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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: **NNWSI Document Reviews - USGS-WRI-84-4345; Sand 84-7202**

Dear Mr. Pohle:

Please find attached the Water, Waste and Land document reviews of "Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada" (USGS-WRI-84-4345) and "Hydrologic Mechanism Governing Fluid Flow in Partially Saturated, Fractured, Porous Tuff at Yucca Mountain" (Sand 84-7202). The reviews were peformed by Dr. McWhorter and Mssrs. Davis and Sniff of Water, Waste and Land. The document reviews received a technical and management review by Mark Logsdon of Nuclear Waste Consultants.

The reviews address both the fundamental physics of flow in variably saturated, fractured rock and the applications of those principles to the Yucca Mountain site. The reviewers conclude that the presentations of phenomena such as fracture flow, flow in the matrix, vapor flow, and the effects of capillary barriers are accurate and correct as statements of generic principles. However, the reviews address several limitations of the applications of these principles to evaluating flow at Yucca Mountain.

If you have any questions about this matter, please contact me immediately.

Respectfully submitted,
NUCLEAR WASTE CONSULTANTS, INC.

Mark J. Logsdon

Mark J. Logsdon, Project Manager

Att: WWL Document Reviews - USGS-WRI-84-4345; Sand 84-7202

cc: US NRC - Director, NMSS (ATTN PSB)
DWM (ATTN Division Director)
Mary Little, Contract Administrator
WMGT (ATTN Branch Chief)

bc: L. Davis, WWL

WM-RES
WM ~~Record File~~
D1021
NWCI

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

Distribution:
J Pohle

(Return to WM, 623-SS)

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D-1021 PDR

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1.0 INTRODUCTION

WWLNUM:	3
DOCUMENT NO.:	USGS-WRI-84-4345
TITLE:	"Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada
AUTHORS:	Parviz Montazer and William E. Wilson
PUBLICATION DATE:	1984
REVIEWER:	Water, Waste & Land, Inc.
DATE REVIEW COMPLETED:	March 20, 1986
DATE APPROVED:	L.A. Davis 3/21/86

Mark J. Logsdon, NWC Project Manager 3/21/86

1.0 INTRODUCTION

WWLNUM: 73

DOCUMENT NUMBER: Sand 84-7202

TITLE: "Hydrologic Mechanisms Governing Fluid Flow in Partially Saturated, Fractured, Porous Tuff at Yucca Mountain"

AUTHORS: J.S.Y Wang and T.N. Narasimhan

PUBLICATION DATE: April, 1985

REVIEWER: Water, Waste & Land, Inc.

DATE REVIEW COMPLETED: March 7, 1986

DATE APPROVED: L.A. Davis 3/21/86

Mark J. Logsdon, WWL Project Manager 3/21/86

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 Summary of Document

A conceptual model describing the flow of fluids through the unsaturated zone at Yucca Mountain is proposed. The proposed model considers the following phenomena in the unsaturated region:

- o Flow through fractured rock
- o capillary barriers
- o Infiltration into fractured rock
- o Lateral movement
- o Capillary fringe

The proposed model gives a representation of the flow in the hydrogeologic units and structural pathways at Yucca Mountain. Areas needing further investigation are identified.

The authors state explicitly that the concepts presented are intentionally descriptive and conjectural but, for the sake of simplicity and directness, the model is presented as if it were an expression of the facts. It is important that this perspective be kept in mind when assessing this document.

2.2 Summary of Review Conclusions

The conceptual model presented in this document provides a basis for preliminary assessment of site performance and as a guide to further investigations as it was intended to do. However, because the model is presented as if it were a "true expression of the facts", a casual reader may be left with erroneous impressions concerning the degree of understanding of the hydrology at Yucca Mountain.

