

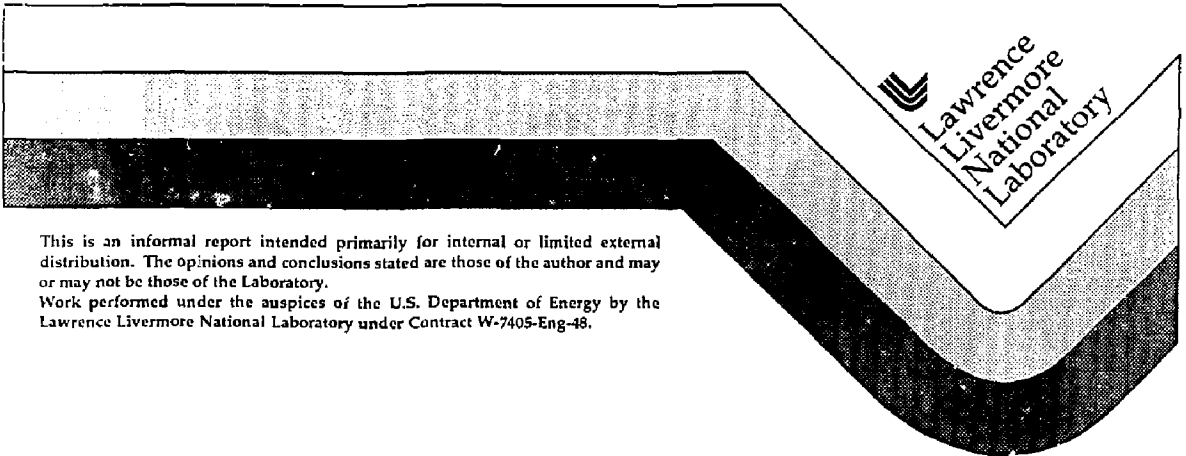
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**PERFORMANCE IMPLICATIONS OF
WASTE PACKAGE
EMPLACEMENT ORIENTATION**

Dale G. Wilder

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Foreword:

This paper was prepared to identify those hydrologic processes that are influenced by the emplacement orientation, and that (in the view of the author) impact long term performance of the Waste Package. The intention of the paper was not to provide detailed or quantitative analyses relative to the issues but rather to identify the processes for which quantitative studies or analyses need to be performed. Thus, many of the ideas are conceptual but are discussed in the paper because they are not contained in other project documents.

At the time that the report was prepared, vertical emplacement was the reference orientation but final orientation was not selected. Subsequent to the preparation of this report, the Yucca Mountain Project completed an emplacement orientation selection-decision analysis process that reaffirmed vertical emplacement as the reference case and directed all studies to be focused on the vertical case without precluding horizontal emplacement. This decision was not made on the basis of analyses of the technical issues defined in this paper. The technical issues identified in this paper are yet to be addressed in a rigorous fashion. Furthermore, since there are no studies proposed to address all of the technical issues raised in this report, it is the judgment of the author that the report serves a necessary function in identifying the processes that need quantitative studies or analyses, although the purpose of the report is somewhat changed.

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Performance Implications of Waste Package Emplacement Orientation

Dale G. Wilder

Lawrence Livermore National Laboratory
Livermore, CA 94550

ABSTRACT

Emplacement borehole orientation directly impacts many aspects of the Engineered Barrier System (EBS) and interactions with the near field environment. This paper considers the impacts of orientation on the hydrologic portion of the environment and its interactions with the EBS. The hydrologic environment is considered from a conceptual standpoint, the numerical analyses are left for subsequent work. As reported in this paper, several aspects of the hydrological environment are more favorable for long term performance of vertically oriented rather than horizontally oriented Waste Packages.

INTRODUCTION

The orientation of emplacement boreholes (either vertical or horizontal) directly impacts many aspects of studies and designs being considered by the Yucca Mountain Project. Early emplacement orientation selection would prevent much duplication in the field testing effort. The purpose of this paper is to identify the potential impacts that emplacement orientation has on the Waste Package (WP) containment and release rate performance. The basis of the concern addressed here is contact of water with the WP container.

The performance allocation and WP strategy rely (in part) on limiting the amount of water that can contact the containers, as well as limiting changes in water quality (DOE, 1988). The Waste Package performance strategy, as discussed in the SCP, relies heavily on the performance of the containers to provide substantially complete containment for a period of time extending 1000 years after repository closure. During the first 100 years, waste package performance is allocated entirely to maintaining container integrity. During the period from 100 to 1000 years, performance is based on most of the containers maintaining their integrity, with failure occurring gradually with time. It is only after 1000 years that performance is allocated to controlled releases that result from gradual leaching of the waste form by aqueous solutions. The most likely failure mechanisms for the candidate container materials involve interactions between the container materials and water. Thus, by limiting the contact of water with the containers, the long-term performance of the WP can be better assured.

Current performance strategies rely on limiting water entry onto WPs for at least 300 years (SCP, 1988). The temperatures of waste during the first 100 years are expected to be sufficient to prevent water entry into the boreholes. Therefore, water contact with waste packages is an issue mainly during the 100 to 1000 year time period when gradual degradation of containers is relied on. The amount of water contacting the containers will influence the rate of degradation of the containers. Therefore, the focus of this paper is the impact of emplacement orientation on water flow into WP boreholes principally from 100 to 1000 years after emplacement.

Current understanding of the hydrologic and geologic conditions within the repository horizon is incomplete and, therefore, performance analyses must consider a range of conditions. The rock-mass is unsaturated, although the degree of saturation is expected to have a mean value of about 65%. Water flux is expected to be low, although actual values are also unknown at this time. There are several possibilities, including vertical flux resulting from upward vapor transport from the saturated zone (Montazer and Wilson, 1984). It is also not clear at this time what percentage of any water that may move

through the rock-mass will flow through the fractures. The amount of water that flows in fractures is a function not only of matrix properties but also of the amount of water available and the aperture of the fractures.

The extent to which water can enter a borehole from matrix flow depends on the balance between suction or matrix potential and the gravity gradients. The balance between suction and gravity for horizontal boreholes is illustrated by Fig. 1. Inflow will occur if the component of the gravity gradient normal to the borehole ($\rho_w g \cos \theta$) exceeds the matric potential. The potential for inflow can be evaluated along any radial direction since the velocity of the flow will be less than zero (sign convention is positive along the radial distance away from the borehole) whenever any inflow occurs. The conditions under which inflow will occur (considering the upper portion of the borehole where gravity gradients act towards the hole) can be written as:

$$P_w - \rho_w g \cos \theta < 0$$

Thus, for $P_w > 0$ (matric potential exists) water can flow from pores into boreholes or openings only when $\cos \theta > 0$ ($0^\circ < \theta < 90^\circ$). Therefore, for vertically oriented boreholes, as long as the matrix is unsaturated, pore water cannot enter the boreholes because of the strong matric potential. Only through fracture flow or some alteration of hydrologic properties, i.e., secondary mineralization which might concentrate pore fluids in the fractures or boreholes, can water enter the vertical boreholes themselves. Flow from the matrix into the openings does not simply depend on geometry, and the simplified equation shown is not sufficient to determine whether flow into a borehole will occur, rather what geometries are necessary for that flow to occur. The more general form of the equation

$$\left(\frac{\rho_w \cos \theta}{-\frac{\delta P_{cgw}}{\delta S_w}} \right) \Big|_{d=r} > \frac{\delta S_w}{\delta d} \Big|_{d=r}$$

(where P_{cgw} is capillary (matric) potential of the water phase of gas-water pore fluid and is a function of saturation and S_w is saturation) must be used to evaluate the potential for pore-fluids to enter the

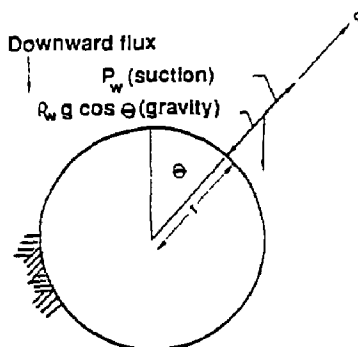


Figure 1. Inflow into horizontal borehole under unsaturated conditions.

boreholes. However, information is lacking to evaluate $\delta P_{cgw}/\delta S_w$ and $\delta S_w/\delta d$ and, therefore, the more simplified equation was used in this evaluation.

Although other aspects, specifically chemistry and WP design options, could change the impacts of the hydrologic response and are closely related to the hydrologic response, they are not discussed in detail in this paper. Where the relationship between these issues and hydrology is germane, they are discussed briefly. It is not the intention of this paper to evaluate all possible parameters that will be considered in making a decision of emplacement orientation; rather, the intent of this paper is to identify (conceptually) the influence of emplacement orientation on hydrologic impacts on WP performance. Detailed numerical analyses of the hydrologic processes are left to future work.

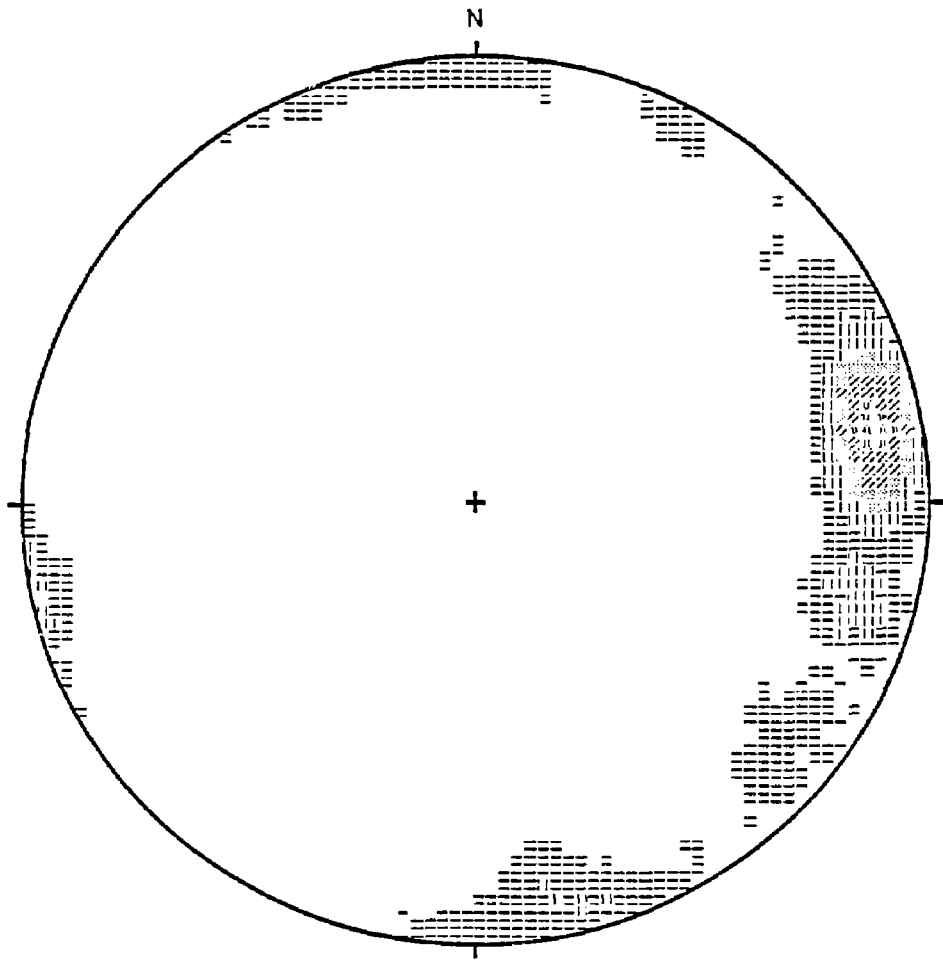
As previously stated, matrix flow under expected limited flux conditions is not expected to adversely impact the WPs. Only the larger flow which could be postulated for fractures under extreme conditions will impact the WPs. To understand the relationship between WP performance and emplacement orientation, one must first understand the relationship between hydrology and orientation. This will be influenced by the fracture system.

