table show approximately one ten millionth of the amount of radionuclide allowed in the EPA standards (40 CFR Part 190) for 10,000 years.

Appendix A of the report under review presents an estimation of the distribution mean and standard deviation of travel time by analytical methods. In this development the same symbol is used for the thickness of an element as for correlation length. This makes it very difficult to review the mathematical development. This is pointed out by the sentence at the top of page A5 which states, "Independence can always be guaranteed by choosing ρ_v large enough so that travel times in each of the N slabs are effectively uncorrelated." If ρ_v is meant to be the thickness of the element it is correct. If ρ_v is meant to be the correlation length the word large should be changed to small. There also are several sentences which describe the construction of a probability density function when the term "estimate" should be used. The authors assume that porosity, permeability, and pore size distribution index are mutually independent random variables. They do point out that this may not be true. In fact, these parameters are all related and may be well correlated. The final equation in this development gives estimates of the mean and variance of the water travel time through a rock unit of thickness, d, in terms of percolation flux and simple statistical measures (mean and variance) of the natural variability of key hydraulic parameters. The relationships provide a means of calculating the distribution of water travel time between the disturbed zone boundary and the water table without recourse to Monte Carlo simulations described previously in this report; this is true provided that the assumptions made in developing the relations are valid. The analytical relationships developed in Appendix A have not been compared with the results of the Monte Carlo simulations.

Appendix B describes the data used for estimating effective porosity, saturated matrix hydraulic conductivity and relative hydraulic conductivity. Much of the data is derived from the report by Peters et al. (1984). The methods used for evaluating the relative permeability are well accepted in the literature.

<u>SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM</u>:

The report under review constitutes the primary support document for travel time estimates presented in the FEA. The report represents a significant contribution to calculation of probable travel times for flow from the repository level to the saturated zone at the NNWSI site. Improvements over previous analyses are the inclusion of the possible correlation between adjacent geologic units and recognizing the possible correlation between hydraulic parameters such as permeability and porosity and pore size distribution. Even though the report did not make use of correlations between these factors it is recognized that they may be correlated and the authors assume that this will be a possible avenue of further endeavor.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The limitations of the report are that hydraulic parameters are assumed to be independent, that the correlation between adjacent columns is not worked into the analysis, and that few data are available to justify the vertical correlation lengths that were used.

SUGGESTED FOLLOW-UP ACTIVITIES:

Reports of this type should be reviewed so that the NRC can remain up-to-date with respect to travel time analyses being performed by DOE.

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WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: SAND86-1598, NUREG/CR-4693

DOCUMENT: Smith, D.M., Updegraff, C.D., Bonano, E.J., and Randall, J.D., November 1986, Assessment of Radionuclide Vapor-Phase Transport in Unsaturated Tuff. Sandia National Laboratories, Albuquerque, NM and Livermore, CA, SAND86-1598, NUREG/CR-4693, 42 p.

REVIEWER: Williams & Associates, Inc., George L. Bloomsburg

DATE REVIEW COMPLETED: April 10, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy Williams

This report considers the transport of radionuclides by vapor and liquid movement in fractured volcanic tuff. The authors show that the conditions for movement of an aerosol are not met and that the only vapor movement would be due to convection or diffusion. A computer program called TOUGH is developed which considers the flow of both air and water in liquid, gas and vapor phases. Heat flow and the energy changes due to condensation and vaporization are considered also. The program is used to simulate the flow of these phases in the radial direction from a storage canister. Bounding distances for vapor movement from the canister are determined as well as the temperature and saturation distribution in the vicinity of the canister. Agreement between theoretical relationships and measured values is not good in some cases but is adequate in other cases.

BRIEF SUMMARY OF DOCUMENT:

This report addresses the possibility of radionuclide transport in the vapor phase from high-level waste canisters placed in unsaturated tuff.

Vapor-phase transport may occur in the form of aerosols (not limited by volatility of the species) or by convection, diffusion and/or dispersion if the species are sufficiently volatile. The mechanics of aerosol transport are described in the report. The formation of aerosols from the liquid phase contained in the fractures in unsaturated tuff is a multiple step process. This process occurs as groundwater moving toward the waste canister is heated, vaporizes, and then flows away from the canister. Because the solubility of air components in the groundwater decreases with increasing temperature, the dissolved air components migrate through the liquid due to a concentration gradient toward the gas-liquid interface. Air components then desorb from the interface into the bulk gas/vapor phase. If the air transport rate is not sufficiently high, the groundwater will become supersaturated and gas bubble formation will occur. Air bubbles then will migrate to the surface of the liquid groundwater film if the film thickness is large compared to the air bubble size. If the air bubble velocity is large enough, the bubble will collapse, thereby producing aerosols. If any one of these steps does not occur aerosols will not form.

The authors consider the aperture size of fractures and the resulting maximum possible film thickness. This film thickness limits the air bubble size and the degree of air supersaturation. The authors show that the bubble size which may exist in the fractures will not be large enough to provide the velocity necessary for aerosol formation; consequently the concept of radionuclide transport as an aerosol may be safely neglected.

The authors next consider the possibility of radionuclide transport by vapor diffusion. They state that "whether the flow is saturated or unsaturated may affect the adsorption of radionuclides on solid particles because the liquid phase may not have access to all adsorption sites." It should be noted, however, that water is the wetting phase and will wet all solid particles. Wet solid particles would allow radionuclides in the liquid phase to have access to all adsorption sites. The authors also state that retardation of radionuclides in the vapor phase will depend on partitioning between the gaseous and liquid phase as well as on adsorption sites which are directly available to the vapor phase. They then conduct a preliminary "order of magnitude" analysis to provide assessment of which transport mechanisms may be important. Equations for vapor movement by convection and diffusion are presented. If the movement by each of these processes is of comparable magnitude, no simple expression relating the vapor and liquid transport exists.

Vapor/liquid distribution coefficients for several elements in groundwater are presented. A computer code called TOUGH was used for simulation of two phase flow of air and water in both the gas and liquid phases, and, fully coupled transport of heat. The equations account for gas diffusion, Darcian flow, and capillary-pressure effects. Vaporization and condensation of water with latent heat effects and conduction/convection of heat flow are included. The flow region may include liquid, gas, and two-phase regions.

Although the volcanic tuff is fractured, it is modeled as an equivalent porous medium. The authors use the Brooks-Corey relationships for relative permeability as a function of saturation. They apparently did not recognize that the exponents in these equations are dependent on material properties; consequently they have used constant values for the exponents which do not necessarily represent the volcanic tuff. The result is that the experimental data show a poor fit when compared to the theoretical curve of relative permeability. The mesh used for computation extends 456 m above the repository and 304 m below the repository. The top boundary has an imposed flux of 0.1 mm/year, while the bottom boundary represents the water table. The first modeling effort was to investigate the distribution of degree of saturation throughout the profile. The calculated degree of saturation agrees poorly with measured values which probably is caused by the use of a single stratum in the computational analysis.

The authors next investigate the use of a two-dimensional model instead of the axisymmetric model used previously. The grid size was the same as before. The purpose of this effort was to examine the degree of agreement between the axisymmetric model and the two-dimensional model. Spatial temperature profiles calculated using the TOUGH code are presented in the report for a period of three years. This simulation shows that the temperature drops sharply at relatively small distances from the canister. The agreement between two- and three-dimensional models is poor.

The data on the radial mobility ratios plotted against radius from the centerline of the canister are presented next. The authors state that agreement between 2-D and 3-D is good; however, a tendency exists for the two-dimensional simulation to overpredict the results of the three-dimensional simulation.

Data on the radial flow rate, the vertical mobility factor, and the vertical flow rates as functions of radius also are presented. To determine the possibility of vapor-phase transport to the far field, calculations are performed to provide an upper bound for the mobility factor. The vertical bounding conditions also are investigated.

The conclusions of the report point out that the concept of radionuclide transport as an aerosol may be neglected. A computer code named TOUGH has been developed to simulate spatial, temporal distributions of liquid and gas velocity, saturation and temperature for typical tuff formation properties. The relative transport rates due to convection in the gas phase as compared to the liquid phase have been investigated. In the immediate vicinity of the canister vapor phase transport of iodine may be important. The bounding calculations for vapor phase transport in the far field also have been performed, but vapor phase transport will not be important for such radionuclides as cesium and heavier species.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

This report should be of significance in evaluating the movement of radionuclides by water vapor movement. It shows that movement as an aerosol will not be significant and only movement by convection, dispersion and diffusion is possible. A computer simulation program for liquid and vapor phase movement is presented.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

Poor agreement exists between theoretical relationships and measured data in some cases. One case probably is due to the selection of poor values for the exponents in the Brooks-Corey equations for relative permeability of the volcanic tuff. The program TOUGH probably needs more verification to assure that it will simulate vapor and liquid movement correctly.

U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

REVIEW OF
"MODIFICATION OF ROCK MASS PERMEABILITY IN THE ZONE SURROUNDING A SHAFT IN FRACTURED, WELDED TUFF"

J.B. CASE and P.C. KELSALL

(SAND86-7001)

TECHNICAL ASSISTANCE IN HYDROGEOLOGY
PROJECT B - ANALYSIS
RS-NMS-85-009

SEPTEMBER, 1987

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September 1, 1987

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RS-NMS-85-009
Communication No. 194

U.S. Nuclear Regulatory Commission
Division of Waste Management
Geotechnical Branch
MS-623-SS
Washington, DC 20555

Attention: Mr. Jeff Pohle, Project Officer
Technical Assistance in Hydrogeology - Project B (RS-NMS-85-009)

Re: Document Review of "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff", by J.B. Case and P.C. Kelsall, Document SAND86-7001

Dear Mr. Pohle:

This cover letter transmits to the NRC staff Water, Waste and Land's review of "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff", by J.B. Case and P.C. Kelsall, Document SAND86-7001. The review was performed by D. McWhorter, L. Davis and T. Sniff of Water, Waste and Land and A. Brown of NWC. The document review has received a management and technical review by Mark Logsdon of NWC. The document review was prepared under Subtask 1.3 of the current contract.

The principal conclusions of the review are:

- The proposed model for permeability as a function of distance from the shaft wall is reasonable, but is based almost entirely on theoretical concepts and should be considered as an untested, theoretical model. The model is considered by the reviewers to be adequate to predict that permeability increases are expected to be significant and may require corrective actions such as grouting.

- o Because the conceptual design of the repository is for location in the unsaturated zone, it is unlikely that shaft sinking would have significant effect on normal groundwater flow, which is considered to occur predominantly in the matrix of the rock. However, zones of modified permeability may reqire separate evaluation with respect to flooding from surface waters. Furthermore, it is possible that vapor transport may be enhanced in such zones, and to the extent that performance evaluations consider that vapor transport of radionuclides or heat may be important, additional evaluations of the validity of the rock mass permeability model also may be required.

If you have any questions concerning this letter or the attached document review, please contact me immediately.

Respectfully submitted,
NUCLEAR WASTE CONSULTANTS, INC.

Mark J. Logsdon

Mark J. Logsdon, Project Manager

Att: Document Review of "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff", by J.B. Case and P.C. Kelsall, Document SAND86-7001

cc: US NRC - Director, NMSS (ATTN: PSB)
HLWM (ATTN: Division Director) - 2
Mary Little, Contract Administrator
HLWM/TRB (ATTN: Branch Chief)
D. Chery, HLWM/TRB
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bc: M. Galloway, TTI
J. Minier, DBS
L. Davis, WWL

Water, Waste & Land, Inc.
CONSULTING ENGINEERS & SCIENTISTS

SEP 0 1 1987

August 31, 1987

Nuclear Waste Consultants
ATTN: Mark Logsdon
8341 South Sangre de Cristo Road, Suite 14
Littleton, CO 80127

Dear Mark:

Enclosed is our document review for SAND86-7001, "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff." The document was reviewed by Adrian Brown of Nuclear Waste Consultants as well as David McWhorter, Tom Sniff, and myself of Water, Waste and Land.

After your review of the report, please forward it to Jeff Pohle of the NRC.

Sincerely,

WATER, WASTE AND LAND, INC.