Several principles of unsaturated flow are discussed in the context of the specific conditions known to exist at Yucca Mountain. These include fracture flow, flow in the matrix, the effect of bedding and textural discontinuities (capillary barriers), and vapor flow. The presentation of these phenomena as generic principles appears accurate and correct. It is the degree to which these phenomena interact to effect the flow at Yucca Mountain that remains in question. We make the following specific points:

a. The tendency for flow to occur preferentially in the fractures or in the matrix is extremely sensitive to the hydraulic properties of both of these flow paths and to the imposed flux (net infiltration). Hard, reliable data on the flux and the hydraulic properties of the fractures are not yet available.

2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

2.1 Summary of Document

The paper presents a conceptual model for the hydrology of a partially saturated, fractured medium. A general statistical theory is developed to describe the flow phenomena in fractures and the flow phenomena which occurs between the matrix and fractures. The theory yields expressions for fracture saturation, fracture permeability and effective areas of matrix fracture flow as functions of pressure. Using these expressions in a numerical model, the drainage of a fractured tuff column was simulated. Specific physical parameters from Yucca Mountain were used for model input. The model indicated that fracture flow properties are important only during highly transient changes in flow from fully saturated to partially saturated conditions. For a partially saturated, fractured, porous system the fluid flow could be simulated approximately without taking fractures into account once the fractures have desaturated.

2.2 Summary of Review Comments

We believe that the model proposed in this report is an important advance in the understanding of the mechanisms governing fluid flow in partially saturated, fractured, porous tuff. Further advances will probably require:

a. Inclusion of film flow on fracture surfaces.

b. Realistic simulation of fracture orientation.

c. More vigorous development of the relation between the hydraulic properties of individual fractures and the overall bulk permeability.

d. A more realistic calculation of the phase-separation constriction factor.

The model should be used to simulate problems of infiltration as well as drainage. It is expected that the relation between fracture and matrix flows will be substantially different for the two cases. Further, it is expected that inclusion of the effects of the air in the matrix blocks will eventually be required. Finally, vapor transport in the fractures is expected to play a significant role in the overall water balance at Yucca Mountain. If so, a liquid flow model uncoupled from vapor transport may give misleading results.

3.0 SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM

Because the licensing of the Yucca Mountain Site will be based to some extent on the results of numerical modeling, the initial work performed in this paper will be important to determining the flow characteristics in the unsaturated zone at the site. The results from the paper make possible a more detailed numerical simulation capability, as more hydrogeologic data becomes available, for the unsaturated zone.

3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The conceptual model which is presented in the report is based on extensive geologic information and relatively few hydrogeologic data for the unsaturated zone. The authors have synthesized the available information into a detailed, qualitative model for the processes which possibly govern flow at Yucca Mountain. The authors point out that the proposed conceptual model is general in scope, and that as more data becomes available, modifications and quantification can be incorporated into the model. The conceptual model is a critical portion of the Yucca Mountain high level waste project and provides focus to the needed data collection, laboratory testing, and numerical modeling efforts.

b. The effect of air in the matrix blocks on the tendency for water in the fracture to "diffuse" into the matrix is discussed primarily in terms of inducing hysteresis into the permeability and water retention functions. Because the matrix blocks exhibit low air contents, water movement into the matrix is expected to be retarded more severely than is accounted for by hysteresis and low moisture capacity. The additional retardation will result from very low permeabilities to air at low air contents.

c. The phenomenon of "capillary barriers" existing at textural discontinuities is well known. However, the effect that such discontinuities have on the flow depends strongly on whether the flow is transient or steady-state. At steady-state, the pressure and permeability simply adjust to the conditions required to transmit the imposed flux. If the discontinuity forms a dipping surface, there is also a tendency for streamlines to be refracted at the discontinuity, just as in saturated flow. However, only those streamlines in close proximity to the lateral, bounding faults will be modified sufficiently to result in "lateral flow" to the fault zone. As a consequence, a sloping textural discontinuity may have less influence on the partitioning of total steady discharge into a lateral outflow component and a vertical outflow component than is implied.