Our understanding of fracture networks at Yucca Mountain is incomplete; however, fracture sets within the Topopah Spring unit (the repository target horizon) are expected to be predominately vertical with dominantly N2°W and N28°W strikes (Scott and Castellanos, 1984). The predominately vertical dip and north to northwest strike fracture orientations are generally consistent with the fracture system mapped by Barton at pavement outcroppings (see Fig. 2).

Fracture spacing cannot be well determined from the vertical cores. Scott and Castellanos (1984), after correcting their data for orientation and geometric bias, reported 42 fractures/m³ for the Topopah Spring member. Since more than 75% of the fractures had inclinations within 10% of vertical, this equates to more than 7 fractures per foot horizontally. If dominant fracture orientations (strike) are considered, the fracture spacing would be even less. Because of the bias introduced in the correction applied by Scott and Castellanos, a fracture spacing of 1 foot will be assumed for purposes of this report. (For discussion of correction bias, see Yow and Wilder, 1983, and Yow, 1985).

DISCUSSION

As previously indicated, as long as the repository horizon rock remains unsaturated, water cannot leave the pores, where it will be under significant negative (suction) pressures, and enter the emplacement boreholes. This assumes that an air gap is maintained so that there will be a capillary barrier to effectively inhibit flow from the pores into the borehole. An analysis of the matrix potentials and the most likely environmental conditions for a horizontal emplacement as discussed by Nitao (1988) indicates the effectiveness of the capillary barrier. Therefore, under expected saturation conditions, there are only two likely ways for liquid water to contact the WP container. The first is through borehole failures that bring rock into contact with the container, thereby providing a wick for the water to contact the WP. The second is by flow in fractures where capillary forces presumably will be less than in the matrix. During heavy recharge events, if the fractures become filled with water at a rate that exceeds the rate of imbibition from fractures into the adjoining matrix, it is possible for the water to flow through fractures. Under these conditions, it may be possible for water to enter those WP emplacement boreholes that are intersected by fractures. A third, but more remote, possibility is for vapor to be driven from rock surrounding a hot waste package(s) into the emplacement hole of a cooler WP where it could condense on the WP container surface, providing the temperature of that WP was below the dew point temperature. This is considered a possibility only for a few containers, probably at the boundary of the repository, and could only occur when overall temperatures dropped considerably, at which time most of the water would have been driven away from the WPs.



Schmidt Equal Area Lower Hemisphere Projection (N = 658)

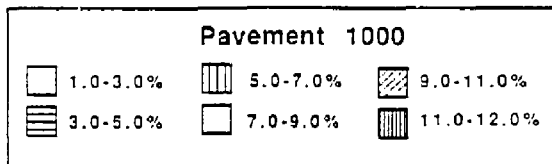


Figure 2. Fracture orientations from pavement mapping (from Yow).

Water Entry onto Waste Packages under Fracture Flow Conditions

Given a fracture spacing of one foot, a 24 to 30-inch-diameter vertical borehole would likely intersect a minimum of 2 to 3 fractures that were parallel to the hole centerline. In a vertical fracture, water will tend to flow vertically downward in the fracture itself (parallel to the borehole) and not into the borehole, unless the fracture intersected the borehole at an angle. The flow paths around the drift are illustrated in Fig. 3. (This argument neglects any water which bypasses seals and flows directly into the borehole from the drift, or that small portion which would flow laterally by capillary-induced spreading or other dispersive processes rather than gravity.) Secondly, unless no fractures intersect the bottom of the borehole, or unless fractures heal or close, water in the borehole should drain freely through vertical fractures in the bottom of the borehole rather than accumulate in the borehole itself. Any water that enters the borehole will tend to flow along the borehole walls until it gets to the bottom of the hole, where it would drain out. Water flow into and out of the borehole is illustrated in Fig. 4. An underlying assumption is that the WP container itself does not touch rock anywhere, including the bottom of the hole. The validity of this assumption depends on the design used; however, other design aspects that will be discussed later make this assumption less important.

For horizontal borehole orientations, the number of fractures likely to be intersected will be approximately one per foot of borehole length. Therefore, horizontal orientation of boreholes would increase the number of fractures intersected by boreholes and thus increase the potential for water to contact WPs relative to vertical borehole configurations. While this increase will not likely be a linear relationship with number of fractures (Bawden, *et al.*, 1980), there will be some increase in potential water inflow. Furthermore, the boreholes will cut the flow paths so that water flowing in the fractures will tend to drip into the boreholes and onto the WP containers. This is true even for low flow rates since water intercepted by the upper (nearly horizontal) segments of the borehole will tend to form pendar drops

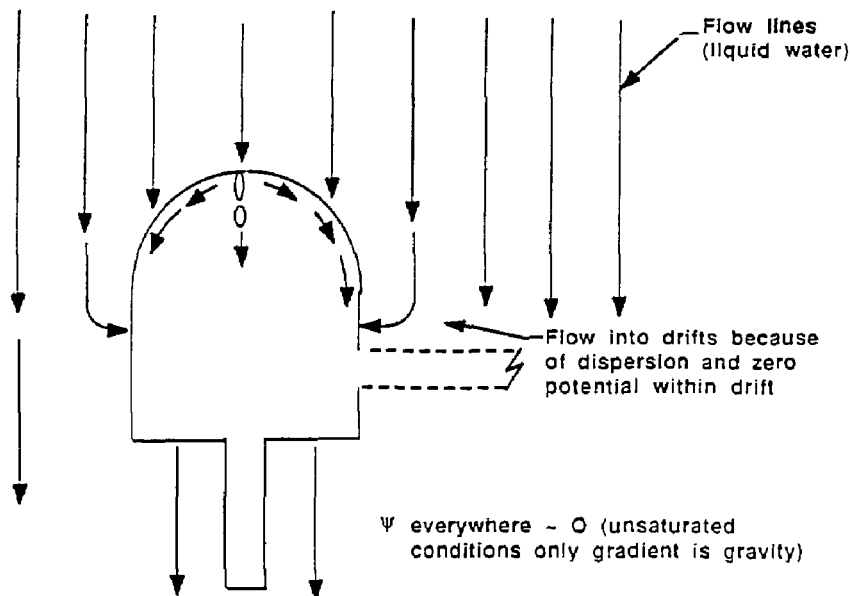


Figure 3. Cross-section of repository along fracture surface showing liquid flow within fracture.

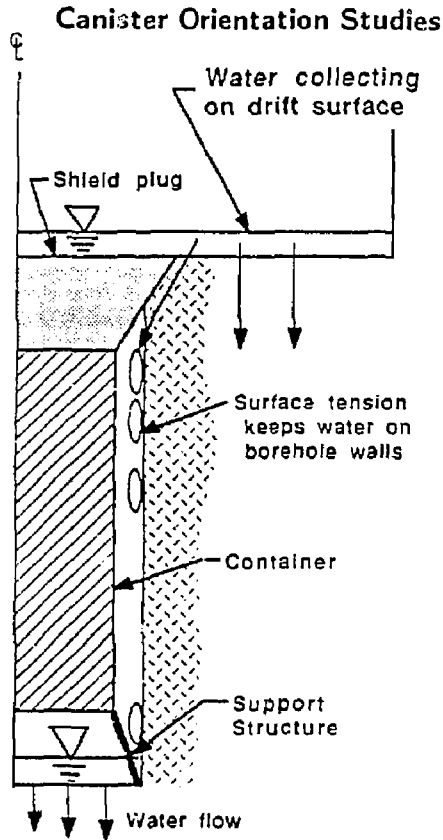


Figure 4. Cross-section of vertical emplacement borehole showing liquid flow within borehole.

until they become large enough to fall directly onto the WP. Since current WP design is for WPs to be supported off the bottom of the boreholes (McCright, *et al.*, 1987), any water falling on the top (upward surface) of the WP (assuming WP temperatures are below the boiling point) will flow around at least a quarter of the WP circumference before it can fall back into the borehole. It is also likely that the water will flow around the WP surface to the bottom of the WP and hang there until the drops become large enough to overcome the surface tension and fall to the lower perimeter of the borehole. These flow paths are illustrated in Fig. 5.

Effects of Salt Disposition on Chemistry of Water Contacting Waste Packages

When the package is hot, water will evaporate or boil from the rock near the WP or from the container surface, thus depositing salts either on the container or in the fractures near the WP. After the package cools, any water that drips onto the container or flows through the fractures containing deposited salts will dissolve those salts. The resulting water may be highly corrosive to the container. The extent to which the deposition and dissolving of salts is an important consideration depends on the

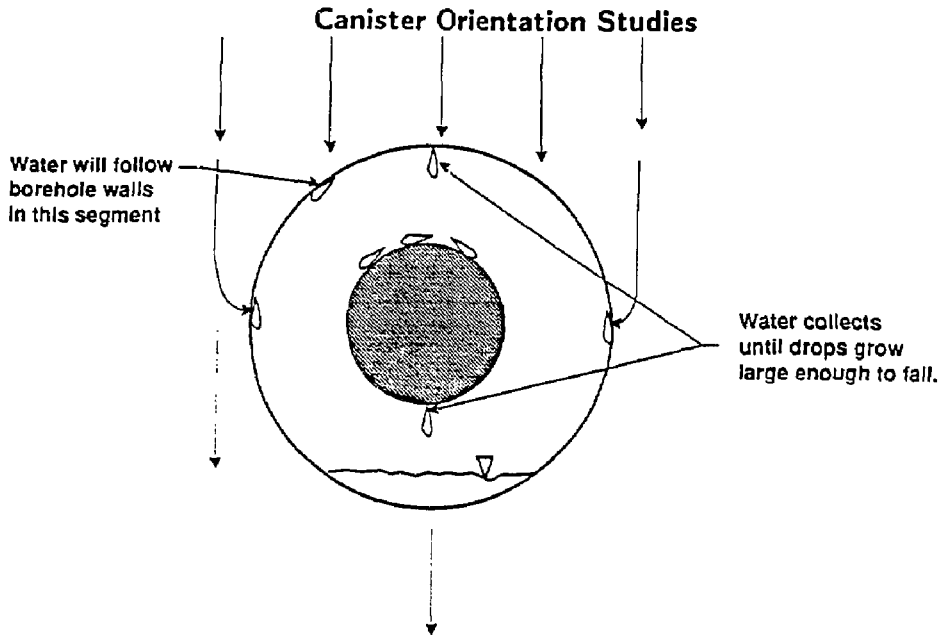


Figure 5. Cross-section showing flow of water along fracture surface intersecting horizontal emplacement borehole.

amount of reflux and repeated evaporation with accompanying salt deposition that takes place. Since groundwater at Yucca Mountain is very dilute, even after a cycle of concentration from deposition/dissolution the total salt content (salinity) may be very low. This salt concentration is of more concern in the horizontal orientation since the amount of potential reflux is greater for the horizontal orientation, as will be discussed later.