Lyle A Davis

Lyle A. Davis
Project Manager

Encl

Creekside Two Building, 2629 Redwing Road, Suite 200, Fort Collins, Colorado 80526 (303) 226-3535

1.0 INTRODUCTION

WWLNUM:	295
DOCUMENT NO.:	SAND86-7001
TITLE:	"Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff"
AUTHORS:	John B. Case and Peter C. Kelsall
PUBLICATION DATE:	March, 1987
REVIEWERS:	David B. McWhorter, Lyle A. Davis, Thomas L. Sniff, Water, Waste and Land, Inc., and Adrian Brown, Nuclear Waste Consultants
DATE REVIEW COMPLETED:	August 31, 1987
SCOPE:	Reviewed from the standpoint of performance assessment in regard to the NRC evaluation of shaft construction and design. The following three specific requests were raised by the NRC in their letter directing WWL to review the document: 1) Conduct a brief review of the bibliography cited in the report to determine if any major references have been omitted. 2) Determine if there is adequate and sufficient basis to defend the model. 3) Evaluate whether the model is better (in a regulatory sense) than an earlier model identified in a Department of Energy letter on "Exploratory Shaft Performance Analysis Study" dated July 15, 1985.
KEY WORDS:	Permeability, stress analysis, blasting damage, fracture permeability
DATE APPROVED:	

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 SUMMARY OF DOCUMENT

This report presents results of a study which investigated whether the vertical shafts to be constructed during site characterization and repository construction will create preferential pathways for water or air to enter (or leave) the repository after sealing. The possible pathways are divided into three zones: the seal material, the interface between the seal material and the host rock, and a modified permeability zone surrounding the original opening. The report considers only the modified permeability zone, with an emphasis on the Topopah Spring unit (and the Tiva Canyon unit which has similar hydrologic and mechanical properties according to the authors). Stress relief calculations are also performed for the nonwelded Calico Hills unit which underlies the Topopah Spring unit.

The two processes which are considered as dominant in the modification of permeability near the openings are stress redistribution and rock damage due to blasting. Stress redistribution around the shaft will occur regardless of the method of excavation employed. This redistribution of stresses may alter the rock mass by creating new fractures. In addition, changes in stress caused by a shaft may result in the opening or closing of existing fractures. Blasting will damage the rock adjacent to the excavation wall which will probably lead to increased fracturing and, therefore, larger permeability.

2.1.1 Stress Modification Effects

The effects of stress redistribution on the alteration of permeability around a shaft opening are manifested on the fracture system, either by creating new fractures or altering existing fractures. Excessive compressive or tensile stresses can cause fracturing of originally intact rock. In addition, changes in the stress field can cause opening or closing of the pre-existing fractures, altering the fracture permeability.

To evaluate the potential for additional fracturing, tangential stress at the shaft wall where it is a maximum was determined using the Kirsch equation. This equation is for a circular opening and assumes that the rock is homogeneous, isotropic and linearly elastic. To estimate the maximum and minimum far-field (undisturbed) in situ stresses required for the Kirsch equation, predicted and measured values of the ratio of horizontal to vertical stress, K_0, were utilized. The predicted values of K_0, obtained with finite element modeling to evaluate gravitational effects, ranged from 0.2 to 0.4 due to topographic variations at Yucca Mountain. Data collected during actual hydrofracturing tests in boreholes resulted in K_0 values ranging from 0.4 to 0.8 indicating that tectonic or residual stress may be contributing to the total horizontal stress. The minimum far-field stress was therefore set to 0.25 times the vertical stress which was calculated based on the overburden weight. The maximum far-field stress was taken as equal to the vertical stress. The analysis was conducted for a shaft depth of 310 m (1020 ft), which is the approximate depth of the repository at the location of the exploratory shaft. The calculated tangential stress ranged from a minimum of -1.72 MPa (tension) to a maximum of 18.82 MPa (compression). By comparing the results of this analysis to the mean intact rock strengths for Topopah Spring welded tuff (tensile strength of 16.9 MPa and compressive strength of 171 MPa) as reported by Nimick et al. (1984), the authors concluded that fracturing of intact rock due to stress redistribution around a shaft is unlikely.

Although it was concluded that shaft emplacement would not cause fracturing of intact rock, the effects of changes in local stress were evaluated with respect to existing fractures. As a conceptual model, the authors point out that fracture permeability should be increased where normal stresses are reduced across fractures or shear stresses are increased. On the other hand, fracture permeability should be reduced where normal stresses are increased. The following assumptions were used to simplify the problem to allow the analyses to be performed:

1. Prior to excavation, in situ stress state is isotropic and the normal stress acting across each fracture is equal to the average far-field value.

2. The only stresses which effect fracture aperture are those which act in the radial or tangential directions. Shear stresses are neglected.

3. After excavation, the stress acting across each fracture can be estimated as the radial stress which occurs at any distance from the shaft wall.

The authors assert that these assumptions are conservative, or tend to over predict permeability increases, for an isotropic stress state.

The rock-mass response to excavation of a shaft can be either elastic (completely reversible) or plastic. When the response is elastic, the radial stress is reduced and the permeability of fractures which are tangential to the shaft should increase. Under elastic conditions, the tangential stresses are expected to increase relative to the in situ stress and the permeability of radial fractures should be reduced. When the rock-mass response is plastic, both tangential and radial stresses are expected to be reduced in the plastic zone near the shaft so that the permeabilities of both tangential and radial fractures will be increased. Outside the plastic zone, elastic response is predicted and the mode of stress redistribution is termed elastoplastic.

Within the elastic zone, the analysis of stresses and displacements is based upon the Kirsch solution as described by Jaeger and Cook (1976). For this solution, both radial and tangential stresses are functions only of the shaft radius, far-field hydrostatic stress, and radius to the point for which the calculations are being performed. The solution predicts that the radial stress at the shaft wall will be reduced to zero while the tangential stress at the shaft wall will be equal to twice the far-field hydrostatic stress. When the stress at the shaft wall exceeds the unconfined compressive strength of the rock, failure is predicted and the analysis must be conducted using the elastoplastic approach.

The method of Hoek and Brown (1980) was used for the elastoplastic analysis. This method of analysis requires that the radial distance to the boundary between the plastic and elastic zones be determined. Within the plastic zone, radial stress is a function of shaft radius, rock mass properties (e.g. unconfined compressive strength), and internal support stress as well as radius to the point for which the calculations are being performed. In the analyses presented, internal support stress was set to zero simulating an unlined shaft or one in which the liner is placed after stress redistribution has occurred. The tangential stress is a function of radial stress and rock mass properties. In the elastic zone (which is located outside the plastic zone) the stresses are calculated with equations which are similar to the Kirsh solution but which have been normalized to stress conditions which exist at the plastic-elastic boundary.

Estimates of rock mass mechanical properties were required to perform the analyses described in the previous paragraphs. Since these parameters have not been measured directly in welded tuff, comparative methods were used to obtain the estimates. Methods proposed by Hoek and Brown (1980) and Protodyakonov (1964) were utilized with the former being emphasized. The method of Hoek and Brown (1980) is a somewhat subjective method by which the Rock Mass Rating (RMR) is estimated based on the unconfined compressive strength of intact rock, rock quality designation, joint frequency, joint condition, and groundwater condition. For each of these parameters, except groundwater condition which was set to the maximum since unsaturated conditions are expected, a range of values were estimated based on currently available laboratory and field data. As a result three RMR values were obtained for the Topopah Spring welded tuff — an upper bound estimate of 84, an expected value of 65, and a lower bound estimate of 48 — and two RMR values were obtained for the Calico Hills nonwelded tuff — an upper bound estimate of 71 and a lower bound estimate of 49. These RMR values were then coupled with an estimated range of unconfined compressive strength for intact rock as determined by laboratory measurement.

A range of in situ horizontal stresses were estimated based on both theoretical concepts and field measurements. According to theory and a rock mass Poisson's ratio of 0.25 as estimated by Nimick et al. (1984) a value of the ratio of horizontal to vertical stress, K_0, of 0.25 can be calculated. As described earlier, finite element modeling and field measurements indicate that K_0 is in the range of 0.2 to 0.8. Therefore, the authors selected a range of K_0 values corresponding to the RMR ranges described in the previous paragraph. The lower bound estimate of K_0 was set to 0.25 while the expected value was set to 0.6 and the upper bound estimate was set to 1.0. Vertical stresses were estimated based on overburden weight as calculated using the unit weight of 2250 kg/m^3 for the Topopah Spring welded tuff as reported by Nimick et al. (1984).

The results of the stress redistribution analyses indicate "that a wide variation in rock mass behavior might be observed depending on depth, in situ stress and rock properties." Elastic response is predicted at depths of both 100 meters and 310 meters when upper bound and expected values of rock mass properties and lower bound and expected values of horizontal stress are used in the calculations. At both depths, the response is elastoplastic when lower bound rock mass properties and upper bound horizontal stress (equal to vertical stress) are used in the calculations. Based on these results, the authors conclude that the expected response is elastic in nonlithophysal zones of welded tuff, but plastic response may occur in lithophysal zones or intensely fractured zones where strength is lower. Plastic behavior is expected for the nonwelded Calico Hills. For the nonwelded Paintbrush tuff, which overlies the Topopah Spring unit, the behavior may be elastic or plastic depending on in situ stresses and rock mass strength. The authors also point out that inelastic deformation can be limited by rapid placement of the shaft liner after excavation.

Since matrix permeabilities of the tuff units at Yucca Mountain tend to be small, the authors assume that stress redistribution will effect only fracture permeability. Therefore, the model employed to relate fracture permeability to stress is based on the cubic law which states that permeability is proportional to aperture cubed. By assuming that the fractured welded tuff system can be represented as a parallel array of fractures the authors show that relative permeability, defined as permeability at in situ stress levels divided by permeability at a decreased level of stress, is a function of aperture width at the two stress levels.

Laboratory studies performed on single fractures in core samples as reported by Peters et al. (1984) provided the basis for relating stress to fracture permeability. The report under review considered only results from the unloading cycle from the peak confining pressure. Peters et al. (1984) concluded that fracture permeability is inversely proportional to effective normal stress, although each sample showed different changes in relative permeability as compared to stress. For the sample which showed the most permeability variation with stress, the relative permeability varied between 1 for an effective normal stress of 12 MPa to almost 100 for an effective normal stress of 0 MPa. For the sample which showed the least variation, the maximum relative permeability was less than 10 (no effective normal stress) and was reduced to 1 at an effective normal stress of about 6 MPa. Field permeability tests performed in a single fracture found in the G-Tunnel, which is located on the Nevada Test Site, also showed that fracture permeability is inversely related to normal stress. These studies also showed that fracture permeability shows little or no stress dependence when the effective normal stress exceeded the pre-existing stress of about 3 MPa.

The results of the laboratory and field studies were used to develop upper and likely estimates of relative permeability as a function of effective normal stress at depths of 100 and 310 meters. For a depth of 100 meters, the upper estimate predicts that relative permeability will vary between 1 and about 100 for stresses of about 2 MPa and 0 MPa, respectively. The likely case for a 100 meter depth predicts a relative permeability range between 1 and about 30 for stresses of 1.5 MPa and 0 MPa, respectively. At the 310 meter depth, the likely estimate of relative permeability ranges from 1 at an effective normal stress of about 4 MPa to about 30 for zero effective normal stress. The upper estimate at this depth ranges from 1 at an effective normal stress of about 7 MPa to nearly 100 for zero effective normal stress.

The rock mass stress-permeability relationships described in the previous paragraph were combined with calculated stress distributions to develop predictions for rock mass permeability near a shaft. The results are presented as graphs of relative permeability as a function of normalized distance from the shaft as calculated for Topopah Spring welded tuff at depths of 100 meters and 310 meters. For both depths, both upper and likely estimates are presented. These graphs indicate that stress redistribution should not effect relative permeability beyond a distance of about six to seven shaft radii from the wall. At a depth of 100 meters, most of the permeability change occurs within one radius of the shaft wall while at 310 meters, significant change may occur up to a distance of about 2 radii from the wall.

2.1.2 Blasting Effects

As currently planned, the majority of the shafts at Yucca Mountain will be excavated by blasting, which can damage the rock adjacent to the excavation wall. The authors of the reviewed report have divided the damaged area around a blast hole into three zones. Immediately around the blast hole, a crushed annulus is formed. The middle zone is the blast fractured zone where a pattern of radial cracks form. The third and outermost zone is described as the extended seismic zone where tensile or shear failure may occur. In a real system the effects of blasting will be influenced by rock strengths as well as heterogeneities which may exist in the rock. Six case histories which describe rock damage and permeability changes due to blasting during tunnel construction were provided. A generalized relationship between charge density and blasting damage for tunnel blasting conditions is available for granitic rocks. These data suggest that blast effects are dependent on charge density and independent of excavation size.