On the other hand, the sloping discontinuity will have a relatively greater effect on lateral flow during the transient phase. It seems that the flow at depth is more likely to be approximately steady, thus discounting the importance of textural discontinuity on the partitioning of total discharge into a lateral fraction and a vertical fraction. Thus, the effectiveness of textural discontinuities above the Topopah Springs welded unit in preventing percolation into the repository horizon may be overstated.

d. Upward vapor transport by convection in the fractures is proposed by the authors to provide still another means of reducing the net downward flux of liquid water in the Topopah Springs unit. Certainly the potential for water transport by this mechanism is of the same order as liquid transport. Careful evaluation of this transport mechanism is warranted.

4.0 DETAILED REVIEW (Problems, Deficiencies and Limitations)

4.1 Retardation of flow by capillary barriers

It is considered that the unsaturated zone could be a natural barrier to the migration of the various radionuclides from the potential host repository. Part of the retardation of radionuclide transport would be due to limitation of water flow into the fractured, welded tuffs which contain the repository. Some restriction of water flow is assumed to be caused by natural capillary barriers. A capillary barrier can be formed between a unit containing relatively fine pores or fractures and an underlying unit containing relatively coarse pores or fractures.

The report states that a capillary barrier exists between the matrix of the Paintbrush non-welded unit and the open fractures of the Topopah Spring welded unit. In addition, a capillary barrier is assumed to exist at the contact between the Tiva Canyon welded unit and the underlying Paintbrush nonwelded unit. After a precipitation event, infiltration is thought to flow rapidly down the fractures of the Tiva Canyon unit until reaching the capillary barrier at the top of the Paintbrush nonwelded unit. As a result of the large effective porosity and lesser hydraulic conductivity of the Paintbrush unit, the velocity is significantly decreased and lateral unsaturated flow of water can occur above this contact. The report also states that perching along fault displacements may occur.

The lack of evidence for the capillary barrier makes it difficult to consider such a diversion of water to be a conservative condition. From a broad overview, the specific lack of evidence for the Tiva Canyon/Paintbrush barrier is as follows:

1. No perched water has been observed at the contact in the references.

2. No spring-discharge along the outcrop of the Tiva Canyon/Paintbrush contact has been observed.

Until evidence shows otherwise, the conservative approach to net infiltration reaching the Tiva Canyon welded unit and the Paintbrush nonwelded unit would be to assume there is no capillary barrier to downward flow.

At the contact between the Paintbrush nonwelded unit and the Topopah Spring welded unit, the report states that no matrix to matrix capillary barrier occurs. However, a capillary barrier is stated to exist between the matrix of the Paintbrush nonwelded unit and the open fractures of the Topopah Spring welded unit. In the same paragraph, it is stated "opening sizes and moisture conditions are such that some sheet flow can occur along the walls of the fracture in quantities that are greater than the flow in the matrix of the welded unit. Again, the conservative approach (for radionuclide travel times) for the conceptual model would be to assume that no capillary barrier exists at the matrix/fracture interface until evidence shows otherwise.

4.0 DETAILED REVIEW (Problems, Deficiencies and Limitations)

4.1 Conceptual Model

The conceptual model developed uses basic principles of soil physics to quantify the flow phenomena which can take place in unsaturated, fractured porous media. The concept that the largest pores will desaturate first as the water phase pressure in the porous medium is decreased below atmospheric pressure is translated to the desaturation of fractures. As desaturation occurs, water will tend to flow across fractures from one matrix block to another through pendular rings located at asperities. Once fracture desaturation initiates, a relatively continuous air phase produces a large resistance to flow parallel to the fracture, significantly reducing the effective fracture permeability. The effect of the unsaturated fractures is to introduce a macroscopic tortuosity to the porous media.

To quantify the hydrology of a fractured porous medium, three relations are developed from theoretical grounds. The relationships required are fluid pressure head/fracture saturation, fluid pressure head/fracture conductivity, and proportion of fracture surface that remains wetted. In the development of these relationships, the following factors are ignored:

1. Film flow on partially saturated rock surfaces.

2. Vapor transport from evaporation-condensation across the liquid phase.

3. Drying processes of isolated liquid pockets surrounded by gaseous phase.

4. Solubility of air in water.

The authors state that it is possible to include these phenomena into the developed quantitative statistical theory.