Increased Fracture Permeability Resulting from Waste Emplacement

In addition to different flow into the boreholes for a horizontal vs vertical emplacement, the environment and thus long-term flow conditions will be altered in a different manner for the horizontal and vertical orientations. During heating, the rock will undergo deformations which will cause deformations of the fractures within the rock-mass. The fracture response to the deformations will include both normal and shear displacements. Research has documented that shear displacement causes greater permanent changes in aperture and permeability (which usually increases unless extreme shearing takes place that crushes all asperities) of fractures than do normal displacements (Bandis, *et al.*, 1983, Barton, *et al.*, 1985, and Wilder, 1987), although both modes exhibit hysteresis. This has implications for the long-term performance of the WP as outlined below.

It is unlikely that water (other than vapor) will enter the boreholes during the period when the waste is hot enough to keep rock temperatures above the boiling point of water. During this time, liquid water will be vaporized and driven away from the boreholes. When the rock cools, fractures that experienced shearing are likely to have greater hydraulic conductivity than they had prior to thermal deformations. The effects of shear displacements are a function of scale as well as orientation. Hoop stresses that may develop around boreholes will modify fracture deformation responses immediately around the

boreholes; however, the extent of these stresses will be limited to the rock in the immediate vicinity of the boreholes. This is in contrast to repository scale stresses that result from waste emplacement, which extend considerable distances from the boreholes into the large scale flow system. Borehole effects will modify the impact of the repository scale effects but will probably not override them. Thus, while hoop stresses may tend to modify the amount of shear displacement (and thus increased permeability) in the immediate borehole or drift vicinity, the overall repository effects will impact the hydrologic regime of the repository (Wilder, 1987).

For vertical emplacement, normal deformations along the vertical fractures will predominate, except directly above or below the WP (see Fig. 6). Therefore, once the rock-mass cools there will be minimal change in fracture conductivity except for those fractures in the regions between the WP and drifts and immediately below the WPs where shear displacements may increase permeability. Increased permeability below WPs will prevent water contact with WPs since it will allow better drainage of the boreholes. Although water that may collect in the drifts could enter the more permeable fractures above the WPs, drift designs provide drainage away from the area of waste emplacement. This drainage should divert part or all of the water that might enter the drifts away from the boreholes. Furthermore, the drifts themselves may serve to shed water to the pillar area, as will be discussed later, and the backfill within drifts (if used) will be more permeable than the rock matrix. This will provide a type of capillary barrier to matrix flow, depending on the pore sizes that result from backfilling, although the porous backfill may also serve to wick water from the rock matrix into the backfill. WP emplacement design (as discussed later) can ameliorate the flow conditions into the borehole. This is more easily accomplished for the vertical emplacement than for horizontal emplacement. The modifications to the flow are depicted by Fig. 7.

Fractures will also have significant shear deformations resulting from different magnitudes of deformation with distances from the heat sources. As the volume of rock-mass that is heated increases, the differential deformations will occur progressively further away from the WP. The differential deformations will cause shear displacements of the predominately vertical fractures in different regions of the rock-mass depending on time and fracture orientation. Once again, when the rock-mass cools, the shear deformations will likely not be entirely recovered (Bandis, *et al.*, 1983, Barton, *et al.*, 1985, and Wilder 1987). Neglecting fracture healing, if downward flux is sufficient for fracture flow to occur, the permanent deformations will result in a potential for greater amounts of water to enter the boreholes than prior to waste emplacement. The impact of shear displacements is expected to be greater in the horizontal emplacement case because most of the fractures will cross the borehole and allow for

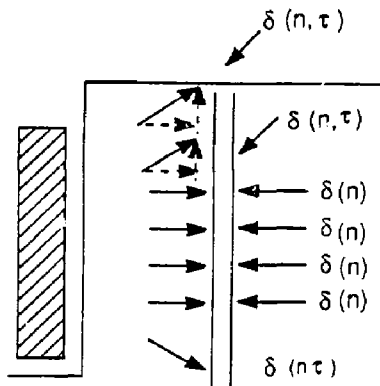


Figure 6. Vertical cross-section showing fracture deformations.

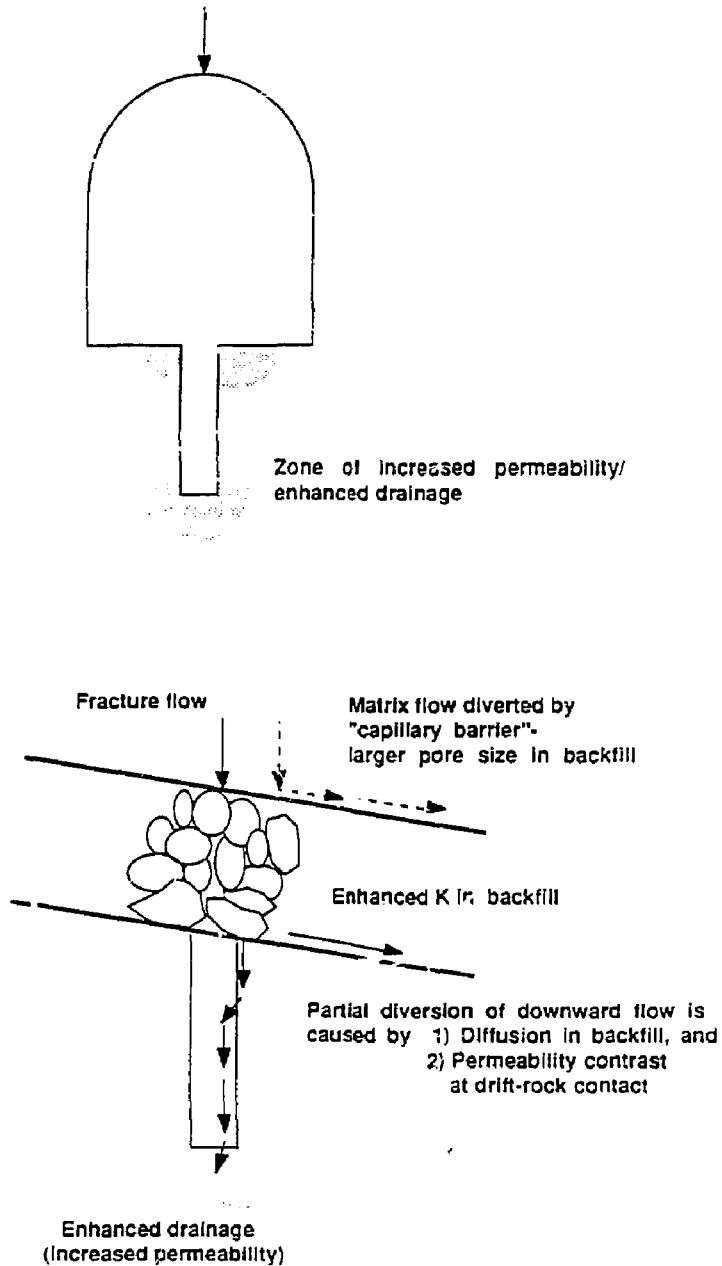


Figure 7. Impact of increased fracture permeability and drift backfill, vertical orientation.

differential movement on successive fractures to relieve the shear deformations of the rock-mass (see Fig. 8). In the vertical orientation the shear will occur along portions of a single (or few) fractures, but fractures that are striking in a tangential direction will experience normal deformations. The increased fracture permeability will be greatest in the area of the WP (see Fig. 9).

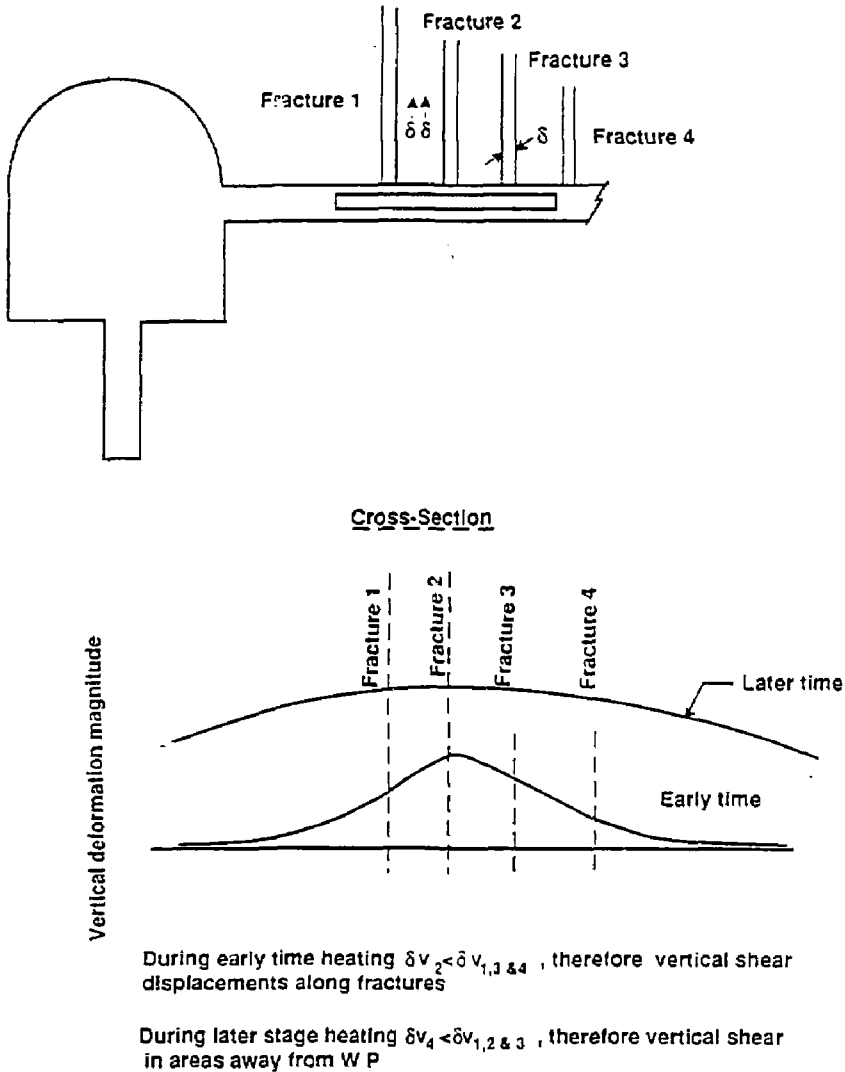


Figure 8. Deformations as function of position along emplacement hole.