Based on the literature review, which included approximately 60 documents, the authors concluded that blast damage would be limited to about 0.5 meter from the shaft wall, assuming that controlled blasting techniques are utilized. As an upper range estimate, it was concluded that blast damage would not extend beyond one meter from the shaft wall. Within the blast damage zone, it was assumed that fracture frequency is increased by a factor of three. It was further assumed that fractures created by blasting are similar in nature to pre-existing fractures. As a result it is predicted that the permeability in the blast damaged zone will increase by a factor of three over the increase that occurs due to stress relief.

2.1.3 Modified Permeability Zone Model

The changes in the rock mass permeability due to the stress redistribution and blast damage were summarized for two cases, the expected and the upper bound. The changes were evaluated at depths of 100 meters and 310 meters in the Topopah Spring unit. For expected conditions at both depths, the equivalent rock mass permeability, which is an average permeability over an annulus one shaft radius wide, is 20 times the permeability of the undamaged rock mass. For the upper bound case, the equivalent rock mass permeability is predicted to be 40 times larger than in situ permeability at a depth of 100 meters. For a depth of 310 meters, the upper bound rock mass permeability is predicted to be 80 times larger than the in situ permeability.

2.2 SUMMARY OF REVIEW CONCLUSIONS

From a geomechanics point of view, the only aspect of this model that has other than empirical support is the failure computations. The direct measurements of the permeability of fractured tuff under various stress conditions are very limited, and do not include one direct measurement of permeability as a function of location in any tuff rock mass adjacent to an excavated opening. Accordingly the model of the expected permeability around the shaft is not validated by the process described. However, the approach used to develop the permeability model described in the report is reasonable and the results obtained (an equivalent permeability increase of between 20 and 80 times) seem consistent with changes that would be expected under careful excavation techniques.

Therefore, it is concluded that the model for permeability as a function of distance from the shaft wall presented in this report is reasonable. However, it is based almost entirely on theoretical concepts and should be regarded as an untested, theoretical model. The model is certainly adequate to conclude that permeability increases are likely to be quite significant and may require corrective measures (e.g. grouting).

3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The amount of radioactivity which can be released to the accessible environment following repository closure is specified in 40 CFR 191. As part of the licensing process, the NRC must independently assess the ability of the repository, including both engineered and natural systems, to meet those standards. Site characterization will include the sinking of an exploratory shaft and several shafts will be necessary to allow waste materials to be emplaced. The potential exists that these shafts may provide a preferential pathway for the escape of radionuclides. An important aspect of performance assessment will include evaluation of how the shafts may effect isolation of the wastes in the repository.

The repository, as currently envisioned, will be located in the unsaturated zone. Therefore, it is unlikely that shaft sinking will have any effect on normal groundwater flow since it is thought that this flow occurs in the matrix with the fractures remaining essentially dry. However, zones of modified permeability around shafts may be important with respect to evaluation of impacts due to unforseen flooding from surface waters. Further, vapor and gaseous transport of radionuclides may be enhanced in such zones. With these considerations in mind, a model which can describe the variations in rock mass permeability near shafts will be required to allow performance assessment calculations to be performed.

4.0 MAJOR REVIEW COMMENTS (PROBLEMS, DEFICIENCIES, AND LIMITATIONS)

4.1 STRESS ANALYSIS

The analysis is the standard evaluation of stress around a circular opening in a homogeneous, elastic medium. While little discussion is provided in the report about the fact that the stress analysis is being performed in a material that is highly fractured, it would appear that the development of a generic position on this matter is only reasonable under the simplifying assumption of homogeneous stress conditions. However, this assumption appears to be nonconservative with respect to stress changes induced by the excavation of the shaft. Based on this assumption, the report concludes that no new fractures will be created by stress changes resulting from excavation. This evaluation is weakened by the omission of the direct consideration of the effects of shear stresses in the vicinity of the shaft. It is possible that shear stresses will be the determining consideration in the stability of the rock in the vicinity of the shaft, and that fracturing is possible under the shear stresses induced. No attempt is made to check this possibility in the report.

The authors state that results of modeling studies indicate a horizontal to vertical stress ratio of 0.2 to 0.4 while direct measurements indicate that the ratio is between 0.4 and 0.8. The greater values obtained with the direct measurements are attributed to tectonic or residual stresses. It seems possible, therefore, that the assumption of an isotropic _in situ_ stress field is inappropriate. A USGS report (Ellis and Swolfs, 1983), which was not included in the references or bibliography, indicated that the minimum horizontal principal stress in the welded tuff units above the static water level at USW-G1 may be less than half that of the vertical stress. Ellis and Swolfs (1983) considered the most significant feature observed on the borehole televiewer log to be the borehole ellipticity. As described, borehole ellipticity occurs when stress concentrations around the drill hole are sufficient to exceed the local _in situ_ shear strength of the rock, causing spalling of the borehole walls. Borehole ellipticity was observed in a consistent east-west orientation throughout most of the logged section of drill hole USW G-1. Although the values of horizontal stress ratio used in the analysis considered in the report under review (0.25 and 1.0) are conservative with respect to cited values (0.2 to 0.8), the effects of an anisotropic _in_ situ stress field on permeability were not investigated. Because of this, the results obtained may not be conservative but development of a model which accounts for an anisotropic stress field may be difficult, if not impossible, at this time.

4.2 FRACTURE STRESS/PERMEABILITY RELATIONSHIP

The entire development of the rock mass stress-permeability relationship is based upon the simplifying assumption that the fractures in the system are parallel and have a constant aperture. Case and Kelsall used the cubic law and a relationship from Snow (1968) for a parallel array of planar joints to determine rock mass permeability. Using this approach, an equation is derived which shows that the change in rock mass permeability as a function of stress is independent of the fracture frequency given the assumption that the frequency does not change in response to stress changes. The parallel array model is an oversimplification and there is no significant discussion in the report as to how the model can be modified to consider radial fractures.

As described previously, the authors rely on one laboratory study (Peters et al., 1984) and one field study (Zimmerman, et al., 1985) as support for development of the constitutive relationship between permeability and stress. Two envelope curves, based on data collected during the laboratory study, are used to relate permeability to stress. These envelopes do not take any cognizance of the apparent importance of in situ stress levels, which is clearly suggested by the field test data, on the relationship between stress and permeability. The procedures used to develop the stress/permeability relationship appears to be highly empirical. It depends strongly on the very low stress permeability condition, which is shown in field tests to be highly dependent on both the method of stress reduction and the nature of the fracture being tested. Nonetheless, it would seem that little better can be done until additional data regarding permeability as a function of stress is collected.

4.3 BLASTING EFFECTS

The change in permeability as a result of damage from blasting operations was estimated based on a review of available literature. Of the 60 or so relevant citations in the report, apparently only two reported actual permeability as a function of distance from the point of blasting. Based on the literature review, the authors assume that blasting damage will be limited to 0.5 meter for the likely case to 1.0 meter for the upper bound case. It is further assumed that, within the damaged zone, fracture frequency (and therefore permeability) is increased by a factor of three and that the fractures created by blasting are identical to natural fractures. While the studies cited tend to support the assumed extent of damage, evidence supporting the assumption that fracture frequency would be increased by a factor of three could not be located. However, these assumptions seem reasonable, especially given the precision of other aspects of the analysis.

5.0 SPECIFIC REVIEW COMMENTS

This section of the document review is dedicated to addressing the specific questions raised by the NRC in their request to review this document. Each of their questions is addressed in the following sections.

5.1 REVIEW OF BIBLIOGRAPHY

The response to the question of completeness of the bibliography has been divided into three categories: blasting damage, fracture permeability relationships, and reports dealing with Yucca Mountain data. Each of these topics are discussed in the following paragraphs.

In general, the bibliography dedicated to rock damage due to blasting (Appendix B) appears to be complete. As part of the review process, we searched a computerized data base which contains mining references. The search was limited to blasting damage as it relates to tunnel and shaft excavation. The search identified eight references which may be important with respect to evaluation of final plans for construction of the exploratory shaft. It does not appear that the references which were discovered through this search contain data which refutes the contention that blast damage, under controlled conditions, will be limited to an annular region between 0.5 and 1.0 meters from the shaft wall. Nonetheless, in the interests of completeness, the NRC staff may wish to add these references to their library. A listing of the references along with the abstract provided by the computerized search are provided in Appendix A.

With respect to fracture permeability, two areas of general references appear to be weak. The first is the group of papers and dissertations describing the pioneering work in the area of the relationship between permeabilility, fracture geometry, and stress (for example, Sharp, 1970; and Louis, 1969). The second is the provision of a bibliography of the recent work in the same area, which is referred to in passing in the report, but not dwelt upon.

The final category of references which we reviewed for completeness concerned reports which provide site specific data for the Yucca Mountain site. We reviewed both the bibliography (Appendix B) and the References section of the report and identified those publications which appear to present actual mechanical (and thermal) data for the Yucca Mountain site. We then compared this list with the publication data base maintained by WWL. Based on this comparison, we have identified five documents which we currently do not have in our data base. A listing of these documents is provided in Appendix B.

5.2 MODEL ADEQUACY

Based on our review, it is our opinion that there is adequate and sufficient basis to defend the model. The model has been developed using a reasonable approach:

a. stress changes modify apertures which modifies permeability;

b. blasting causes additional fractures, further enhancing permeability;

c. the effects can be combined.

The experimental basis for the quantification of the model appears to be weak, although it may be adequate for licensing purposes if (as seems likely based on the 1985 document) the enhanced permeability zone is of limited importance in the performance of a repository in tuff. This could be dramatically improved by direct measurement of an actual blasted drift/shaft in tuff, which could be conducted as part of the Exploratory Shaft activities.

5.3 COMPARISON WITH EARLIER MODEL

This model is better than the earlier model presented by the DOE in July of 1985. The new model is based on a scientifically rational approach, using accepted principles of stress analysis and fluid mechanics, supported with at least some laboratory and <u>in situ</u> data. The model can be calibrated against actual experience in tuff during construction of the Exploratory Shaft and thus allows appropriately accurate evaluations of the performance of the repository.

6.0 REFERENCES

Ellis, W.L. and Swolfs, H.S., 1983. "Preliminary Assessment of In-Situ Geomechanical Characteristics in Drill Hole USW G-1, Yucca Mountain, Nevada," USGS-OFR-83-401, U.S. Geologic Survey, Denver, Colorado.

Hoek, E. and Brown, E.T., 1980. Underground Excavations in Rock, Institution of Mining and Metallurgy, London, England, 527 pp.

Jaeger, J.C. and Cook, N.G.W, 1976. Fundamentals of Rock Mechanics, Halsted Press, London, England, 583 pp.

Louis, C., 1969. A Study of Groundwater Flow in Jointed Rock and its Influence on the Stability of Rock Mases, Doctoral Thesis, University of Karlsruhe, English translation Imperial College Rock Mechanics Research Report #10, London, England.

Nimick, F.B., Bauer, S.J. and Tillerson, J.R., 1984. "Recommended Matrix and Rock-Mass Bulk, Mechanical, and Thermal Properties for Thermomechanical Stratigraphy of Yucca Mountain, Keystone Document No. 6310-85-1 (Memorandum to T.O. Hunter), Sandia National Laboratories, Albuquerque, New Mexico.

Peters, R.R., Klavetter, E.A., Hall, I.J., Blair, S.C. Heller, P.R. and Gee, G.W., 1984. "Fracture and Matrix Hydrologic Characteristics of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada", SAND84-1471, Sandia National Laboratories, Albuquerque, New Mexico.

Protodyakonov, M.M., 1964. "The Size Effect in Investigations of Rock and Coal", Proceedings of the International Conference on Stress in the Earth's Crust, Henry Krumb School of Mining, New York, NY, Unpaginated Addendum.

Sharp, J.C., 1970. Fluid Flow Through Fissured Media, Ph.D. Thesis, University of London [Imperial College].

Snow, D.T., 1968. "Rock Fracture Spacings, Openings, and Porosities", J. Soil Mech. Found. Div., Proc. Amer. Soc. Civil Engrs., Vol. 94, pp. 73-91.

Zimmerman, R.M., Wilson, M.L., Board, M.P., Hall, M.E., and Schuch, R.L., 1985. "Thermal-Cycle Testing of the G-Tunnel Heated Block", Proceedings 26th U.S. Symposium on Rock Mechanics, A. A. Balkema, Boston, Massachusetts, Vol. 2, pp. 749-758.