As stated in the DOE Draft Environmental Assessment and Montazer and Wilson's Conceptual Model of Flow in the unsaturated zone, Yucca Mountain, Nevada (1984), a geohydrologic unit above the host rock exists which would divert the downward infiltration of water beyond the limits of the emplaced waste. Part of this barrier consists of a capillary barrier which is probably formed between the matrix of Paintbrush non-welded unit and the fractures of the Topopah Spring welded unit. The barrier is formed where the water filled pore sizes in the non-welded unit are smaller than the aperture of fractures in the underlying welded unit. From a theoretical standpoint, no flow into fractures can occur until atmospheric pressure exists at the base of the pores. As stated by Montazer (1984), the pore and fracture opening sizes and saturation conditions are such that some sheet flow can occur along the walls of the fracture in quantities that are greater than the flow into the matrix of the welded unit.

Since the model developed by Wang and Narasimhan and described in the paper reviewed ignored film flow on partially saturated rock surfaces, the utility of the model in evaluating some of the flow phenomena at Yucca Mountain is decreased. It is recommended that film flow on partially saturated rock surfaces be incorporated into the model.

4.2 Fracture Orientation

Fracture orientation data used in the numerical model were based on information obtained at test hole USW G-4. Fractures and fracture orientation were analyzed from the core samples and downhole television camera and compass. The fractures can be divided into two major categories:

1. Joints, which are defined as fractures where fracture faces show no apparent evidence of differential movement.

2. Shear fractures, which show evidence of differential movement in the form of minor offsets of pumice fragments, slickensides, and associated brecciation.

The frequency of fractures is strongly influenced by the degree of welding. In the densely welded zone of the Topopah Spring Member, measurement of fracture inclinations indicated that approximately 36 percent are inclined between 0^{o} and 30^{o} (Spengler and Chornack, 1984). Fractures inclined between 61^{o} and 90^{o} account for about 46% of the fractures (Spengler and Chornack, 1984).

The authors have grouped the fractures into two categories:

1. Nearly vertical - 56% of the fractures have steeply dipping inclinations ($>45^{o}$).

2. Nearly horizontal - 44% of the fracture have small inclinations ($<45^{o}$).

The averages of the cosine of the dip angles for the two groups are $(COS)_V = 0.27$ and $(COS)_H = 0.92$. Using these values, the average vertical fracture would have an inclination of 74^{o} and the average horizontal fracture would have an inclination of 23^{o}.

For the fractured tuff column simulations of the Topopah Spring Member using the TRUST numerical model, two vertical fracture sets and one horizontal fracture set were used to partition the tuff formation into discrete fracture blocks. Only one vertical column of blocks bounded by four vertical fractures were modeled since the midplanes of the bounding vertical fractures are no-flow boundaries due to symmetry. Horizontal fractures were explicitly simulated.

Because the actual orientation of fractures in the welded Topopah Spring Member are not vertical and horizontal, the results from the numerical model presented are difficult to translate into actual conditions. While the advantages of specifying a set of vertical and horizontal fractures relative to setting up a numerical model are obvious, the differences between model results and actual flow phenomena are hard to relate quantitatively. It is recommended that the TRUST model should be used with the stated average fracture orientations to determine if significant differences in matrix/fracture flow behavior occur.

4.2 Net Infiltration of Water

The document estimates the average annual precipitation to be about 150mm/year and an average recharge rate of between 0.5 to 4.5 mm/yr. The report states that infiltration of water at Yucca Mountain probably occurs either directly into fractures within bedrock exposures or from surface runoff seeping into alluvium beneath the channels of washes. The amount of water that is not evapotranspired and that percolates downward and laterally in the unsaturated zone is very small, because of the minor amount of precipitation and the rapid evapotranspiration rates. Any surface runoff is infrequent and of short duration. Direct measurement of infiltration and recharge have not been made at Yucca Mountain.