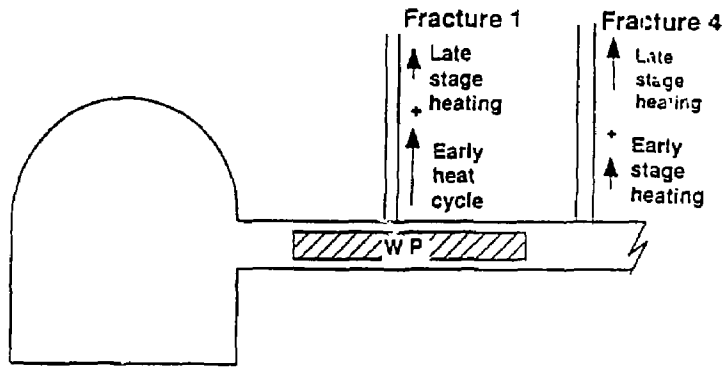


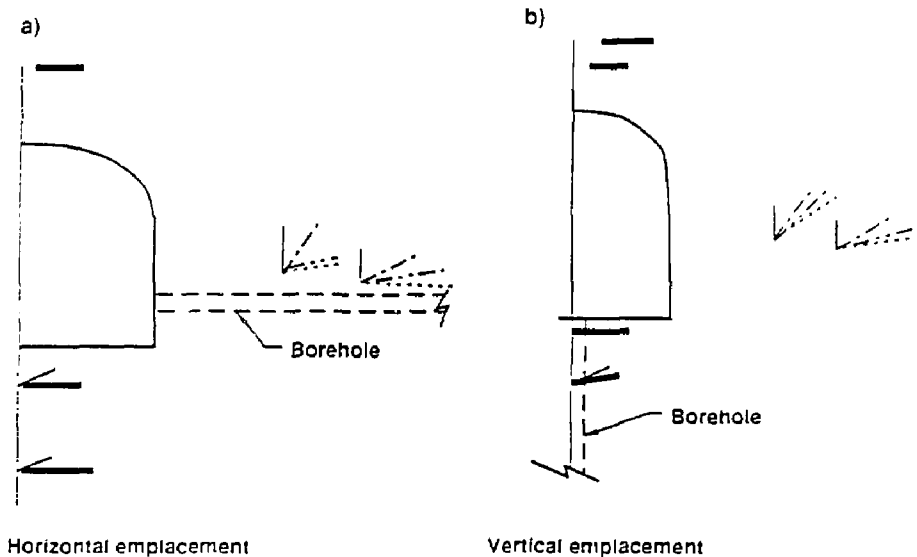
Figure 9. Relative shear displacements due to heating.

Fracture Permeability Increase from Repository Excavation

Numerical analyses of the stresses that result from excavation and waste emplacement were performed for both horizontal and vertical emplacement modes (St. John, 1987). The analyses used the drift configurations that were considered appropriate for the two emplacement orientations (although shorter borehole lengths, for the horizontal case, than considered in this paper are now being considered). The results are summarized in Fig. 10. As is apparent for both emplacement configurations, the orientation of the maximum principal stress vectors in the pillars between panels change from vertical before waste emplacement to nearly horizontal after closure (100 years post-emplacement). The changes in stress orientation beneath the drifts themselves are less pronounced, almost non-existent. Direct analyses of resulting deformations or strains are not available; however, a reasonable assumption can be made that the largest deformations of the rock and fractures will occur in the direction of the maximum principal stress change orientations. Where these orientations are oblique to the fractures, shear deformations will result; normal deformations will predominate otherwise. Figure 11 summarizes the regions of the intermediate scale rock-mass surrounding the WPs where shear deformations will occur along the predominantly vertical fractures.

Construction and Emplacement Impacts on Quantity of Water Potentially Contacting WPs

In addition to the above factors, the quantity of water available to enter the WP must be considered. Two issues or factors related to the amount of water available will be considered in this section. First, potential for net removal of water from the system, which obviously would decrease the volume of water that could potentially contact the WPs; and, second, the location of remaining water and therefore potential to migrate into WP boreholes. A third factor which may be an important consideration is the creation of preferential flow paths for existing flux resulting from increases in saturation. These flux flow paths could be either matrix flow wherein flux can move more rapidly since only small additional volumes of water would be required to nearly saturate the matrix or fracture flow wherein flux could flow in fractures since matric potential would be decreased by increased saturation. While the third issue may have a significant impact on WP performance there is not sufficient information to properly evaluate it at this time. Therefore, this issue is not discussed in further detail.



Legend

- δ max orientation during excavation
- - - - δ max orientation 10 yrs. after emplacement
- δ max orientation 35 yrs. after emplacement
- · - · - δ max orientation 100 yrs. after emplacement
- δ max. orientation lines coincide for different times

(Information summarized from St. John, 1987)

Figure 10. Orientation of maximum principal stress.

Effects of Dry-Out and Steam Condensation on Potential Water Contact with WPs

Water that is removed during heating will flow as vapor principally along fractures (Daily, *et al.*, 1987) to cooler regions where the water vapor will condense. Presumably any water removed from the dried out zone would need to be replaced in the rock-mass matrix before water could flow through the dried out zone and into the emplacement boreholes. Removal of condensate would delay the time when rehydration was completed to the point that water could enter WP boreholes.

The condensate might be imbibed into the rock matrix in the condensation area, where it would remain until the degree of saturation increased sufficiently to allow either fracture or matrix flow. Since the matric potential is a function of the degree of saturation, if the degree of saturation is raised sufficiently, a downward flux (or increase therein) will be created and imbibed condensate (or an equivalent volume of percolating water) could migrate downward and away from WP borehole areas. Furthermore, if the volume of condensate is sufficient to exceed the imbibition rate, water will flow in the fractures rather than be imbibed into the matrix.

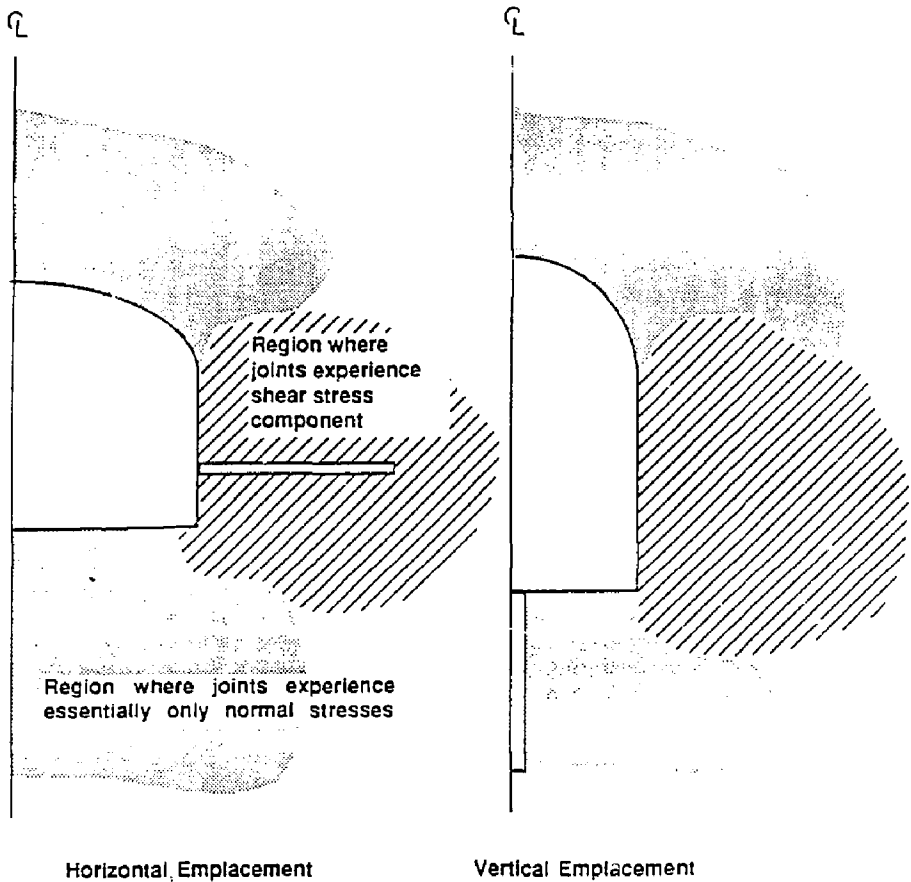


Figure 11. Regions of rock undergoing shear displacements (based on maximum principal stress orientations of St. John (1987), as well as analyses within this report) as a result of waste emplacement.

Gravity-driven water migration through either pores or fractures will occur at saturations less than 100%. The degree of saturation in the undisturbed condition is expected to be approximately 65%. Thus, unless the volume of rock where condensation occurs is considerably larger than the volume of rock that is dried-out, there should be a net downward migration of a significant portion of the water removed from the dried-out zone. If condensation takes place in a smaller volume of rock than was dried-out, an even greater percentage of the water from the dried-out zone will migrate away from the dried-out zone, since the degree of saturation would increase more rapidly to the point where downward flow took place, after which all subsequent condensation would be able to migrate.

Further, as shown by Montazer and Wilson (1984), the "dominance of fracture flow starts at a lesser degree of saturation under wetting than under draining conditions," and this phenomenon is most pronounced in rocks with low matrix permeabilities. Condensation is equivalent to wetting, so fracture flow

would occur at lower saturation in the regions of condensation than would occur under uniform saturation conditions.

Regardless of whether the water from condensation remains in the matrix or flows in fractures, the ultimate issue is how much of the water removed during dryout remains in the system in a position where it can move back to the WP environment once the rock-mass cools. Figures 12 and 13 depict the moisture/vapor flow conditions based on location of the boiling point isotherm with time, as predicted by Hertel and Petney (1989). As can be observed in Fig. 12b, water vapor driven from the near-field environment during the first few years after emplacement for vertical emplacement will either escape into the drifts, or condense as liquid water in the rock beyond the boiling point isotherm. Because much of the vapor from the rock-mass above the WP can preferentially escape into the drift very little condensation will occur in rock above the top of the WP. The increased saturation that results from the condensation will increase the potential for fracture flow and gravity drainage as well as imbibition into rock with lower saturation. This will effectively remove most of the water from the 10 m of rock surrounding the WPs from locations where it could potentially return to the WP environment. After 20 years the boiling point isotherms from adjoining drifts will coalesce (see Fig. 12c) so that moisture removed will tend to condense in equal amounts above and below the WP but the condensation will be greatest at the pillar mid-planes. Furthermore, condensation above the WP emplacement horizon will be restricted from

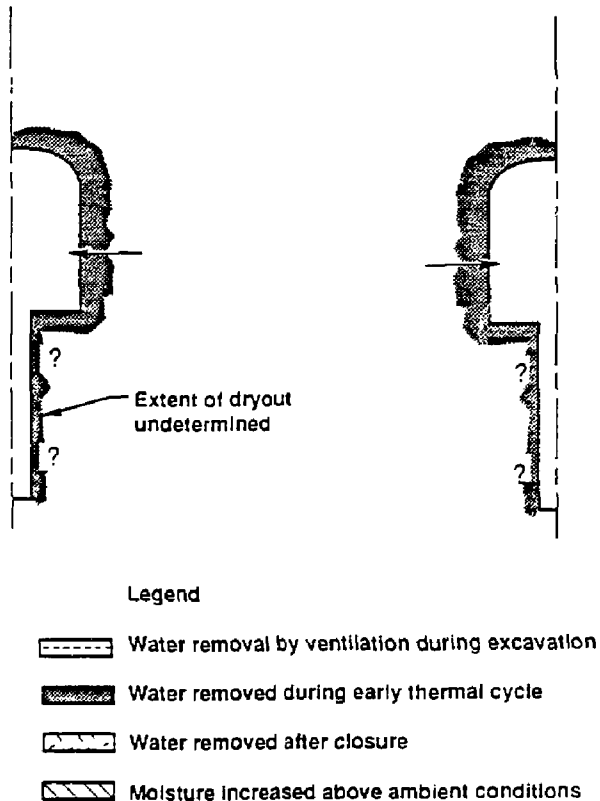


Figure 12a. Construction and pre-emplacment.