APPENDIX A

ADDITIONAL REFERENCES

ROCK DAMAGE CAUSED BY BLASTING

Rustan, A., Naarttijaervi, T., Ludvig, B., 1985. CONTROLLED BLASTING IN HARD INTENSE JOINTED ROCK IN TUNNELS. CIM Bulletin v 78, n 884, Dec., 1985, p 63-68, Lulea Univ of Technology, Lulea, Swed.

Full-scale tests have been done at LKAB in hard intense jointed magnetite ore. Four different types of perimeter charges have been tested: tube charges, ANFO mixed with plastic beads, detonating cord and linear-shaped charges. Three types of initiation of the perimeter holes have been used: conventional (half-second delay detonators), instantaneous and ultra short cutblasting initiation (1.5 ms delay). Cutblasting with detonating cord in the perimeter holes gave the smallest damage to the surrounding rock. A new classification system for controlled blasting regarding the damage to the surrounding rock has been devised. (Edited author abstract)

Konya, C. J., Britton, R., Lukovic, S., 1984. REMOVING SOME OF THE MYSTERY FROM PRESPLIT BLASTING. Journal of Explosives Engineering v 2, n 1, p 20-22.

Increased highway construction and structured rock engineering during the last two decades promoted presplit applications. Basic research has not kept pace. Researchers are still looking for better ways to control explosive induced fractures, especially in geologically complicated rock. Techniques developed in the last century, such as borehole notching, may be suitably adapted to increase further the efficiency of modern-day methods.

Chertkov, V. Y., 1983. THEORETICAL EVALUATION OF THE CHARACTERISTICS OF INCREASED MICROCRACK ABUNDANCE IN EXPLOSIVE BREAKING OF BLOCK STONE. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 19, n 3, May-Jun 1983 p 197-202.

On the basis of kinetic concepts of destruction, theoretical estimates are made of: (1) the maximum amplitude pressure of the blast pulse on the blast-hole walls in a medium with a certain initial microcrack density corresponding to the condition of absence of crushing and crumbling; (2) the size of an enhanced microcrack concentration zone; (3) the microcrack distribution in that zone; and (4) the possible size and number of initial radial cracks in the blast-hole walls. 8 refs.

Spivak, A. A., Kondrat'ev, Yu. V., 1979. INFLUENCE OF CHARGING DENSITY ON BLASTING PARAMETERS IN A SOLID MEDIUM. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 15 n 1 Jan-Feb 1979 p 29-35.

This article gives the results of a laboratory investigation of the explosion of compact charges with densities of 0.4 and 1.0 g/cm**3 (loose and pressed singly precipitated PETN) and 0.5 g/cm**3 (loose double-precipitated PETN), as well as the comparative characteristics of explosions of a compact charge and of a charge in an air cavity. Using repeatedly remelted sodium thiosulfate as the model medium, it is shown that a decrease in the effective charging density can reduce the extent of the zone of overcrushing of the material by blasting. 9 refs.

Tregubov, B. G., Taran, E. P., Balagur, Y. A., Trufakin, N. E., 1981. EXPERIMENTAL INVESTIGATION OF A CONTAINED EXPLOSION OF ELONGATED CHARGES. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 17, n 6, Nov-Dec 1981 p 532-538.

It is shown that the best material for stemming is hard rock chips, with coarseness 3-10 mm. The length of stemming which can remain unejected from the borehole amounts to 140-150 r_0, but this length can be reduced somewhat, as even in the case of ejection of the stemming the zone of shattering is almost unchanged, but destruction of the mouth of the borehole occurs. The average radius of the zone of crushing in hard rock amounts to approximately 9 r_0, and the radius of intense fracture formation attains 18 r_0. Fracturing of the rock mass decreases in inverse proportion to the square of the distance from the axis of the charge. With the interaction between contained charges arranged at an optimum distance of 15-20 r_0, the zone of shattering is increased by a factor of approximately one and a half in comparison with a single charge. 7 refs.

Isakov, A. L., Sher, E. N., 1983. PROBLEM OF THE DYNAMICS FOR DEVELOPMENT OF DIRECTIONAL CRACKS DURING BLAST-HOLE FIRING. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 19, n 3, p 189-196.

A comprative analysis is made of three proposed theoretical solutions of the problem of propagation of two diametrically directed radial cracks during firing of a blast-hole charge without tamping in a uniform brittle material. It is shown that a quasi-static approach with a time lag is suitable for describing the test process over the whole range of radial crack movement velocities. It is established that (a) the size of the embryonic cracks (notches) has practically no effect on the final dimension of the radial cracks developing from them; (b) the value of the polytropic factor for detonation products used in the calculation also has no apparent effect on the final result; (c) in contrast to zonal problems for breakdown, an increase in the scale of explosion leads to a marked increase in the relative dimensions of radial cracks; (d) the value of the critical stress intensity factor has a weak effect on the final result, whence it follows that the accuracy of determining calculated values of K_{Ic} in this problem does not have to be high; (e) a reduction in the initial pressure in the blast-hole to several kilobars by intoducing an annular air gap around the explosive charge causes practically no reduction in the final dimensions of the cracks obtained in this way, and this is what makes it desirable to use higher-power explosive charges during directional breakdown of rock by blasting. 7 refs.

Fourney, W. L., Dally, J. W., Holloway, D. C., 1978. CONTROLLED BLASTING WITH LIGAMENTED CHARGE HOLDERS. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts v 15, n 3, p 121-129.

A series of experiments, which demonstrate that fracture control can be achieved in a blasting process, are described. Fracture was produced in polymeric and rock models along specified radial planes to form control planes and/or fragments. Fracture control was achieved by utilizing a ligamented split tube for charge containment. The split tube, under the action of the gases from the explosive, produces highly concentrated stresses on the borehole at the slit locations. These concentrated stresses initiate cracks which propagate radially outward to form the controlled fracture plane. The mechanisms involved in fracture control were examined by using dynamic photoelasticity and high-speed recording methods. Photoelastic records which show the dynamic state of stress and propagating cracks are described. These results were employed in evaluating the effectiveness of the charge holders in controlling the fracture process in blasting. 5 refs.

Dolgov, K. A., 1976. INFLUENCE OF JOINTING ON THE EFFICIENCY OF ROCK CRUSHING BY BLASTING. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 12, n 4, p 454-457.

On comparing the blasting efficiencies, it is seen that the greatest influence on the results of blasting is exerted in markedly jointed and very markedly jointed rocks. In these rocks the degree of crushing by the blast is less, and the blasting efficiencies are less by 20 and 28% respectively than in slightly jointed rocks. The calculated values are, of course, valid only for the given blasting conditions. In practice, for a given value of d_f for markedly jointed and very markedly jointed rocks, in order to increase the blasting efficiency the specific explosives consumption and the cost of drilling and blasting are reduced. 5 refs.

APPENDIX B

REPORTS/PUBLICATIONS WHICH CONTAIN DATA FOR THE YUCCA MOUNTAIN SITE WHICH ARE NOT CONTAINED IN THE WATER, WASTE AND LAND, INC. PUBLICATION DATA BASE

Bauer, S.J., Holland, J.F. and Parrish, D.K., 1985. "Implications about Insitu Stess at Yucca Mountain", Proceedings of the 265h U.S. Symposium on Rock Mechanics, A. A. Blakema, Boston, Massachusetts, Vol. 2, pp. 1113-1120.

Langkopf, B.S. and Gnirk, P.R., 1986. "Rock Mass Classification of Candidate Repository Units at Yucca Mountain, Nye County, Nevada", SAND82-2034, Sandia National Laboratories, Albuquerque, New Mexico.

Nimick, F.B., Bauer, S.J. and Tillerson, J.R., 1984. "Recommended Matrix and Rock-Mass Bulk, Mechanical, and Thermal Properties for Thermomechanical Stratigraphy of Yucca Mountain, Keystone Document No. 6310-85-1 (Memorandum to T.O. Hunter), Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H., 1983. "Analysis of Rock Mechanics Properties of Volcanic Tuff Units from Yucca Mountain, Nevada Test Site", SAND82-1315, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H. and Bauer, S.J., 1985. "Analysis of the Elastic and Strength Properties of Yucca Mountain Tuff, Nevada", Proceedings of the 26th U.S. Symposium on Rock Mechanics, A.A. Balkema, Boston, Massachusetts, Vol. 1. pp. 89-94.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: SAND85-7117

DOCUMENT: Ross, Benjamin, December 1987, A First Survey of Disruption Scenarios for a High-Level-Waste Repository at Yucca Mountain, Nevada. Prepared by Sandia National Laboratories, Albuquerque, NM for the U.S. Department of Energy, 139 p.

REVIEWER: Williams & Associates, Inc., Gerry Winter

DATE REVIEW COMPLETED: May 31, 1988

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

This review addresses only the hydrogeologic portions of the subject document, particularly those portions that relate to conceptual models. The document is quite thorough; it includes discussions of various natural phenomena and human activities that could impact the disposal of high-level radioactive waste at Yucca Mountain. The potential movement of waste from the repository is considered under various sequences and scenarios. One principal conceptual model for flow in the unsaturated zone is used in the scenarios presented in this document; however, some slight variations of this model also were employed to describe flow in the unsaturated zone. These variations are called "hypotheses" by the author of the document. The document considers changes in sea level, erosion, flooding, groundwater flow, dissolution, irrigation, and several other topics that could affect the movement or retrieval of radioactive waste from a repository at Yucca Mountain. The document describes these various scenarios in detail that is adequate for the purpose intended. The scenarios presented appear to be reasonable with a few minor exceptions.

The major problem that we encountered in the review of this document is the use of a single conceptual hydrogeologic model for groundwater flow at Yucca Mountain. This single conceptual model limits the possible scenarios that can be considered. The document should be expanded at a later date to incorporate valid alternative conceptual models.

BRIEF SUMMARY OF DOCUMENT:

The purpose of the document under review is to identify scenarios for a high-level waste repository located in the unsaturated zone at Yucca Mountain, Nevada. The scenarios involve disruptive events and processes. The document states that only long-term performance of the repository is discussed with respect to the containment of radioactivity. It states that a complete analysis of the scenarios is left for a future document. Scenarios were listed previously by Hunter et al. (1982; 1983). This document considers those scenarios presented by Hunter et al. Only those failure mechanisms that are considered credible for a repository in the Topopah Spring Member are explicitly included or rejected in the document under review.

The document states that some guidelines are required to determine which scenarios must be considered. Two guidelines are presented. The first guideline establishes that a scenario need not be considered further if its occurrence in 10,000 years is highly unlikely. The second guideline states that scenarios need not be considered further if the scenario cannot lead to releases of 100 curies or more of radioactivity within the 10,000 years after closure of the repository (p. 2).

The document points out specifically that the report is preliminary. The document states that the list of scenarios must be expanded and refined during site characterization. The document also points out that comment and peer review are necessary to obtain a reasonably complete list of scenarios.

The document is based on several assumptions. Six different barriers are assumed to impede the release of radioactivity from the repository to the environment. These six barriers are 1) canisters in which the spent fuel is packed, 2) fuel cladding, 3) the resistance to dissolution of the waste itself, 4) movement downward through the Topopah Spring welded tuff member, 5) movement downward through the underlying Calico Hills nonwelded tuff unit, and 6) lateral movement through the saturated rocks underlying the repository (p. 7). The document states that a seventh barrier may be present as well. This seventh barrier is a capillary barrier created by an air gap between the waste package and rock. The document assumes that portions of the Prow Pass welded tuff, the Crater Flat nonwelded tuff, and the Bullfrog welded tuff are unsaturated. These tuffs are not discussed separately because the author believes that they serve the same function as the Calico Hills nonwelded tuff. The capillary barrier is assumed to be overcome in the scenarios discussed in the document.

This document assumes the baseline conceptual model described by Montazer and Wilson (1984). The document states that the conceptual model presented by Montazer and Wilson (1984) has not been confirmed fully (p. 8) and that alternative conceptual models cannot be ruled out at this time. The variations or alternative hypotheses considered are:

- Flow through the Topopah Spring welded unit: instead of being limited to the rock matrix, flow occurs through fractures.

- Areas of high moisture flux deep in the unsaturated zone are controlled not structurally, as Montazer and Wilson (1984) suggest, but by the location of zones of greater infiltration rates.

- Ground-water velocities in the saturated zone are lower than those calculated by the EA (Section 6.3.1.1.5). This difference might be caused by the fact that the true hydraulic gradient is less than the upper-bound estimates used in the EA, or because the regional average hydraulic conductivity is less than measured in well tests because of the presence of flow barriers (p. 8-9).

Phenomena relevant to the failure of one or more barriers to the release of radioactivity are considered in this document. The phenomena were published by a working group of the International Atomic Energy Agency (IAEA, 1983). The document considers each process or event for the likelihood of occurrence at Yucca Mountain. Credible events are considered with respect to the movement of wastes to the accessible environment. Some mechanisms are discounted immediately based on simple physical arguments.

The list of 57 phenomena is appended to this review as Table 1 (IAEA, 1983). Microbial activity has been added by the author to the list for consideration in this document. The events and processes are considered first by the author for probability of occurrence. Those processes whose occurrence is credible are described in terms of possible barrier-failure sequences. The barrier-failure sequences are described in two categories. The two categories are those processes that lead to direct releases of radioactivity and those processes that could enhance releases indirectly by groundwater transport (p. 12).

The document develops 84 sequences that are summarized and appended to the document. This appendix (A) is attached hereto. This appendix lists those sequences which the author believes require further consideration. The sequences include effects created by climatic change, stream erosion, flooding, faulting and seismicity, geochemical changes, undetected faults and shear zones, undetected dikes, extrusive magmatic activity, faulty waste emplacement, irrigation, large-scale alterations of hydrology, undiscovered boreholes, undiscovered mine shafts, exploratory drilling, resource mining, climate control, differential elastic response to heating, nonelastic response to heating, temperature-driven fluid migration, local mechanical fracturing, corrosion, chemical reaction of waste package with rock, geochemical alteration, and microbial activity. The sequence numbers used in the following sections are listed in Appendix A.

The sequences listed as 9, 10, and 11 are based on variations of infiltration rate in the unsaturated zone. The document cites Claassen (1983) as arguing that small floods do not result in recharge. He argues that present-day groundwaters were derived from seasonal flows of snowmelt at the end of the Pleistocene. Montazer and Wilson (1984) assume that the areas under the washes are, in general, not areas of higher moisture flux through the Topopah Spring Member (p. 25). Montazer and Wilson believe that most water that infiltrates through the washes moves laterally when it encounters a capillary barrier consisting of the nonwelded unit of the Paintbrush Tuff Formation above the Topopah Spring Member. They perceive that the areal distribution of moisture flux in the Topopah Spring Member is controlled by structure. The document admits, however, that Montazer and Wilson might be wrong on this point. The document points out that it may be possible to combine the alternative models described by Claassen (1983) and Montazer and Wilson (1984). Such a combination suggests that infiltration from the usual floods on Yucca Mountain is diverted by capillary barriers and does not proceed downward directly to the Topopah Spring Member. In rare instances of major floods, water infiltrates and is assumed to overcome the capillary barrier that presumably restricts vertical flux. Percolation is supposed to be greatest beneath the washes in this case. The document also suggests that infiltration could occur on Yucca Mountain everywhere, but mostly after infrequent major precipitation events. The usual year-to-year precipitation would be removed by evapotranspiration. The document suggests that steady-state conditions may not exist in the unsaturated zone. Instead, the response is assumed to be transient and based on events that occurred 10's, 100's or even 1,000's of years ago.

The document discusses a variation on the conceptual model which results in sequence No. 18 (p. 32). This scenario assumes that fracture flow occurs in the unsaturated Topopah Spring Member under existing hydrologic conditions. The document assumes that the moisture flux is much less than the saturated hydraulic conductivity of this member. Consequently only the smallest fracture apertures will be saturated. A second variation of this scenario assumes that alteration products might clog these fractures, thereby diverting flow into larger fractures. The net effect of this water movement is a higher groundwater velocity.

Sequence No. 22 results from assuming that a greater hydraulic conductivity exists in the carbonate aquifer than in the overlying tuff aquifer (p. 36). A fault is hypothesized to provide a pathway for water movement from the water table tuff aquifer down to the underlying carbonate aquifer. A higher groundwater velocity would result based on an assumed greater hydraulic conductivity in the carbonate aquifer and a greater hydraulic gradient in the carbonate aquifer.

The document dismisses the importance of sequences that could be associated with failure of the shaft seal or failure of exploration borehole seals (p. 43). The failure of such seals is considered unimportant because any moisture which would enter a shaft or borehole would dissipate quickly into the surrounding rock. Fernandez and Freshley (1984) is cited as the appropriate reference.

Sequence No. 31 is based on an analysis which assumes that irrigation water applied to the land surface near the repository could move laterally into areas of drier rock, thereby increasing moisture flux through the repository (p. 46). The document states that Midway Valley is the nearest area to the repository that is suitable for irrigation. Midway Valley is about one kilometer from the site boundary. The floor of Midway Valley is approximately 200 meters above the proposed repository level. Suction in the Topopah Spring Member in the repository block is stated to be 100 meters to 1,000 meters. Montazer and Wilson (1985) is the cited source of suction pressures. The document states that the gradient that drives unsaturated flow toward the repository would be on the order of unity or somewhat less than unity.

The document lists 17 types of barrier-failures. This list is appended to this review as a "Summary of Sequences Affecting Each Barrier." The appropriate sequences are assigned to the types of barrier failures. The 17 categories of barrier-failure include direct release, repository flooding, colloid formation, increased water flux through the unsaturated zone, localized regions of high flux through the repository, water diverted toward the waste package, accelerated dissolution mechanism, accelerated cladding-corrosion mechanism, accelerated canister-corrosion mechanism, canister breakage, fracture flow in the Topopah Spring welded unit without increased moisture flux, reduced sorption in the Topopah Spring welded unit, water table rise above the Calico Hills nonwelded unit, fracture flow in the Calico Hills nonwelded unit, new discharge points, faster flow in the saturated zone and acceleration of pre-existing fracture flow (p. 93-94).

The report considers 57 processes and events that might affect a repository. The 84 different sequences identified in the document could lead to failure of one or more of the barriers. The sequences identified in this document are grouped into 17 types of barrier failures. The document states that these types of barrier failures should provide the basis for further work in the analysis of disruptive events and process scenarios (p. 115). The document notes that the amount of redundancy in the Yucca Mountain repository system is notable. The more likely barrier disruption sequences affect only one or a few of the barriers. The sequences that show little evidence of redundancy include direct release, saturation of the Calico Hills unit, and flooding of the repository.

<u>SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:</u>

This document presents a description of possible release scenarios from the repository to the accessible environment. The report considers variations of a primary conceptual model of groundwater flow in the unsaturated zone. The various scenarios or sequences are discussed and considered with respect to their possible occurrence. The occurrence of these possible sequences is important to the site characterization program. Characterization must be geared toward understanding the groundwater flow processes in the unsaturated and saturated zones. This listing of sequences of failure provides a basis for designing the characterization plan. The list of sequences in this document also constitutes a vehicle for predicting worst case scenarios that have the shortest groundwater travel times.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The greatest limitation of the document is its dependence upon the primary conceptual model for groundwater flow that is being considered at this time. This conceptual model was described by Montazer and Wilson (1984). The document does attempt to consider minor variations that are termed "alternative hypotheses." The document in fact does consider these "alternative hypotheses" but fully developed alternative conceptual models are not presented in the document. However, the author must be given credit for his realization that a conceptual model is the fundamental guideline required for developing these release sequences.

The issue of alternative conceptual models is important in the consideration of mechanisms of infiltration in the unsaturated zone. Claassen (1983) and Montazer and Wilson (1984) are cited as presenting different conceptual models for recharge to the unsaturated zone. The absence of alternative conceptual models in this document is a deterrent to the consideration of various sequences of failure. The document attempts to combine variations of a conceptual model. The author of the document should be credited with his attempt to overcome this shortcoming.

The report describes a possible variation in which fracture flow occurs in the unsaturated Topopah Spring (Member) welded unit under existing conditions (p. 32). The occurrence of fracture flow in the unsaturated Topopah Spring Member under present conditions is possible but is dependent upon the value of the saturated hydraulic conductivity of that member and on the flux occurring in that member. In order to achieve fracture flow in the Topopah Spring welded tuff member it is necessary to obtain saturated conditions which means that the saturated hydraulic conductivity must be less than the flux at that location. This issue has not been addressed adequately in the document.

The document suggests a possible scenario in which a greater hydraulic conductivity exists in a lower carbonate aquifer than in the shallower tuff aquifer. The document then assumes that greater hydraulic gradients occur in the carbonate aquifer than in the tuff aquifer (p. 36). It is unlikely, but not impossible, for higher gradients to occur in a unit with higher hydraulic conductivity. The two variables generally are not compatible. The presence of high hydraulic gradients almost always reflects the presence of low hydraulic conductivities because of the increased resistance to groundwater flow. Higher hydraulic gradients almost always are associated with lower hydraulic conductivities rather than greater hydraulic conductivities. As stated, this combination of greater hydraulic conductivity and higher hydraulic gradient is not impossible but it is highly improbable.

The document (p. 43) dismisses the possibility that failure of the shaft seals or failure of the borehole seals is important in the consideration of the release mechanisms of radionuclides to the environment. We believe this dismissal is too early in the process. We acknowledge that flow in the shaft or down boreholes probably would move into the matrix of the tuffs. Such movement would occur only in the unsaturated zone and under certain specific hydrogeologic conditions. We believe adequate caution dictates that these two sequences of release be considered further.

The document states that irrigation water could be applied in Midway Valley. This valley is apparently the nearest area to the repository that is suitable for irrigation. The distance from the site boundary (1 kilometer) makes the possibility of lateral flow from Midway Valley to the repository unlikely. The floor of Midway Valley apparently is about 200 meters above the proposed repository level. The suction pressures in the Topopah Spring Member appear to be high (100 to 1,000 meters) but the movement of fluid along this flow path seems improbable. In essence, perched zones of saturation would be required to accomplish such movement. We believe further consideration of this sequence is appropriate.

REFERENCES CITED:

Claassen, H.C., 1983, Sources and Mechanisms of Recharge for Ground Water in the West-Central Amargosa Desert, Nevada--A Geochemical Interpretation. U.S. Geological Survey, Denver, CO, Open-File Report 83-542.

Fernandez, J.A., and Freshley, M.D., 1984, Repository Sealing Concepts for the Nevada Nuclear Waste Storage Investigations Project, Sandia National Laboratories, Albuquerque, NM, SAND83-1778.

Hunter, R.L., Barr, G.E., and Bingham, F.W., 1982, Preliminary Scenarios for Consequence Assessments of Radioactive-Waste Repositories at the Nevada Test Site. Sandia National Laboratories, Albuquerque, NM, SAND82-0426.

Hunter, R.L., Barr, G.E., and Bingham, F.W., 1983, Scenarios for Consequence Assessments of Radioactive-Waste Repositories at Yucca Mountain, Nevada Test Site. Sandia National Laboratories, Albuquerque, NM, SAND82-1277.

IAEA, 1983, Concepts and Examples of Safety Analysis for Radioactive Waste Repositories in Continental Geological Formations. International Atomic Energy Agency, Vienna, Austria, Safety Series No. 58.

Montazer, P., and Wilson, W.E., 1984, Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada. U.S. Geological Survey, Lakewood, CO, Water-Resources Investigations Report 84-4345.

Montazer, P., and Wilson, W.E., May 1985, Conceptual Model of Fluid Flow in Unsaturated Fractured Tuffs. presented to American Geophysical Union, Spring Meeting, Baltimore, MD.

Table 1

IAEA list of phenomena potentially relevant to scenarios for radioactive-waste repositories

Natural processes and events

- Climatic change
- Hydrology change
- Sea-Level change
- Denudation
- Stream erosion
- Glacial erosion
- Flooding
- Sedimentation
- Diagenesis
- Diapirism
- Faulting/seismicity
- Geochemical changes
- Fluid interactions
  - Ground-water flow
  - Dissolution
  - Brine pockets
- Uplift/subsidence
  - Orogenic
  - Epeirogenic
  - Isostatic
- Undetected features
  - Faults, shear zones
  - Breccia pipes
  - Lava tubes
  - Intrusive dikes
  - Gas or brine pockets
- Magmatic activity
  - Intrusive
  - Extrusive
- Meteorite impact

Human activities

- Faulty design
  - Shaft seal failure
  - Exploration borehole seal failure
- Faulty operation
  - Faulty waste emplacement
- Transport agent introduction
  - Irrigation
  - Reserviors
  - Intentional artificial Ground-water recharge or withdrawal
  - Chemical liquid waste disposal
- Large-scale alterations of hydrology
- Undetected past intrusion
  - Undiscovered boreholes
  - Mine shafts
- Inadvertent future intrusion
  - Exploratory drilling
  - Archaeological exhumation
  - Resource mining (mineral, water, hydrocarbon, geothermal, salt, etc.)
- Intentional intrusion
  - War
  - Sabotage
  - Waste recovery
- Climate control

Table 1

IAEA list of phenomena potentially relevant to scenarios for radioactive-waste repositories (concluded)

Waste and repository effects	
Thermal effects • Differential elastic response • Nonelastic response • Fluid pressure, density viscosity changes • Fluid migration Mechanical effects • Canister movement • Local fracturing	Chemical effects • Corrosion • Waste package-rock interactions • Gas generation Radiological effects • Material property changes • Radiolysis • Decay-product gas generation • Nuclear criticality

APPENDIX A

Table of Barrier-Failure Sequences

This appendix consists of a table listing the barrier-failure sequences identifed in Chapter 2. Some of the sequence descriptions are abridged versions of those presented in Chapter 2.

Climate Change

1. An increase in infiltration due to climate change at the repository site increases the unsaturated water flux through the repository.

2. An increase in recharge due to climate change raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit.

3. A higher water table short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

4. Regionally higher water tables create discharge points closer to the repository, reducing the distance to the accessible environment. The rise in the regional water table floods the repository.

5. Perched water develops above the repository, diverting downward flow through the repository into localized zones.

6. Perched water develops at the base of the Topopah Spring welded unit. Flow through the Calico Hills unit is diverted into fracture zones draining the perched water table.

Stream Erosion

7. Entrenchment of the Amargosa River at Alkali Flat lowers base levels and increases regional gradients. Regional hydraulic relations are such that water-table lowering at Yucca Mountain is insignificant, but increases in ground-water velocity are significant.

8. Beds of intermittent streams now resting on the Tiva Canyon welded tuff unit erode through to the underlying nonwelded unit. These washes form a barrier to lateral flow in the Tiva Canyon and divert flow downward. Regions of high flux are formed below them.

Flooding

9. Flooding of the washes on Yucca Mountain is a major source of infiltration, and zones of higher moisture flux exist permanently or seasonally below washes. One or more of these zones is not detected during site characterization.

10. Occasional major floods provide sufficient infiltration to overcome the capillary barrier that usually diverts flow laterally, creating temporary wetter zones beneath the washes.

11. Most percolation through the deeper unsaturated portions of Yucca Mountain occurs following major precipitation events whose recurrence interval is tens, hundreds, or thousands of years. After future events, there are periods of tens to hundreds of years during which percolation through the unsaturated zone is increased over the present relatively dry conditions. Fracture flow then occurs in the Topopah Spring unit and perhaps other hydrogeologic units between the repository and the water table.

12. Movement of a new or existing fault shears canisters along the line of the fault. The same fault also creates a "trap" for moisture moving laterally through the Tiva Canyon welded unit, and so the sheared canisters are placed in a region of enhanced downward moisture flux.

13. Fracture dilation along a new or existing fault creates zones of enhanced permeability in the Calico Hills and Paintbrush nonwelded units. Erosion of an arroyo at the surface and increased hydraulic conductivity of the Paintbrush unit create a zone of increased percolation along the fault. Moisture moves through fractures along the fault.

14. The downdip side of a new or existing fault moves up. The fault thus forms a "trap" for laterally moving moisture in the Tiva Canyon welded unit. A new region of enhanced flux through the Topopah Spring unit is created.

15. Fracturing along a newly mobilized fault creates a permeable pathway through the flow barrier north of the repository block. The magnitude of the resulting change in the flow system is sufficient to raise the water table under the repository to the top of the Calico Hills nonwelded unit.

16. As in the previous scenario, fault-caused fracturing breaches the flow barrier north of the repository block. Flow is blocked by another barrier, not apparent from the current head distribution, and the resulting rise in water table floods the repository. The water passing through the repository discharges through springs in Fortymile Wash.

Geochemical Changes

17. Precipitation of zeolites or other minerals in the saturated zone reduces effective porosity without significantly improving the sorptive properties of the rocks.

18. Fracture flow occurs in the unsaturated zone at current percolation rates. Precipitation or alteration of minerals blocks the small-aperture fractures and diverts the flow into larger fractures, increasing the water velocity.

Undetected Faults and Shear Zones

19. A wet zone below a minor fault through the Tiva Canyon lower contact escapes detection during repository construction, and waste is emplaced in it.

20. An undetected major fault dips below the repository. The fault has greater permeability than surrounding unfaulted rock, and enhanced moisture flow along it passes through the Calico Hills nonwelded unit in fractures.

21. An undetected major fault dips below the repository. Because of the formation of fault gouge, matrix hydraulic conductivity in the fault is less than the moisture flux, and so moisture flows through the Calico Hills nonwelded unit along fractures in or just above the fault.

22. An undetected fault provides a path for water movement from the tuff aquifer beneath the western portion of the repository to an underlying carbonate aquifer.

Undetected Dikes

23. An undetected dike passing through the Calico Hills nonwelded unit beneath the repository has very low matrix permeability but fairly high fracture permeability. Moisture infiltrating along the dike moves through fractures.

Extrusive Magmatic Activity

24. A basaltic volcano erupts through the repository. The volcano is fed through a dike; waste canisters within the dike mix with the magma, and their contents are erupted.

Faulty Waste Emplacement

25. Canisters are placed by mistake in wet zones.

26. Drains installed to divert water around canisters are improperly built or omitted altogether over some canisters.

27. Canisters are left lying on the floor of repository drifts. These canisters have poorer heat removal than those properly emplaced, and their increased horizontal cross-section raises the amount of water they intercept. Water drips on the canisters and corrodes them even while their temperatures are well above 95° C.

28. Canisters are placed closer together than planned. As a result, temperatures inside the packages are higher than anticipated and corrosion of fuel cladding is accelerated.

29. Some waste canisters are manufactured so improperly that they fail early.

30. Some waste canisters are punctured or abraded during emplacement.

Irrigation

31. Irrigation in Midway Valley increases the moisture flux through the repository.

Intentional Ground-Water Recharge or Withdrawal

32. Water is collected in covered cisterns above the repository to enhance ground-water recharge.

33. Irrigation wells are drilled in Midway Valley.

34. Irrigation wells are drilled in Crater Flat or Jackass Flats.

35. Pumping rates increase in the presently irrigated area around the town of Amargosa Valley. The water table is significantly drawn down, and the hydraulic gradient increases.

36. Mine dewatering is carried out directly below the repository. The saturated zone is eliminated as a barrier.

Large-Scale Alterations of Hydrology

37. An active management scheme is introduced for the Alkali Flat-Furnace Creek Ranch ground-water basin, by which hydraulic gradients in the saturated zone beneath the repository are increased.

Undiscovered Boreholes

38. A horizontally emplaced waste canister lies in the trace of an old undiscovered borehole. Moisture conditions are wetter than now thought, and water flows in fractures in the old borehole.

Undiscovered Mine Shafts

39. An old prospect in a wash retains water after floods, and therefore is a source of enhanced infiltration. The wet zone beneath it is not detected during repository construction, and waste is emplaced in it.

Exploratory Drilling

40. Exploratory drillers intercept a waste canister and bring waste up with the cuttings.

41. Water introduced into the unsaturated zone as drilling fluid by exploratory drillers drains downward, through the repository.

42. An exploratory borehole creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

43. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the borehole. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

Resource Mining

44. Builders of a mine shaft intercept a waste canister and bring radioactive waste up with the mine waste.

45. Water introduced into the unsaturated zone for mining above the repository drains downward through the repository.

46. A mine shaft creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.

47. Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the mine. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

Climate Control

48. An increase in recharge at the repository site due to artificial climate change increases the unsaturated water flux through the repository.

49. An increase in recharge due to climate modification raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit and induces fracture flow in the welded Topopah Spring unit.

50. Recharge induced by large-scale climate modification raises the regional water table sufficiently to flood the repository.

51. A higher water table due to climate modification short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

52. Perched water develops above the repository because of climate-modification-induced recharge, diverting downward flow through the repository into localized zones.

53. An increase in recharge due to climate control causes perched water to develop at the base of the Topopah Spring welded unit. Flow through the Calico Hills nonwelded unit is diverted into fracture zones draining the perched water table.

Differential Elastic Response to Heating

54. Thermal expansion closes most fractures near the repository. Pre-existing fracture percolation is diverted into fractures of larger aperture.

55. Differential thermal expansion of surrounding rocks stresses canisters, leading to stress-corrosion cracking.

56. Differential thermal expansion of surrounding rocks creates stresses that shear canisters.

57. Rock movements driven by thermal expansion of underlying units open fractures through the Paintbrush nonwelded unit. This creates local zones of increased flux through the unsaturated units below.

Nonelastic Response to Heating

58. Thermally induced fracturing of rocks immediately surrounding waste canisters creates capillary barriers to movement of moisture between blocks of the rock matrix. The matrix is locally saturated, forcing flow out into the fractures and resulting in film flow or droplet impact on waste packages. The result is accelerated localized corrosion and waste dissolution.

Temperature-Driven Fluid Migration

59. Water accumulates above a repository during the thermal period because of evaporation and condensation. When gravity-driven flow resumes, a large volume of water contacts canisters, and flow goes through fractures.

60. Emplacement of waste in the floor of repository drifts creates a large thermal gradient across the drifts. Moisture condenses on the roof and drips onto canisters, accelerating corrosion.

61. Temperature inhomogeneities in the repository lead to localized accumulation of moisture above it. Wet zones form below the areas of moisture accumulation.

62. A thermal convection cell arises in the saturated zone beneath the repository. The thermally driven outward water flow in the upper portion of the tuff aquifer increases ground-water velocities.

Local Mechanical Fracturing

63. Rockbursts propel rocks into waste packages and puncture the canisters.

Corrosion

64. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small previously stressed areas. These areas are focuses of localized attack.

65. Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small areas that happen to have previously been stressed. Stress-corrosion cracking ensues.

66. The canister material is subject to stress-corrosion cracking, but the initiation time is too long to be detected in tests. Canisters fail by this mechanism a few decades after the repository has been sealed.

67. Canisters are sensitized by long-term storage at moderately hot temperatures in the repository. Stress-corrosion cracking (or perhaps intergranular corrosion) ensues in a stressed zone.

68. Zircaloy cladding is subject to stress-corrosion cracking at repository temperatures, but initiation times are too long for detection in in-reactor service or in the repository testing program.

69. After canister breach, colloids of corrosion products sorb normally higly retarded radionuclides and carry them away unretarded.

Chemical Reaction of Waste Package With Rock

70. Water dripping or running over waste contains ions that precipitate uranium. The precipitation reaction removes uranium from solution and increases the rate of fuel dissolution.

71. Waste and rock are placed in close juxtaposition by mechanical failure of emplacement holes or drifts, or by small movements on faults. Reactions between uranium, rock minerals, and water in contact with both precipitate uranium, leading the spent fuel to dissolve more rapidly than if constrained by the equilibrium solubility of uranium.

72. The high dissolved-silica content of natural waters entering the repository causes rapid corrosion of Zircaloy fuel cladding.

73. Colloids are formed from the rock by alteration under thermal, mechanical, and chemical stresses. Normally well-retarded radioelements such as plutonium and americium sorb to the colloids.

74. Waste-contaminated water reacts with rock, and colloid phases of minerals containing radioelements are formed by coprecipitation. The colloids are transported with little or no retardation.

Geochemical Alteration

75. During the period of heating of rocks around the repository, minerals adjacent to the residual water-bearing pores are altered to clays. These clays clog the pores. When the repository cools, water flows through fractures.

76. During the thermal period, zeolite minerals in fracture fillings are altered to less sorptive phases.

77. Waters moving away from the hot region around the repository precipitate minerals derived from dissolved constituents of tuff and cements used in repository construction. These minerals clog pores and divert subsequent flows into fractures.

78. Evaporation of ground water in the hot zone near the repository horizon leaves precipitates that plug pores. As a result, when gravity-driven flow resumes, water near the repository is diverted into fractures. Initially, there is a pulse of corrosive brine.