In describing the conceptual model for Yucca Mountain, the report states that water infiltrating hydrogeologic units exposed at the land surface either is returned to the atmosphere by evapotranspiration or percolates downward beyond the effects of evapotranspiration. Units exposed include alluvium, the Tiva Canyon welded unit, the Paintbrush non-welded unit, and the Topopah Spring welded unit. A large portion of the water infiltrated into the alluvium and colluvium material is stored in the first few meters of the soil and is lost to evaporation during dry periods. Percolation of infiltrated water through the exposed fractures of the Tiva Canyon welded unit is relatively rapid because of the large fracture permeability and small effective porosity of the unit. (Infiltration mechanisms in the exposed portions of the Topopah Spring welded unit are similar to those of the Tiva Canyon welded unit). A large proportion of the infiltrated water normally is percolated sufficiently deep within the fractured tuff to be unaffected by the evaporation potential that exists.

As stated in the section "Concepts of Unsaturated Flow", the depth to which water flows in fractures during infiltration is a function of rock matrix saturation, moisture capacity, permeability, and the intensity of the infiltration, among other things. Rapid infiltration rates, small matrix permeability, and small matrix moisture capacity enhance deep fracture flow. Therefore, on the exposed portions of the Tiva Canyon and Topopah Spring welded units, the potential exists for a large portion of the infiltrated water to become net infiltration.

The report does not address the percentage of surface area at Yucca Mountain exposed as welded tuff. If the potential exists for a large proportion of the infiltrated water on these surfaces to become net infiltration, portions of the exploratory block may experience fluxes greater than presented.

4.3 Non-Conservative Flux Calculation

Several references to data and information from the unsaturated zone borehole USW UZ-1 are made through the report, yet no published report is shown in the bibliography specifically pertaining to USW UZ-1. The report states that drill cuttings from USW UZ-1, which were obtained using dry drilling methods show no significant differences in the moisture contents when compared with samples collected from other boreholes which were drilled using wet methods. The report then says that this comparison provides some confidence in the validity of the saturation data for the Calico Hills nonwelded unit. However, a discrepancy exists between boreholes USW UZ-1 and USW H-1 matrix

4.3 Simulation of Drainage

The simulation of drainage of a column of fractured porous medium demonstrated several salient features of the interaction between the fractures and the matrix. However, other important phenomena are not demonstrated by the drainage problem. The relative fracture/matrix components of the flux during an infiltration event are equally important as during drainage and are likely to be very different.

4.4 Equivalent Bulk Permeability

The development of the hydraulic properties of a single fracture were rather carefully and fully developed in terms of the distribution of apertures for the single fracture. Relatively little was presented on the relation between the properties of a single fracture and the behavior of the bulk medium containing many fractures with presumably different properties. Apparently, calculation of the hydraulic properties of a single fracture from a field measured permeability as was done in this report is tantamount to assuming that all fractures in the bulk medium have the same hydraulic properties.

4.5 The Phase-Separation Constriction Factor

Incorporation of a parameter or function to account for increased tortuosity of flow along the fracture as the saturation decreases is an important feature of the model. It was necessary for the authors to assume a very simplified geometry to enable calculation of their phase-separation constriction factor. It seems likely that it will be necessary to calculate this factor for random location of asperities and more complex geometries of the pendular water associated with the asperities.

5.0 RECOMMENDATIONS

It is recommended that the model be updated to include film flow, vapor transport, and air solubility. Some of these phenomena are considered important in the conceptual model presented by Montazer and Wilson (1984). Improving the model to include them may provide insight into their relative importance to the overall flow field at Yucca Mountain.

It is also recommended that the model be reformulated using more realistic fracture orientations. The results of such modeling efforts would demonstrate the importance (or lack of) of fracture orientation on the solution obtained.

It is further recommended that infiltration events be modeled. As the authors point out, fractures are important during the transient-flow period. An infiltration event followed by drainage period represents a highly transient flow phenomena. Modeling of such an event may provide additional insight into the details of combined fracture and matrix flow.