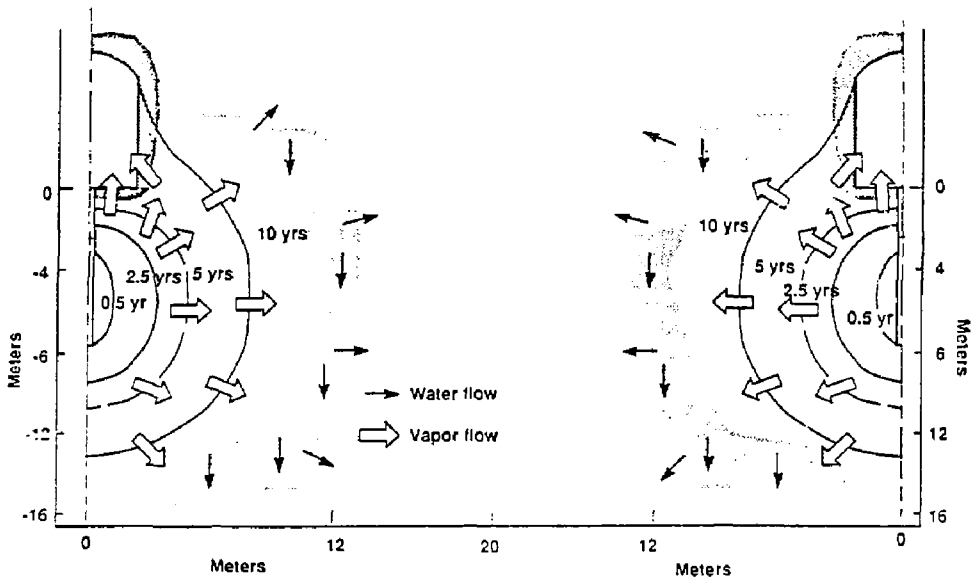


Figure 12b. Ten years post-emplacement modified from Hertel and Petney (1989).

downward migration by the boiling point isotherm which will create a perched type water condition above the WP horizon. In contrast, the condensation below the WP horizon will be unrestricted in downward migration. This will result in a more uniform moisture distribution below the WPs and pillar areas, but with potentially less water remaining in this portion of the rock-mass.

After 100 years the boiling point isotherms are essentially flat lying with respect to the WP so that moisture removal and collection will tend to be uniform from that point on. However, less moisture will condense above the WP than the pillar mid-plane for two reasons. First, the moisture that was in the rock-mass of the drift would be removed during excavation and therefore would not be driven off during early thermal pulse and secondly during the early (first 10 years) thermal rock cycle much of the water removed from immediately surrounding WPs would have either escaped into the drifts or condensed and migrated to elevations below the WPs. An analysis of the amount of moisture per unit area that would be condensed during the first 100 years of drying was made assuming that all water removed above the WP center migrated vertically upward and was deposited in a position directly above the rock-mass from which it was driven. This analysis assumed 65% saturation and 15% porosity and was strictly "back-of-the-envelope" so that it should only be considered as a first approximation. As can be seen on Fig. 14 approximately $1.7 \text{ m}^3/\text{m}^2$ of water would be expected in a position directly over the vertical WP with the amount of water increasing with horizontal distance from the WP to a maximum of approximately $3.1 \text{ m}^3/\text{m}^2$ of water at the mid-pillar position. It would be expected that these differences would diminish as the boiling point isotherm continued to move out with increasing time until ultimately temperatures started to collapse. Only the relatively small volume of water which is transported directly above the WPs and the drifts will be available to migrate back to the area of the WPs. The larger volume of water transported to regions above the pillar would tend to flow vertically downward and only the small portion of this water that spread laterally would be able to come in contact with the WPs.

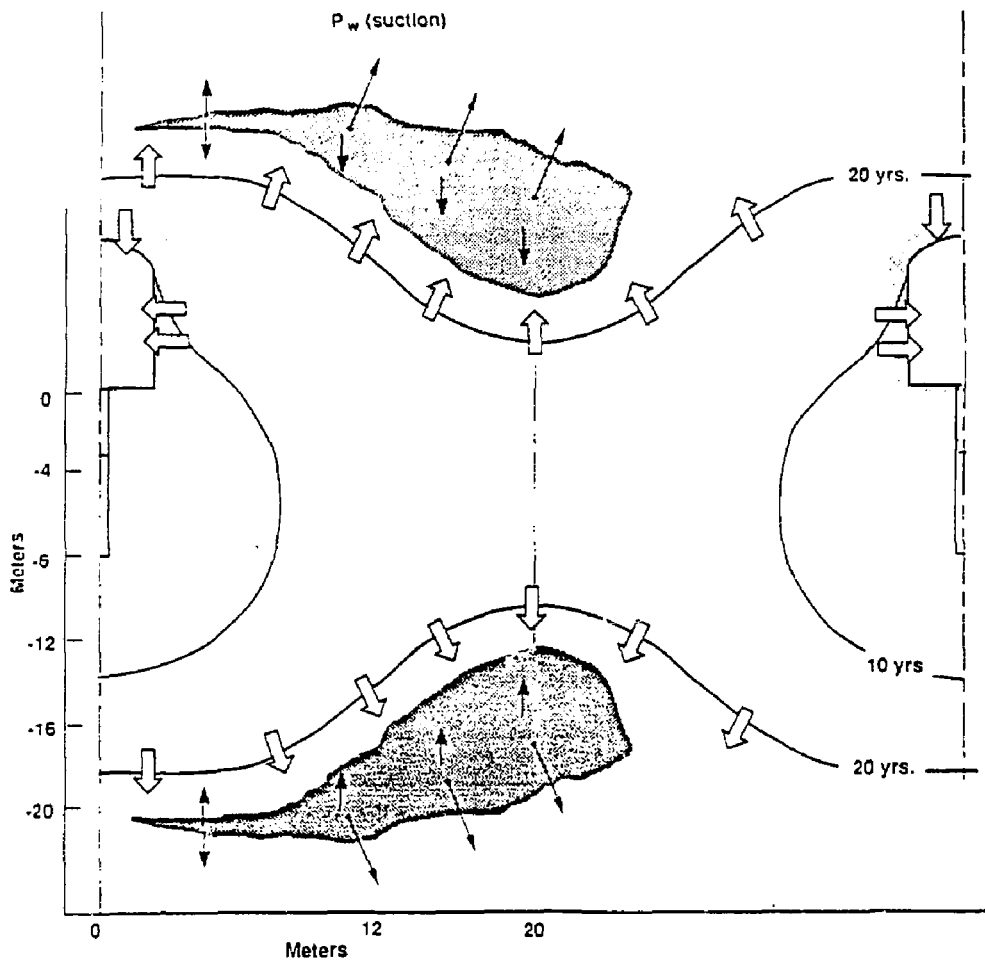


Figure 12c. Twenty years post-emplacment modified from Hertel and Petney (1989).

As can be observed on Fig. 13b, water vapor driven from the near-field environment of horizontally emplaced WPs during the first 10 years will largely condense in the rock-mass directly above or below the WPs. In contrast to the vertical emplacement case a relatively small volume of the moisture from the rock-mass immediately around the WPs will be able to escape into the drifts. Water that condenses will raise the saturation of the rock above the WPs and boiling point isotherm to a greater extent than in the mid-pillar region. Therefore, gravity flow will not be as effective in removing the build up of water from the WP environment as it would in the vertical case. Hertel and Petney analyses indicate that the boiling point isotherms from adjoining drifts do not coalesce until after 50 years (post-emplacment) but before

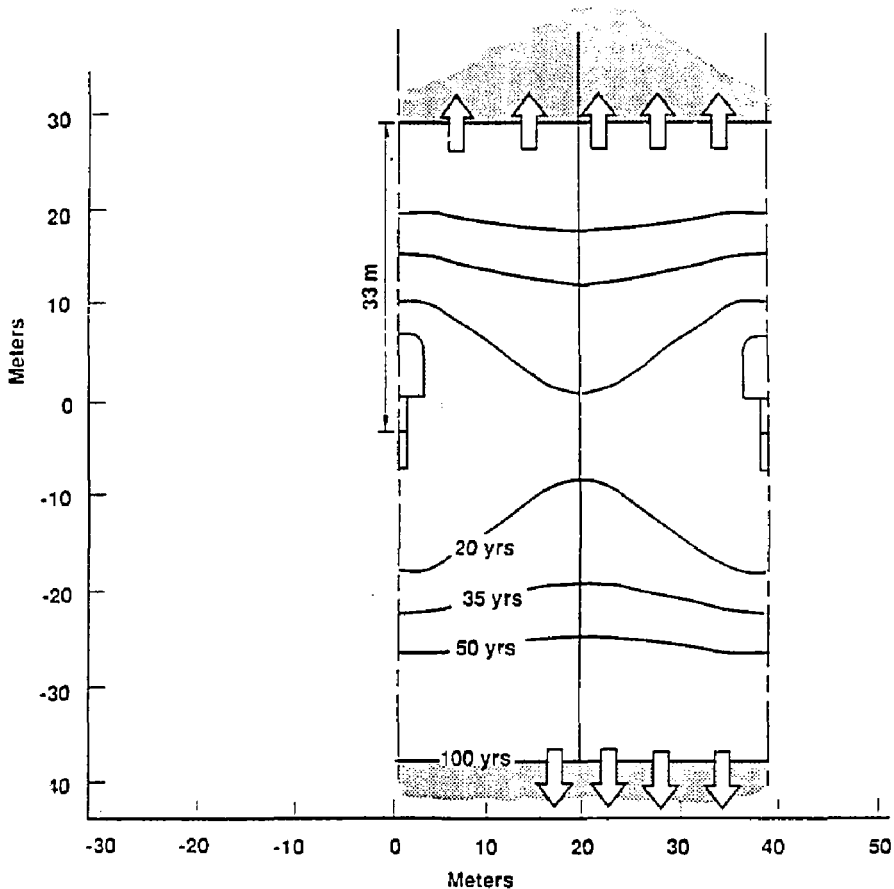


Figure 12d. One hundred years post-emplacment modified from Hertel and Petney (1989).

100 years. Therefore, the downward migration of water can continue for many years which may result in significant volumes of water removed by gravity flow even though the gravity flow mechanisms would be less effective than for the vertical emplacement case.

Because the isotherm shapes are similar from 10 years to almost 75 years, there will be no basic change in the hydrologic processes occurring during this time so those processors described for the first 10 years will continue except that the moisture will continue to move further from the WPs. There will be a greater percentage of lateral movement towards the pillar mid-plane because the isotherm's radius of curvature is greater. However, this is not substantial and the overall processes as described will remain the same.

After 100 years, the boiling point isotherms have coalesced (see Fig. 13c) and moisture/vapor movement will be nearly vertical in the regions directly above and below the WPs with a component towards the mid-pillar in the rock-mass beyond the ends of the emplacement holes. The same back-of-the-envelope calculation of volume of water condensed during the first 100 years of drying was made for the horizontal emplacement case. In this analysis, the volume of water in the rock above the WP elevation

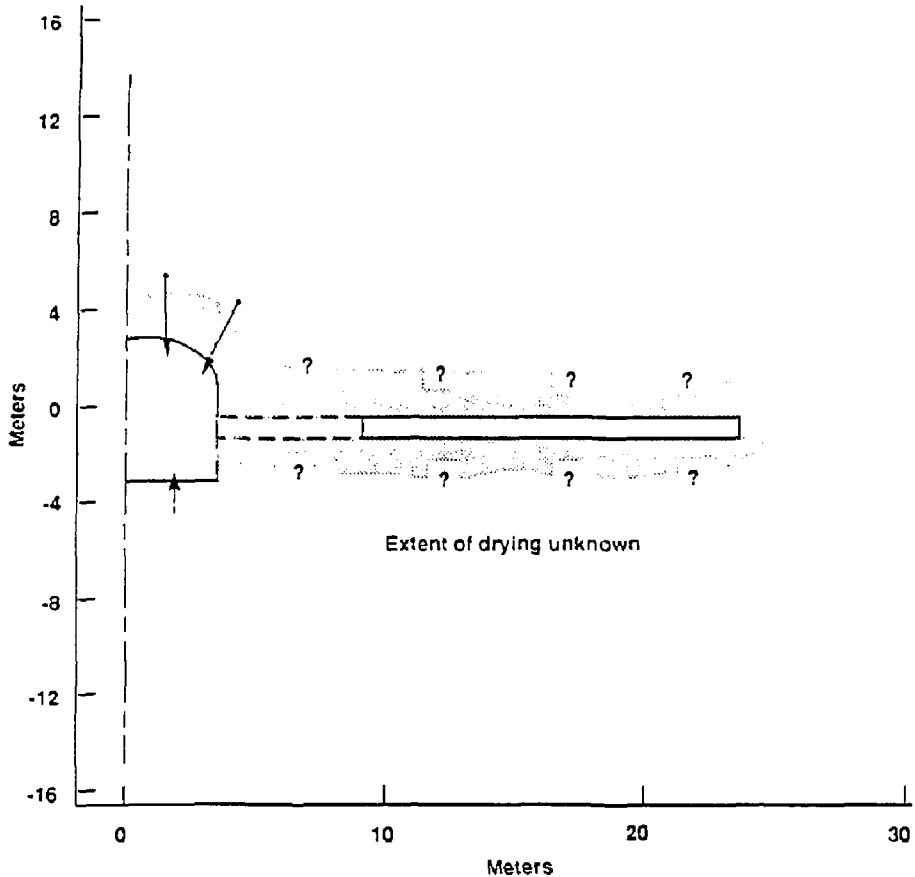


Figure 13a. Construction and pre-emplacment.

extending to the boiling point isotherm was calculated. The plot of this volume is shown on Fig. 14. As is apparent, the volume of water deposited in the rock-mass above the WPs varies from about $3.6 \text{ m}^3/\text{m}^2$ at the end of the WP closest to the drift decreasing to about $3.3 \text{ m}^3/\text{m}^2$ at the end of the WP deepest in the emplacement hole. Once again it is expected that the boiling point isotherms will continue to move away from the WPs until the cool down. As the isotherms move further from the WP horizon, the relative spatial differences in amount of water would diminish.

Thus, in the horizontal case a significant amount of water would be condensed in a position where it could potentially return to the WP emplacement holes.

Effects of Drift Ventilation on Post-Emplacement Water Flow

The amount of water driven off during heating and deposited above the waste packages is also influenced by how much of the original water is removed by ventilation. Hopkins, *et al.* (1987) report that drift ventilation appreciably lowers drift wall saturation. They looked at the impact for 0.5 mm/yr

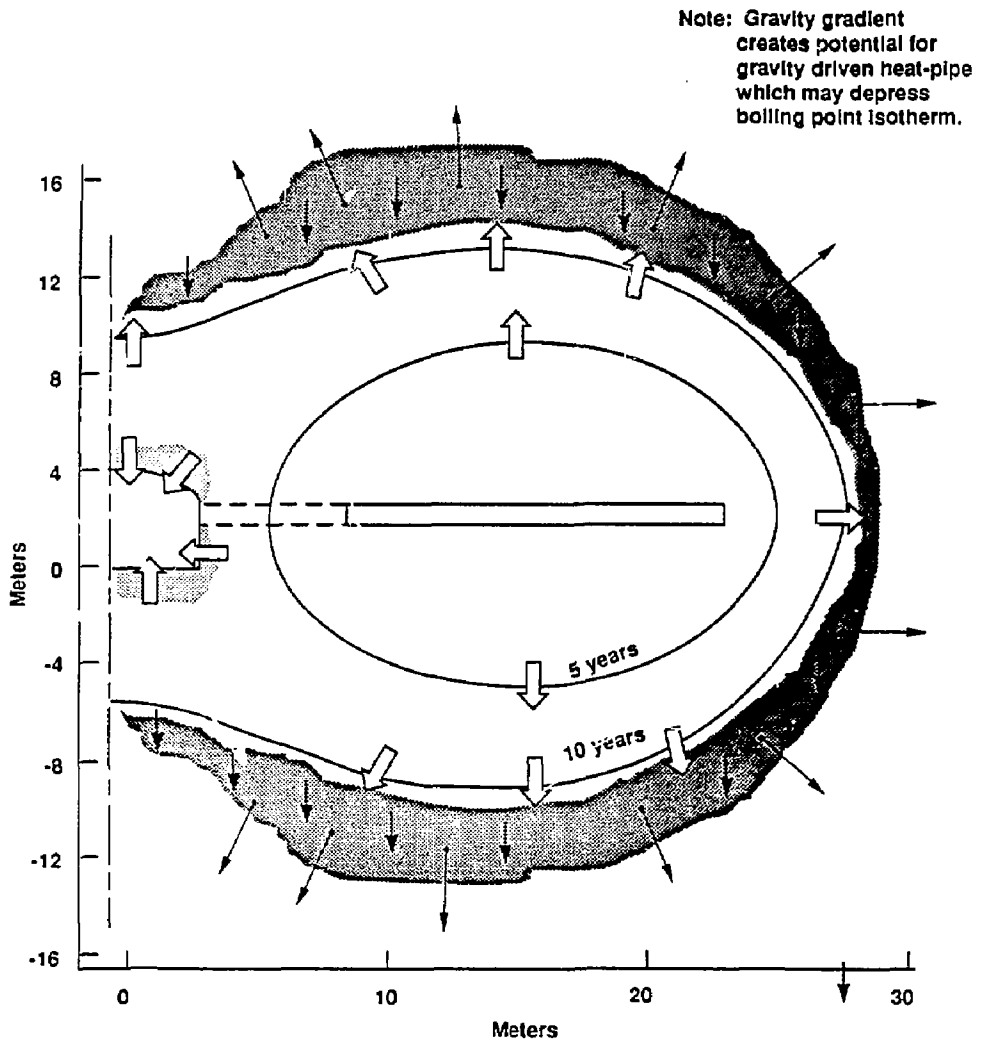


Figure 13b. Ten years post-emplacment modified from Hertel and Prohney (1989).

and 0.1 mm/yr downward flux and vertical emplace-ment and found significant drying from the ventilation system, the effects of which would remain for about 225 or 380 years, respectively. These analyses did not consider the drying out that results from the thermal loading of the WPs, but can indicate the impact that ventilation has on the rock-mass. The impact of combined ventilation and thermal loading would be more dramatic than for ventilation alone since the saturation of the rock-mass surrounding the drifts will be lowered due to ventilation but the rock will not be entirely dried out.

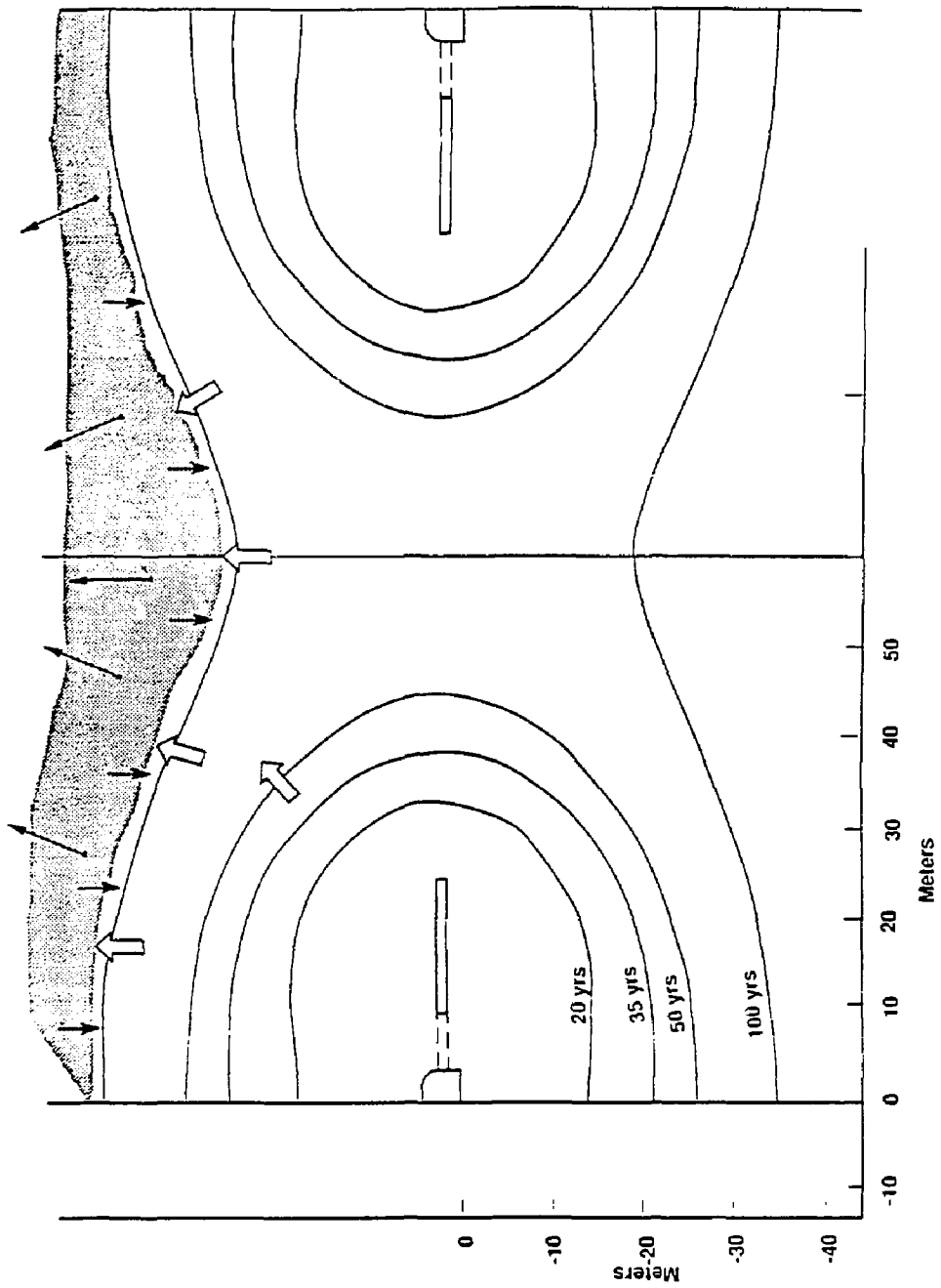


Figure 13c. One hundred years post-employment modified from Hertel and Petney (1989).

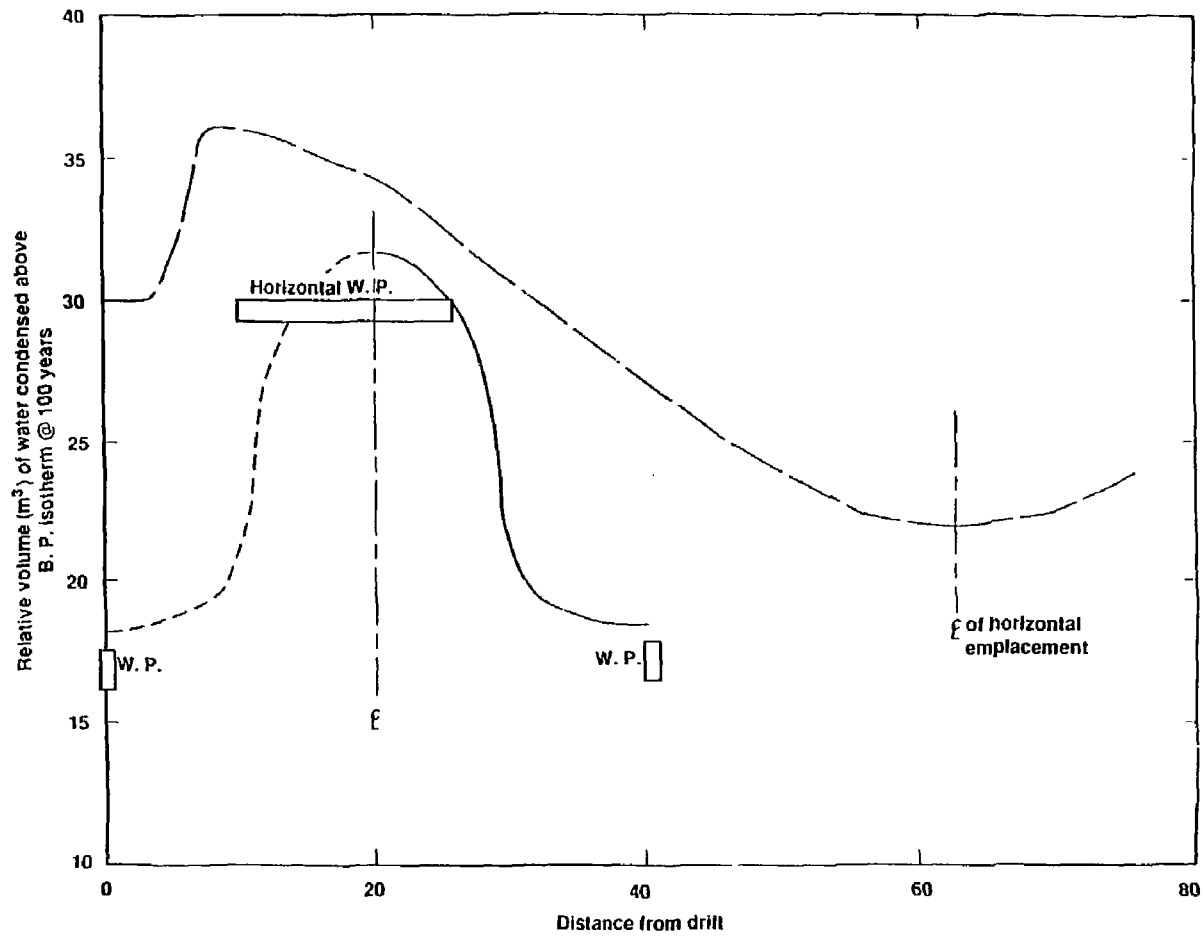


Figure 14. Volume of water condensed as a function of position.

Hopkins, *et al.* show a generally symmetrical zone of decreased saturation (from almost 90% to less than 60%) surrounding the drifts after 50 years of constant ventilation. This is indicated as the first stage of dry out shown on Figs. 12 and 13. During the first few years (possibly 40 years depending on repository operations) after waste emplacement, the drifts will remain open. During this early heating phase the moisture from the rock-mass surrounding the WP will be driven into drifts. As long as the vapor flow path to the drift is sufficiently short then a preferential pathway through the drift is significant. For this analysis, the author judged that preferential flow would occur through the drift for path lengths not exceeding 10 meters. Since it has been reported that air flow is fairly unrestricted through the mountain in response to barometric pressure changes, etc., it seems unlikely that the presence of the drifts will create significantly enhanced flow pathways for fracture flow path lengths to the drifts greater than 10 meters. Therefore, the effects of ventilation alone are sketched conservatively on Figs. 12 and 13 to extend approximately 1-2 m and the flow during dryout was assumed to be preferentially into the drifts for 5-10 meters.

Since the rock-mass surrounding the drifts is directly above the waste in the vertical orientation, ventilation dryout will significantly enhance WP performance for this orientation. Firstly, the rock-mass above the WPs will be at lower saturations before waste emplacement so that less water will remain to be driven off after WP emplacement, and thus less water will condense and accumulate above the WPs. Secondly, during the emplacement period and the years after emplacement until drift backfilling or repository closure, much of the water vapor driven off by heat will be removed by the ventilation system unless panel drifts are sealed off after waste emplacement is completed. Thirdly, even if ventilation ceases after emplacement, much of the vapor will likely be condensed above the drift where it would be imbibed into rock matrix that had been dried by ventilation to a lowered state of saturation. This condensate would remain until sufficient water transport occurred under natural flux conditions to increase the saturation above pre-repository values. Fourthly, with drier rock the temperatures will be elevated over a greater rock-mass volume (less heat used in latent heat during vaporization) so that a larger volume will be dried out. Finally, as reported by Philip (1987), under unsaturated conditions a drift may be designed to shed water off to the sides of the drift before it could infiltrate into the drift. This should potentially protect vertically emplaced WPs from water entry into boreholes. Therefore, the time at which water from the rock above the emplacement holes could enter vertical WP boreholes will be delayed relative to horizontal WP boreholes.

In summary, there are several differences in the impacts of construction and waste emplacement activities on the quantity of water that could contact WPs that depend on the emplacement orientation. For horizontal emplacement, the impact of the water from the dried-out rock-mass will be much different. Firstly, water may not be removed by ventilation from rock surrounding the waste packages prior to emplacement (depending on hole length, standoff distance, and ventilation practices). Secondly, a significant portion of condensation of the water driven off after emplacement will occur in an area of rock above the WPs (see Fig. 13). Thirdly, after the rock-mass cools, the water above the WPs will be able either to flow directly down the fractures onto the containers or to saturate the rock near the WP to its original (or near original) moisture conditions. If there is an overall downward flux and the saturation of the rock above the WP was increased by condensate, then an increased amount of the flux would be carried by the fractures thus increasing the rapidity with which water could potentially reach the WPs.

Effect of Chemical Alterations in the Rock-Mass

In addition to the removal of water from the dried-out zone, the impact of heat on water migrating downward (if any) under normal flux conditions and on chemical changes induced by the rock/water interactions at higher temperatures must also be considered. Chemical reactions between water and rock will likely be influenced by elevated temperatures. Also, the condensate chemistry will likely be different from the ambient pore water (lower in salts). During the period of high temperatures, this water may react with the minerals in the rock until an equilibrium condition is reached where the water may be similar to ambient water. When water, which might subsequently flow through the pores and fractures of the rock-mass under normal flux conditions, comes in contact with the condensate and with the salts

left behind when the water vaporized, it will likely interact with the condensate and salts to come to a new equilibrium condition. The effects of these interactions cannot be assessed at this time.

Fracture Healing Induced Modifications of Water Flow

Li and Daily (1984 and 1988) and Daily, *et al.* (1987) have reported that heat-induced drying results in possible fracture healing. If the healing is total and permanent, then the impact would be the same for horizontal or vertical orientations. However, if the healing is reversible by subsequent leaching, then the vertical orientation would produce the more stable healing since only a small portion of the percolating water would contact the healing materials.

Waste Package Issue Resolution Strategy

An important hydrologic consideration is the extent to which the WP Issue Resolution Strategy (IRS) will be satisfied. Water migrating into the dried-out zone will lower the temperature more rapidly than will conduction alone. In the vertical emplacement mode, a large percentage of the water driven off during the first 20 years of heating will likely flow to an elevation below the WPs (see Fig. 12) or be removed by ventilation (depending on ventilation rates and drift closure). During the early heating period, this water will not flow back into the dried-out zone and therefore will not impact the rock temperature immediately around the borehole (see Figs. 12b and 12c).

Furthermore about 5% of the moisture originally contained within the rock volume that would be heated to the boiling point during the first 20 years after waste emplacement would have been removed either by the mining process itself (the moisture removed with the rock) or by the ventilation system.

For horizontal emplacement, the moisture removed during excavation and by ventilation would not influence the temperature distribution significantly since much less than 5% of the moisture contained within the volume of rock heated to the boiling point during the first 20 years after emplacement would be removed by either mining or ventilation. Further, a heat pipe might occur where water would first be vaporized and travel upward until it condensed. The water might then collect in that portion of the rock until sufficient volume of water accumulated so that gravity would exceed matric potential. Once water flows back into the region of rock where temperatures were above the boiling point it would then re-vaporize. The latent heat to re-vaporize this water would directly impact the volume of rock that could be dried out as well as the temperature distributions and time history of temperatures. This mechanism might also influence the shape of the isotherm and how rapidly it extended away from the WPs but would have minor influence on the total amount of water that accumulated above the WPs. These heat pipe effects could be significant since once sufficient saturation is built up flow can occur both in the matrix due to saturation gradients as well as in the fractures. If a heat pipe is established, it could adversely impact the WP performance strategy which is based on limiting the amount of liquid water contacting WPs.

In the case of horizontal emplacement, the potential for heat pipe effects will be concentrated above the WPs during the first 50-75 years since that is where the major volumes of moisture condensation would occur (see Fig. 13). In the case of vertical emplacement, the isotherm becomes essentially horizontal between 35-50 years, but the location most likely to develop heat pipe effects would be above the mid-pillar where the largest volume of condensate would accumulate. This may influence the shape of the boiling point isotherm and thus influence where moisture accumulation will most likely occur.

The above discussion was based on the work of Hertel and Petney (1989), which did not account for fracture vs matrix flow. However, until detailed hydrothermal analyses are completed it appears that there will be significant differences in the potential for heat pipes to develop for the horizontal and vertical orientations.

Effect of Backfilling of Drifts on Waste Package Performance

Backfilling of drifts at time of closure may also have different impacts on the WP performance for vertical versus horizontal emplacement. The backfill material will most likely be crushed tuff excavated from the repository drifts. This material may be stored on the surface (particularly for early drifts) or may be moved from drifts being excavated into drifts where waste emplacement had been completed. (It is not clear at this time if backfilling of drifts during the retrieval period will be allowed.) The storage (particularly on the surface) and handling of muck will decrease the degree of saturation of this material. The backfill will then act as a gap-graded porous medium (no continuous fractures will remain after backfilling) with lower saturation than the rock matrix. Until the saturation of the backfill increases to that of the surrounding rock, it will act as a sink for moisture. Whether this backfill material will act as a wick to moisture from rock-mass above the drift or as a capillary barrier to flow will depend largely on the degree of saturation of the backfill material, on the relative pore size of the backfill, and on the amount of contact between the backfill and the crown of the drift. However, once cool down has occurred, the backfill will absorb moisture and hold it until the degree of saturation is at least as great as that of the underlying rock-mass. The backfill will also alter fracture flow above the drifts to porous media flow through the backfill, thus dispersing it over a wider area. Thus only a fraction of the water flowing in fractures above the drifts will be able to flow through drift backfill, and re-enter the same fractures below the drifts. The remainder of the water from above the drifts, that is not held in the backfill, is not diverted down drift along the contacts between rock and backfill, or does not re-enter fractures, will be imbibed from backfill into the rock-mass. Additionally, because of permeability contrasts between backfill materials and drift surfaces (and possibly even anisotropic permeability of backfill materials resulting from backfill procedures), it is possible that sub-horizontal permeabilities will be greater than vertical permeabilities through the rock/drift segments. This would divert water down drift along contacts between backfill and rock. All of these processes would act as a partial barrier to flow into WP boreholes.

Mechanical Stability of Emplacement Boreholes

A performance issue for the WP not directly related to the hydrology, and therefore not discussed at length in this paper, nevertheless can impact the hydrologic aspects and should be recognized. This has to do with the stability of boreholes. Unless the strength of the intact rock is exceeded or the rock-mass creeps, any rock entering the boreholes will be a result of block motions along fractures, rather than failures of the rock. Blocks entering the boreholes can serve as a pathway for water to wick onto the waste packages. Since the fractures are predominately vertical, the dimensions of unstable blocks are potentially much larger for vertical-emplacment boreholes than for horizontal boreholes. Blocks larger than the borehole could not move into the boreholes. Since blocks will be smaller for horizontal boreholes, these boreholes are potentially less stable. Therefore, the vertical-emplacment boreholes should be more stable than horizontal-emplacment boreholes. Since borehole stability (assuming no liner is present) will be a function of orientation of boreholes relative to fractures (among other parameters), this needs to be considered in the decision of emplacement orientation.

Waste Package Emplacement Design Flexibility

A final point to be made is the potential for designing the boreholes and repository facilities to help ensure WP performance. In the case of vertical emplacement, three fairly easily achieved design features can be used to ensure that the WPs remain dry for as long as possible. The first is to drill the boreholes deeper than required for waste emplacement to provide a sump for water to flow into. Because the sump provides increased vertical dimension, borehole drainage through fractures as well as imbibition into rock would be increased, thus minimizing the bathtub effect. Second, a capillary barrier between the WP container and the rock-mass could be ensured by either hanging the WP in the hole or, if the WP was supported by the bottom of the hole, by placing a gravel or similar non-porous aggregate backfill material

in the sump portion of the borehole. The final material specification could be determined to balance between prevention of inflow into the borehole by wicking (non-porous aggregate has no matric potential) and providing material to wick away any moisture from the WP which may collect on the bottom contact of the WP. Finally, a seal plug or cap could be installed above the borehole to intercept any water flowing vertically downward through the drift above the WP borehole and deflect that water to the sides of the drift where it would not be in a direct flow path in the borehole. These designs are illustrated in Fig. 15. Other than inclining the boreholes to provide drainage and installing liners, no similar design features could be easily applied to the horizontal emplacement orientation. An inclined borehole should allow water to flow towards the collar and escape into the drift. It is not clear whether in so flowing that water would contact the WPs or whether the water vapor would collect on surfaces and drip onto containers. The issue of liner lifetime and whether they could survive 10,000 yrs to protect WPs during the time frames that they will be required to function is also not known. Because of these unknowns, it does not appear that these design options are as reliable as are the ones for vertical orientation.

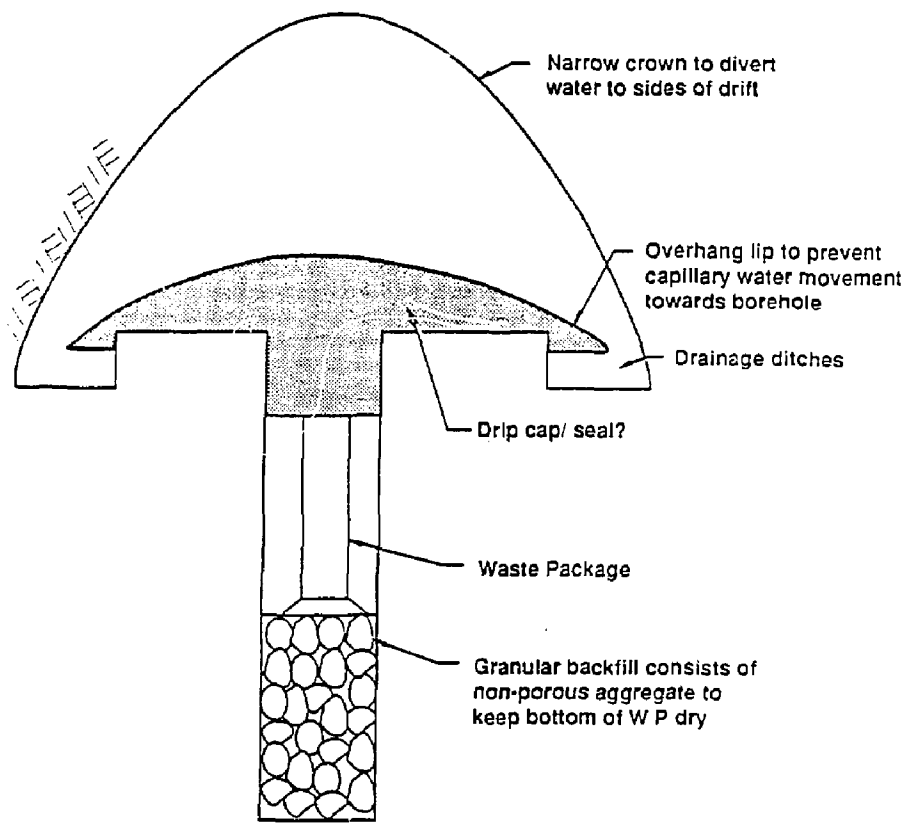


Figure 15. Design aspects of vertical emplacement orientation to ameliorate water contact with WP.

CONCLUSIONS AND RECOMMENDATIONS

Several Waste Package Performance issues related to the hydrologic or waste package environment have been identified as being influenced by the emplacement orientation. From a Waste Package Performance standpoint, the vertical orientation is preferable. The issues and summary of findings follow:

- The considerably larger number of fractures intersected by horizontal boreholes in comparison with vertical boreholes will potentially allow greater volumes of fracture flow water resulting from very heavy recharge events to enter horizontal boreholes. In addition, the orientation of the intersection between vertical fractures and horizontal boreholes is more conducive to water entry into these boreholes than is the case for vertical boreholes. This latter factor is even more pronounced in unsaturated conditions where there is not a significant pressure head, only gravity or elevation head.
- Water is more likely to fall directly onto WPs in horizontal boreholes than in vertical boreholes. In horizontal holes, a portion of the borehole wall is nearly horizontal so water can collect until it drips into the hole. In vertical boreholes, water collecting on the wall surface would run down the borehole wall to the bottom of the hole.
- The potential for salts deposited at the time of water vaporization to influence WP performance is greatest in horizontal holes. Two factors must be considered. First, the groundwater at Yucca Mountain is expected to be very dilute and therefore, the amount of salt deposited upon vaporization will be very small for a single cycle of vaporization. The potential for refluxing of water or entry of additional water to continue the build up of salts is greater in the horizontal orientation. Secondly, the potential for water that leaches the salts to then contact the WPs is greater in the case of the horizontal WP orientation. Both of these factors may be of less concern if a liner can be designed that will survive for a 10,000 year period when WPs have performance objectives.
- There is greater potential in horizontal boreholes for increased fracture opening after cooldown and, therefore, for flow through those fractures into the WP boreholes. This is because, in the case of horizontal waste emplacement, there is greater shear formation during the heating and subsequent cooling cycle which enhances the permeability of the fracture system. In the vertical emplacement mode, deformations will be predominantly normal (perpendicular) to the vertical fractures. In the horizontal orientation, deformations of the predominantly vertical fracture system will have a significant component of shear.
- Water driven off as vapor will more likely return to the horizontal WPs than to the vertical WPs. In the horizontal case, a significant portion of the condensate will collect directly above the WPs. In the vertical orientation, most of the condensate will collect laterally away from the WPs.
- Ventilation of the drifts may remove a significant amount of moisture from the rock-mass surrounding the drifts. In the vertical orientation, the dried-out zone will be directly above the WPs so that less water will be available to enter the WP boreholes after cooldown. In the horizontal emplacement, the ventilation-dried zone will not be principally above the WPs. In the vertical case, the ventilation system will also remove a larger percentage of water during the early portions of the thermal cycle (after emplacement but before closure), since the water vapor will tend to rise (density difference) and can easily enter the drifts by traveling upward in the vertical fracture system. In the horizontal case, vapor would rise above the drifts where it would not be readily removed. Ventilation

influences not only the amount of water potentially entering WP boreholes, or more precisely how soon water can begin to enter the boreholes, but also will influence rock-mass temperature distribution. With less water to vaporize, more of the heat generated by the waste will be added to the rock-mass.

- Drift backfill will likely be at lower saturation than rock matrix. This would delay the time when water flowing through the matrix could enter the vertical boreholes, and will tend to divert a significant portion of any water that flows through the fractures above the drift. The result would be that much of the water from fractures above the drift would not flow into the fractures below the drift that would provide pathways into the boreholes, but rather would spread out in the backfill and the rock matrix.
- Borehole stability will likely be enhanced in the vertical case in comparison with the horizontal emplacement case. This will affect not only loading on WPs, but also the potential for wicking of water into the WPs.
- Engineering design to prevent adverse effects of water on the WPs can be more readily achieved for vertical emplacement than for horizontal emplacement.

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