79. Evaporation of ground water in the hot zone near the repository horizon leaves precipitates. When gravity-driven flow resumes, the precipitates redissolve, and after a short period of fracture flow, the flow returns to the matrix. There is a considerable period of flow of corrosion brines with elevated dissolved solids.

80. There is fracture flow in the Topopah Spring welded unit even under undisturbed conditions. Chemical reactions induced by repository heat plug smaller-aperture fractures. After the thermal pulse ends, percolation is diverted into larger fractures.

81. Water passing through the warm region around the repository is depleted of calcite by temperature-induced precipitation. Below the repository, the calcite-poor water dissolves out calcite veins in the Calico Hills nonwelded unit.

Microbial Activity

82. Microbial activity accelerates canister corrosion.

83. Microbial activity accelerates cladding corrosion.

84. Radionuclides are incorporated into microorganisms or sorbed on their surfaces. Waste dissolution is accelerated. The nuclides taken up by microorganisms are unaffected by chemical sorption or matrix diffusion.

3.7 Summary of Sequences Affecting Each Barrier

The above discussion allows us to list a relatively small number of types of barrier failure. The sequences may be classified as follows, with sequence 12 falling into two categories.

A. Direct release - 24, 40, 44.

B. Repository flooding - 4, 16, 50.

C. Colloid formation - 69, 73, 74, 84.

D. Increased water flux through the unsaturated zone - 1, 11, 31, 48, 59, 78.

E. Localized regions of high flux through the repository - 5, 8, 9, 10, 12, 13, 14, 19, 25, 26, 32, 38, 39, 41, 42, 45, 46, 52, 57, 61.

F. Water diverted toward the waste package - 27, 58, 60.

G. Accelerated dissolution mechanisms - 70, 71.

H. Accelerated cladding-corrosion mechanisms - 28, 68, 72, 83.

I. Accelerated canister-corrosion mechanisms - 29, 55, 64, 65, 66, 67, 79, 82.

J. Canister breakage - 12, 30, 56, 63.

K. Fracture flow in the Topopah Spring welded unit without increased moisture flux - 43, 47, 75, 77.

L. Reduced sorption in the Topopah Spring welded unit - 76.

M. Water-table rise above the Calico Hills nonwelded unit - 2, 15, 49.

N. Fracture flow in the Calico Hills nonwelded unit - 6, 20, 21, 23, 53, 81.

O. New discharge points - 33, 36.

P. Faster flow in the saturated zone - 3, 7, 17, 22, 34, 35, 37, 51, 62.

Q. Acceleration of pre-existing fracture flow - 18, 54, 80.

The barriers affected by these types of failures may be summarized as follows:

Waste form - A, B, C, D, E, F, G, M.

Cladding - A, B, D, E, F, H, J, M.

Canister - A, B, D, E, F, I, J, M.

Topopah Spring welded tuff unit - A, B, C, D, E, K, L, M, Q.

Calico Hills nonwelded tuff unit - A, B, C, D, E, M, N.

Saturated tuffs - A, B, C, M, O, P.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: UCRL-15620, SANL 324-001

DOCUMENT: Changes in Permeability and Fluid Chemistry of the Topopah Spring Member of the Paintbrush Tuff (Nevada Test Site) When Held in a Temperature Gradient: Summary of Results. D.E. Moore, C.A. Morrow and J.D. Byerlee, Lawrence Livermore National Laboratory, June 1984.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: May 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

Permeability and heat flow experiments were conducted on small cylindrical samples of tuff from the Topopah Springs and Bullfrog units. The permeability of some samples increased due to heating but no change occurred in other samples. Water quality measurements showed no change of pH when water flowed through the Topopah springs samples but an increase of pH up to 10.6 occurred when high temperature (250°C) water flowed through the Bullfrog tuff. The authors conclude that heating to 150°C causes little effect on permeability or water quality in the Topopah Springs tuff.

BRIEF SUMMARY OF DOCUMENT:

Permeability experiments were conducted to determine the effect of heat from radioactive decay on tuffaceous rock. The objective was to measure the effects of localized heating around canisters on the permeability and chemistry of the rock and associated groundwaters. The two tuff units tested were the Bullfrog Member of the Crater Flat tuff and the Topopah Spring Member of the Paintbrush tuff.

Cylindrical samples, 7.62 cm in diameter and 8.89 cm in length with a 1.27 cm diameter drill hole in the center were tested. A coiled resistance heater was placed within the hole in the center of the core which produced a temperature gradient between the center and the outside of the core for permeability measurements. Water flowed radially through the tuff from the higher temperature center of the core to the lower temperature at the outer edge in response to a small pore pressure gradient applied between the center and outside of the core. The water used in the experiments was natural groundwater collected from the Nevada Test Site. The rock sample was thermally insulated on its sides. One sample of the Topopah Spring Member had an original permeability of 3 microdarcies but after undergoing heating to 150 degrees the permeability increased to 8 microdarcies and ultimately to approximately 10 microdarcies. The permeability of a second sample of tuff remained between 60 and 70 microdarcies even after heating to a borehole temperature of 90°C.

Water samples were tested after flowing through the cylinders and analyzed for 13 dissolved species. Values of pH for all of the fluid samples were between 6.9 and 8.1. Experiment one showed a slight trend toward decreasing pH with time and a tendency to increase pH with decreasing temperature. The dissolved constituents varied with time, in some cases increasing and in other cases decreasing.

Experiments similar to those in the Topopah Springs Member were conducted on the Bullfrog Member. Initial permeabilities in the Bullfrog samples ranged from .5 to 8.5 microdarcies and showed slight to obvious higher permeabilities upon initial heating. The increase was attributed to thermal cracking. In the higher temperature (250°C) experiments the permeabilities decreased following the initial increases; but eventually returned to the initial room temperature values. Chemical tests on the water showed pH values up to 10.6. Much larger amounts of dissolved material were observed than in fluids from the comparable Topopah experiments. In their conclusion the authors state that heating to temperatures of at least 150°C has little effect on permeability. Interaction of the groundwater with the Topopah Spring Member caused only minor changes in water composition.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

Information contained in the report on the heating effect on the tuffaceous material may be of interest when the actual repository is designed.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

A limitation on this experiment is that it was done under saturated conditions whereas the rock in the repository will display unsaturated conditions. The difference caused by this factor could be significant.

SUGGESTED FOLLOW-UP ACTIVITIES

This work should be kept in mind in case such information is needed to design the waste repository.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: UCRL-15620, SANL 324-001, USGS-OFR-84-0273

DOCUMENT: Changes in Permeability and Fluid Chemistry of the Topopah Spring Member of the Paintbrush Tuff (Nevada Test Site) When Held in a Temperature Gradient: Summary of Results. D.E. Moore, C.A. Morrow and J.D. Byerlee, Lawrence Livermore National Laboratory, June 1984.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: May 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

Permeability and heat flow experiments were conducted on small cylindrical samples of tuff from the Topopah Springs and Bullfrog units. The permeability of some samples increased due to heating but no change occurred in other samples. Water quality measurements showed no change of pH when water flowed through the Topopah springs samples but an increase of pH up to 10.6 occurred when high temperature (250°C) water flowed through the Bullfrog tuff. The authors conclude that heating to 150°C causes little effect on permeability or water quality in the Topopah Springs tuff.

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Experiments similar to those in the Topopah Springs Member were conducted on the Bullfrog Member. Initial permeabilities in the Bullfrog samples ranged from .5 to 8.5 microdarcies and showed slight to obvious higher permeabilities upon initial heating. The increase was attributed to thermal cracking. In the higher temperature (250°C) experiments the permeabilities decreased following the initial increases, but eventually returned to the initial room temperature values. Chemical tests on the water showed pH values up to 10.6. Much larger amounts of dissolved material were observed than in fluids from the comparable Topopah experiments. In their conclusion the authors state that heating to temperatures of at least 150°C has little effect on permeability. Interaction of the groundwater with the Topopah Spring Member caused only minor changes in water composition.

<u>SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:</u>

Information contained in the report on the heating effect on the tuffaceous material may be of interest when the actual repository is designed.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

A limitation on this experiment is that it was done under saturated conditions whereas the rock in the repository will display unsaturated conditions. The difference caused by this factor could be significant.

SUGGESTED FOLLOW-UP ACTIVITIES

This work should be kept in mind in case such information is needed to design the waste repository.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: UCRL-53130

DOCUMENT: Pawloski, G.A., May 1981, Water Contents of Samples from the Nevada Test Site: Total, Free (Natural State to 105°C) and More Tightly Bonded (105-700°C). Lawrence Livermore National Laboratory.

REVIEWER: Williams & Associates, Inc., George L. Bloomsburg

DATE REVIEW COMPLETED: May 13, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The report under review describes the development of improved methods of determining the water content of materials surrounding nuclear test sites. The use of the epithermal neutron logging technique is investigated by measuring the moisture content of samples from a logged borehole in the laboratory. The moisture in the soil was differentiated into free water, more tightly bound water and zeolitic and inner layer water.

The author concludes that the logs can be used to differentiate alluvium from tuff because of differing moisture content and that in some cases various tuff units may be differentiated from each other. A limited amount of the data were available from the Paintbrush unit which occurs in Yucca Mountain; however, none of the data actually were derived from Yucca Mountain.

BRIEF SUMMARY OF DOCUMENT:

The objective of the investigation was to develop a better method for measuring the water content in soils surrounding underground nuclear test sites. At the time the report was written, water content was measured by taking sidewall soil samples promptly at the drill site and measuring water content later. A neutron log may be used for moisture measurement in saturated rocks. The device actually measures hydrogen ion content in the wall of the drill hole. In the case of measuring water in the soil, extraneous hydrogen may exist that affects the reading of the neutron log. The author discusses the use of an epithermal neutron log to measure total water content which would give better data and would be less expensive than discrete sidewall sampling.

To confirm the correct operation of the epithermal neutron sonde the total water content was measured in laboratory samples from holes in which the epithermal neutron log had been run. The components of water consisted of free water, water driven off by heating to 105°C, more tightly bound water lost in the 105-700°C temperature range, and zeolitic and the inner layer water which is removed by heating to 700°C. The total water content was calculated from the values of free and more tightly bonded water.

A total of 374 NTS samples were tested for more tightly bonded water content. The samples were taken from twelve different drill holes in tuff and alluvial materials. A detailed description is presented of the methods used to determine the more tightly bonded water.

The experimental standard deviation for the more tightly bonded water was determined to be ±0.0059 of the weight fraction. Calculations for total water content are presented. Results are presented in the form of graphs of water content versus depth in meters. Three curves are shown; one for total water, a second for free water, and a third for more tightly bonded water. The majority of the materials tested were alluvium. A limited amount of data for the Paintbrush tuff exist. These are the only data presented for materials which occur in Yucca Mountain. A correlation between total water content and lithology is presented. It appears to be possible to assign total water content values by lithologic units. Differentiation of alluvium from tuff by water content is possible and in some cases the various tuffs may be differentiated. After the epithermal neutron sonde is calibrated it may be possible to differentiate lithologic units by the water content values determined by methods presented in this report.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

This paper does not appear to be of significance to the High-Level Waste Repository Program. Few data are for materials which occur in Yucca Mountain; no data are derived from the region of the repository. Some of the methodology developed for determining water content possibly could be of significance in the repository program.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The weakest portion of the report is that research did not include data for Yucca Mountain. However, at the time the report was written, Yucca Mountain was not of great interest to the High Level Waste Repository Program.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: UCRL-53602

DOCUMENT: Lin, W., and Daily, W., 1984, Transport Properties of Topopah Spring Tuff. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53602, 20 p.

REVIEWER: Williams & Associates, Inc., James L. Osiensky

DATE REVIEW COMPLETED: February 18, 1987

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report under review describes laboratory experiments conducted on samples from the Topopah Spring Member of the Paintbrush tuff. Electrical resistivity, ultrasonic P-wave velocity, and permeability to water were measured on intact and fractured samples of Topopah Spring tuff. These measurements were taken at a confining pressure of 5.0 MPa, pore pressures to 2.5 megapascals (MPa), and temperatures to 140°C. Electrical resistivity measurements were used to monitor fluid flow in the rock samples. Ultrasonic velocity also was used to evaluate fluid flow; however, the velocity measurements did not give detailed information on the dehydration and rehydration processes. The permeability of the unfractured sample was found to be independent of temperature, dehydration and rehydration cycles, and time. Permeability of the fractured sample was found to decrease by more than one order of magnitude after each dehydration and rehydration cycle. The decrease in permeability of the fractured sample is attributed to fracture healing due to the redeposition of minerals such as silica.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents the results of electrical resistivity, ultrasonic P-wave velocity and permeability to water measurements on intact and fractured samples of Topopah Spring tuff. The experimental conditions were designed to simulate a nuclear waste repository environment. Tests were conducted under a hydrostatic confining pressure of 5.0 megapascals (MPa), pore fluid pressure up to 2.5 MPa, and temperatures ranging up to 140°C.

The samples from the Topopah Spring Member of the Paintbrush tuff used in the experiments were collected from Fran Ridge at the Nevada Test Site. An auxiliary sample was obtained from a depth of 373 meters in borehole USW G-1. These samples were machined into right circular cylinders approximately 9 centimeters (cm) long and 2.54 cm in diameter. Testing of the samples was conducted during dehydration, rehydration, and full saturation with respect to water. Page 5 of the report outlines the steps taken from the initial saturation of the samples at room temperature through the various cycles of dehydration and rehydration at various temperatures and pore water pressures. The confining pressure was held constant throughout the experiment.

Table 2 of the report lists the permeability values obtained under the various experimental conditions. According to the report, the permeability (to water) of the intact sample was independent of temperature and time over the two month period of the experiment. Repeated dehydration and rehydration did not change the permeability of the intact sample of tuff; however, the permeability (to water) of the first fractured sample was found to decrease by approximately one order of magnitude for each dehydration and rehydration cycle that it was subjected to.

A second fractured sample of tuff was tested to investigate the potential for fracture healing under the conditions of the experiment. This sample was tested to evaluate the effects of temperature changes. The sample was not subjected to cycles of dehydration and rehydration. Constant saturation was maintained throughout the experiment. Figure 3 of the report shows that an increase in temperature from 23°C to 96°C caused the permeability to decrease by more than an order of magnitude. The report notes that further increases or decreases in the sample temperature did not have a significant effect on the permeability. The authors of the report suggest that the decrease in permeability shown on Figure 3 was due to healing of the fracture by mineral deposition rather than the effects of temperature alone.

In addition to permeability measurements, electrical resistivity and ultrasonic velocity measurements were made during the cycles of dehydration and rehydration. Figures 4 and 5 of the report present plots of resistivity versus time for the intact tuff sample and the first fractured tuff sample, respectively. Both Figures 4 and 5 show a rapid increase in resistivity during the first drying stage, followed by a much slower increase in resistivity during the second drying stage. The report suggests that the rapid increase in resistivity probably is due to the rapid escape of water from the sample; the much slower increase in resistivity is attributed to the slow release in moisture held in microfractures or microcavities. According to the report,

> The resistivity versus time behavior of the intact and fractured sample during the third drying period (after the steam flow) is about the same. During this dehydration, both samples show resistivity maxima followed by a decrease of resistivity with time.

Figure 6 of the report is a graph of the relative variation of the electrical resistivity as a function of time during the drying process for the fractured and unfractured samples. Figure 6 indicates that the dehydration time for the fractured and intact samples was nearly the same. However, the presence of the fracture in the fractured sample apparently caused drying of that sample to be nonuniform relative to the unfractured sample. The authors of the report note that it is not clear why the moisture distribution, but not the evaporation rate, would be affected by the presence of the fracture.

Figure 7 of the report shows the spatial distribution of resistivity measurements of the fractured sample for steam saturation and for the intact and fractured samples for water saturation during the resaturation process. According to the report, during the rehydration process of the intact sample, the saturating fluid was imbibed by the sample in a fairly uniform manner perpendicular to the flow direction. The report notes that flow of water in the fractured sample was nonuniform. The report suggests that fracture roughness contributed to the nonuniform flow of water. Steam flow in the fractured sample was more uniform than the water flow.

The P-wave ultrasonic velocity measured on the intact and fractured samples are plotted against time in Figures 9a and 9b, respectively. The report notes that measurements were not sensitive enough to yield detailed information about the dehydration and rehydration processes.

According to the report, when the fractured tuff sample was removed from the pressure vessel, the fracture was observed to have healed so that the pieces of tuff in the sample were bonded together. Analysis of the fracture by scanning electron microscopy indicated that layers of silica were deposited on the fracture after the drying and resaturation cycles. Testing of the strength of the fracture healing showed that the tensile strength of the healed fracture was about half that of the intact sample. According to the report, a second fractured sample containing a natural fracture with the surface conditions similar to the first sample was tested to isolate the main factor contributing to the fracture healing. According to the report, testing of the fracture in the second sample indicates that "fracture healing by water transport of minerals (mainly silica) in the fracture occurs as temperature increases about 100°C." The report notes that it is not known whether further fracture healing would be induced by elevated temperatures alone or whether other factors are important.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review describes a series of experiments conducted on rock samples from the Topopah Spring Member of the Paintbrush tuff. The purpose of the experiments was to subject the tuff to pressures and temperatures expected in the vicinity of a geologic repository in Yucca Mountain. The experiments were conducted under the Waste Package Task of the Nevada Nuclear Waste Storage Investigations. The report is not significant to the NRC Waste Management Program with respect to prewaste emplacement conditions. However, the report is significant with respect to evaluation of the conditions expected after waste emplacement.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review presents a detailed description of the experimental procedures performed during testing of tuff samples from the Topopah Spring Member. In addition to the usual limitations inherent in laboratory scale experiments, the primary limitation of the report is the fact that many of the results cannot be interpreted uniquely.

SUGGESTED FOLLOW-UP ACTIVITIES:

The report under review deals with the effects of conditions expected during post-waste emplacement. The report should be of most interest to the NRC staff involved directly with evaluation of the waste package.

WMGT DOCUMENT REVIEW SHEET

FILE #:

DOCUMENT #: UCRL-53602

DOCUMENT: Trimmer, D., 1982, Laboratory Measurements of Ultralow Permeability of Geologic Materials. American Institute of Physics, REV. SCI. INSTRUM. 53 (6), p. 1246-1254.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: Draft, October 9, 1986

ABSTRACT OF REVIEW: **APPROVED BY:** Roy Williams/al

The report under review describes an apparatus for measuring permeability of geologic materials as a function of confining pressure, pore pressure, and deviatoric stress. Permeabilities (intrinsic permeability) on the order of 10^{-11} to 10^{-24} m^2 may be measured along with electrical conductivity, acoustic velocity and amplitude. The testing method described in the report should be of interest to people involved directly with the measurement of permeability of core samples.

BRIEF SUMMARY OF DOCUMENT:

The report under review presents a description of a new apparatus for measuring permeability of geologic materials as a function of confining pressure [to 200 megapascals (MPa)], pore pressure (to 25 MPa) and deviatoric stress (500 to 800 MPa). The apparatus described in the report is capable of measuring permeabilities two to three orders of magnitude lower than those that have been reported in the literature.

Permeability measurements are made on large samples (0.15 meters in diameter by 0.28 meters in length). The permeability of the sample is measured by inducing a pore water pressure gradient between the ends of the sample while water transport through the sample is monitored. According to the report, permeabilities as low as 10^{-17} m^2 (hydraulic conductivity equal to 9.8×10^{-9} cm/sec) are measured with a conventional steady-state flow technique. A transient pulse technique is used for rock samples having permeabilities between 10^{-17} and 10^{-24} m^2. The transient pulse technique is necessary because the water flow rates through samples with permeabilities less than 10^{-17} m^2 are too small for convenient direct measurement. According to the report, a modified transient pulse technique is used for samples with permeabilities in the range of 10^{-22} to 10^{-24} m^2. For these very low permeabilities, the time constant of the system is very long. Under these conditions, establishment of equilibrium requires two weeks to six months. Therefore, in order to simplify the testing procedure, the author makes the assumption that the system reaches equilibrium when the pressure in the upstream reservoir has changed less than 0.1 MPa in 10^6 seconds (approximately one week). According to the report, measurement is terminated when either the pressure in the upstream reservoir has decayed by 1.0 MPa (50% of the pressure step) or the time has exceeded 10^6 seconds.

Equation 2 of the report describes the pressure-time history for water flow through a compressible sample-reservoir system. This equation is as follows:

$$\frac{\partial^2 P}{\partial x^2} = \frac{\mu \beta \phi_e}{k} \frac{\partial P}{\partial t},$$

$$\phi_e = \phi_c + \frac{\beta_r - (1+\phi_c)\,\beta_s}{\beta},$$

for $t>0$, $0<x<L$, and with boundary conditions

$$\frac{\partial P}{\partial x} = \frac{\mu V_1 \beta}{Ak} \frac{\partial P}{\partial t} \qquad x = 0, t>0,$$

$$\frac{\partial P}{\partial x} = \frac{\mu V_2 \beta}{Ak} \frac{\partial P}{\partial t} \qquad x = L, t>0,$$

and initial conditions

$$P(x,0) = P_0 \qquad 0<x\leq L,$$

$$P(0,0) = P_0 + \Delta P,$$

where:

P = pressure,
X = distance from the upstream end of the sample,
ϕ_e = the effective sample porosity,
ϕ_c = the interconnected porosity of the sample,

β = the compressibility of water,
β_r and β_m = the compressibilities of the sample (bulk and mineral matrix, respectively,
V_1 and V_2 = the volumes of the upstream and downstream reservoirs, respectively),
ΔP = the step increase in pressure, and
t = the time since ΔP was applied.

Because of the large size of the samples, the pore volumes of the samples are large relative to the reservoir volume. Because the water storage in the rock is significant, Equation 2 cannot be simplified. Therefore, the author of the report modeled the experiment using a finite element computer code.

According to the report, a parameter study indicated that for a given sample geometry, pore fluid, and reservoir volume, the pressure-time history is a function of permeability and effective porosity. The report suggests that the permeability of a sample can be inferred by visually comparing experimental pressure-time histories with numerically generated histories if the effective porosity is known.

According to the report, Equation 4 can be used to determine effective porosity for samples with time constants that are small enough to allow sample equilibrium. Equation 4 is as follows:

$$(P_o+\Delta P)\, V_1 + P_o\, (V_2+AL\phi_e) = P_f\, (V_1+V_2+AL\phi_e)$$

or

$$\phi_e = \frac{(P_o+\Delta P-P_f)\, V_1 + (P_o-P_f)\, V_2}{(P_f-P_o)\, AL}$$

The report notes that for samples that display time constants too long to allow effective porosity to be determined from Equation 4, effective porosity must be determined by comparing the experimental data with numerically generated curves.

According to the report, the next step is to generate a family of curves with the appropriate effective porosity and various permeabilities. The permeability of the sample then is inferred by visually matching the experimental data to numerically generated pressure-time histories. Figures 3A and 3B of the report present examples of numerically generated pressure vs log time histories. According to the report (p. 1248), the shaded portions of the curves are given the most weight in determining permeabilities for the following reasons:

1. The thermal transient induced by the initial pressure pulse has disappeared by this time.

2. The slope is greatest allowing maximum (curve matching) resolution.

3. This portion of the curve is relatively insensitive to the water-storage term.

Test samples are prepared from diamond drill core that is approximately 0.17 meters in diameter. The samples are ground and cut to form right circular cylinders that are 0.15 meters in diameter and 0.28 meters long. Pages 1249 through 1252 describe the sample preparation and the testing apparatus.

Figure 13 of the report presents permeability data as well as normalized conductance, acoustic velocity, and amplitude data for the Westerly granite. Figure 14 of the report presents the same type of data for fractured Westerly granite. The report notes that as in the case of intact rock, the acoustic and conductance data show a good correspondence with the permeability data.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

The report under review presents a description of a testing method for measuring permeability in geologic materials as a function of confining pressure (to 200 MPa), pore pressure (to 25 MPa), and deviatoric stress (500 to 800 MPa). The testing procedure described in the report under review is not significant with respect to the NRC Waste Management Program at the present time. The report should be of primary interest to people involved directly with laboratory measurements of very low permeability geologic materials.

PROBLEMS, DEFICIENCIES OR LIMITATIONS OF REPORT:

The report under review presents a description of testing techniques and data analysis, sample preparation, a description of the apparatus used in the experiments, and a discussion of typical results. The primary limitation of the testing method is that the effective porosity and permeability of the core sample is determined by comparing experimental data to numerically generated curves. The portions of the curves that are given the most weight in determining permeabilities are very similar. Because of this similarity it is difficult to decide which curves yield the best match with the experimental data. The curve matching procedure is very subjective.

SUGGESTED FOLLOW-UP ACTIVITIES:

No follow-up activities are necessary.