5.0 RECOMMENDATIONS

The conceptual model provided in this report certainly seems to identify the potential flow mechanisms that may affect repository performance. Many of the mechanisms presented result in decreasing the net vertical flux into the hydrogeologic unit which has been targeted for the repository. Published data does not provide evidence supporting the existence (or absence) of these mechanisms. The data acquisition plan should be carefully and critically reviewed to insure that the data are gathered so that the existence of the important mechanisms which reduce flow into the repository horizos are verified. In general, this will required a detailed and precise water balance which may be difficult to obtain.

With respect to the conceptual model, it is recommended that the effects of resistance to air flow between matrix and fractures be evaluated. Such an evaluation would require use of a two-phase flow model. In addition, the conditions under which the vapor transport mechanisms which may occur in fractured tuff should be investigated.

potentials, even though a similarity exists between the water-content measurements from the two boreholes. The in-situ potentials measured in USW UZ-1 are one to two orders of magnitude smaller. This discrepancy is being evaluated by the DOE.

The in-situ potential gradient measured in USW UZ-1 and USW G-1 and the effective permeabilities obtained from core analysis were used to calculate the flux in the matrix of the Topopah Spring welded unit. The calculated downward flux ranged from $1x10^{-7}$ to $1x10^{-4}$ mm/yr, which was substantially less than previously reported values. Estimates of flux in the Paintbrush nonwelded unit range from 10 to 30 mm/yr, both in upward and downward directions when only vertical flow is considered.

Since a similarity exists between the water-content measurements from USW UZ-1 and USW H-1, and drill cutting from USW UZ-1 are similar in moisture content to drill cuttings from other wells, the conservative approach to the calculation of flux values would be to use the matrix potentials reported for borehole USW H-1. By using the in-situ potential from USW UZ-1, which is several orders of magnitude smaller than USW H-1, the flux values obtained are significantly less than those obtained using the USW H-1 data.

4.4 Drainage into Topopah Spring Welded Unit through Structural Features

During drilling of test well USW UZ-1 (Whitfield, 1985) a large volume of water was encountered in the densely welded tuff of the Topopah Spring Member at a depth of 387 meters. The bottom of the unsaturated zone at this location was estimated to be about 470 meters. Chemical analysis of the water from USW UZ-1 indicated that communication exists between test wells USW UZ-1 and USW G-1. Polymer, which was used in the drilling fluid of USW G-1 was found in the water at USW UZ-1. Test well USW G-1 is located 305 meters to the southwest of test well USW UZ-1.

The report states that limited fracture flow may occur near the upper contact of the Topopah Spring welded unit, however, movement into the matrix diminishes the extent of fracture flow in the deeper parts of this unit. The evidence contradicts this statement. The contamination of water at USW UZ-1 by drilling fluid polymer from USW G-1 indicates significant lateral flow within the deep, densely welded Topopah Spring Member. Flow from fractures in the unsaturated Topopah Spring Member of test well USW H-1 was also observed with a down-hole television cameral log.

The diversion of infiltration by the Tiva Canyon/Paintbrush contact is questionable, and when consideration is given to the possibility of subsurface fault zones becoming conduits for downward flow, there may be areas in the primary repository area that have significant downward flux. Such considerations may significantly shorten travel-times to the accessible environment.

6.0 REFERENCES

Montazer, P. and W. E. Wilson, 1984. "Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada," USGS Water Resources Investigations Report 84-4345, 55 pages.

Spengler, R. W. and Chornack, M. P., 1984. "Stratigraphic and Structural Characteristics of Volcanic Rocks in Core Hole USW G-4, Yucca Mountain, Nye County, Nevada," USGS Open File Report 84-789, 77 pages.

6.0 REFERENCES

Whitfield, M. S., 1985. "Vacuum Drilling of Unsaturated Tuffs at a Potential Radioactive-Waste Repository, Yucca Mountain, Nevada," Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone.