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The Impact of Repository Heat on Hydrological Behavior at Yucca Mountain

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Introduction

The U.S. Department of Energy is investigating the suitability of Yucca Mountain as a potential site for the nation's first high-level nuclear waste repository. The site consists of a series of fractured, nonwelded to densely welded tuff units and is located about 120 km northwest of Las Vegas, Nevada, in an area of uninhabited desert.[1] The potential repository location is in Topopah Spring moderately to densely welded tuff, approximately 350 m below the ground surface and 225 m above the water table.[2] Favorable aspects of Yucca Mountain relate primarily to its arid nature, which results in unsaturated conditions at the potential repository horizon.

To safely and permanently store waste, the potential repository system must limit gas- or liquid-phase transport of radionuclides to the accessible environment for tens of thousands of years. In the failure scenario of greatest concern, water would contact a waste package, accelerate its failure rate, and eventually transport radionuclides to the water table. The degradational mechanisms of greatest concern for waste package integrity, such as stress and pitting corrosion or microbial attack, require the presence of liquid water. The rates for many of these degradational mechanisms are enhanced under warm, moist conditions. It should be noted that most of the potential high-level nuclear waste repository sites under consideration by other nations are below the water table in the saturated zone. In the saturated zone, 100% of the rock pore space is filled with liquid water. Therefore, for a repository located in the saturated zone, the presence of liquid water is a given; consequently, the degradational mechanisms depend primarily on the geochemistry near the waste packages.

For a repository located in the unsaturated zone, the primary concern is whether liquid water may contact the waste package. This contact can arise from two effects. First, mobile liquid water, particularly flowing in fractures, may contact the waste package. Second, if the relative humidity of the gas phase is sufficiently high, a liquid film can exist on the surface of the waste package even if mobile liquid water is absent. Note that the relative humidity depends on the temperature and the liquid saturation in the surrounding rock. The liquid saturation is defined as the fraction of the rock pore space that is filled with liquid water. If either the liquid saturation is sufficiently low, or the temperature is sufficiently high, the resulting low relative humidity will substantially reduce the rates of many of the degradational mechanisms. Moreover, even for breached waste packages, waste-form dissolution cannot occur if liquid water is absent.

Major Potential Sources of Fracture Flow

The fractured rock mass at Yucca Mountain consists of fractures and rock matrix. Fluid flow in the unsaturated zone involves the movement of liquid water (the liquid phase) and gas (the gas phase) through the fractures and rock matrix. Under ambient conditions, the gas phase contains about 98.5% air and 1.5% water vapor. Most of the liquid water is tightly held in the pores of the rock matrix by capillary forces. Typically, more than half of the matrix pore space is occupied with liquid water, with the remaining pore space occupied by the gas phase. Except for regions with a perched water table, capillary forces cause most of the fractures to be drained of liquid water; consequently, the fractures are mostly gas filled.

In studies of high-level radioactive waste isolation, modeling and theoretical advances in nonisothermal, multiphase flow have demonstrated the critical importance of disequilibrium flow processes between the fractures and the matrix.[3,4] Matrix permeability at Yucca Mountain is extremely small, so matrix flow is of little concern for repository performance. Rather, fracture flow is the most likely means of generating a significant source of liquid water. This water may arise from three potential origins:

(1) natural infiltration of rainfall and snowmelt,

(2) condensate generated under *boiling conditions*, and

(3) condensate generated under *sub-boiling conditions.*

The first source of liquid water arises from the ambient system; the second and third sources are generated by radioactive decay heat, primarily from spent nuclear fuel. Heat-driven, buoyant vapor flow, occurring either on a sub-repository scale or on a mountain scale (Figs. 1a and b), may play an important role in generating the second and third sources of liquid water. Zones of sharply contrasting bulk permeability of the fractured rock mass can also influence vapor and condensate flow, under both boiling and sub-boiling conditions. Of particular concern are conditions that promote the focusing of vapor and condensate flow, which could cause water to drip onto waste packages (Fig. 1c).

Repository heat also drives buoyant, liquid-phase convection in the saturated zone (Fig. 1b). Analyses of this type of flow indicate that it is likely to be the dominant means of driving radionuclide transport in the saturated zone for tens of thousands of years.[6,7] A bulk permeability distribution that facilitates deep convection mixing of radionuclides in the saturated zone would be more likely to meet a dose-based standard than a stagnant water table.

Table I summarizes the time and length scales involved in how repository heat influences the three major sources of fracture flow. Mountain-scale effects depend on the overall heating conditions for the entire repository. We have shown[5–8] that the most useful macroscopic thermal loading parameter quantifying the time-integrated heat content of

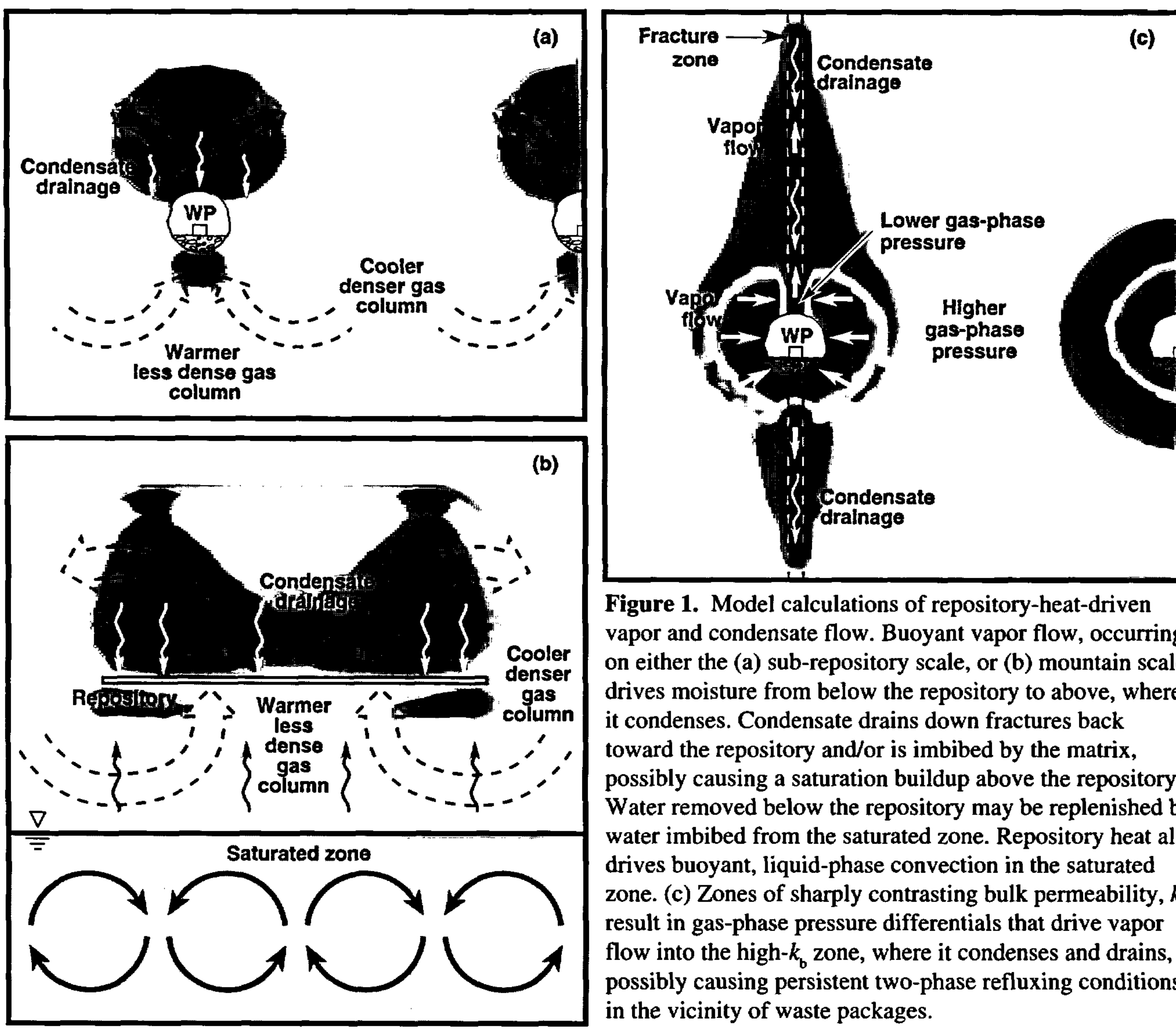

Figure 1. Model calculations of repository-heat-driven vapor and condensate flow. Buoyant vapor flow, occurring on either the (a) sub-repository scale, or (b) mountain scale, drives moisture from below the repository to above, where it condenses. Condensate drains down fractures back toward the repository and/or is imbibed by the matrix, possibly causing a saturation buildup above the repository. Water removed below the repository may be replenished by water imbibed from the saturated zone. Repository heat also drives buoyant, liquid-phase convection in the saturated zone. (c) Zones of sharply contrasting bulk permeability, k_b, result in gas-phase pressure differentials that drive vapor flow into the high-k_b zone, where it condenses and drains, possibly causing persistent two-phase refluxing conditions in the vicinity of waste packages.

the waste in the repository is the Areal Mass Loading(expressed in metric tons of uranium per acre, MTU/acre). Mountain-scale effects depend primarily on the Areal Mass Loading of the entire repository, and they are insensitive to the details of waste package emplacement, such as waste package size and spacing, and fuel age. These effects also depend on the distribution of thermal and hydrological properties throughout the entire unsaturated zone.

Sub-repository-scale effects depend on the local heating conditions around waste packages. Important factors include (1) the number of spent nuclear fuel assemblies per waste package, (2) the spacing between waste packages, and (3) the age of the spent nuclear fuel. In general, the number of fuel assemblies per waste package is directly related to the waste package size. Larger waste packages are capable of containing a larger number of assemblies; consequently, they have a higher thermal output. Younger fuel has a higher thermal output than older fuel for some period of time. The Local Areal Mass Loading depends on the waste package size and spacing. For a given Local Areal Mass Loading, sub-repository-scale effects are very different, depending on whether widely spaced, large waste packages or tightly spaced, small waste packages are used. These effects also depend on the near-field distribution of thermal and hydrological properties within a few tens of meters of the waste packages.

In addition to generating condensate flow, repository heat can redistribute the liquid saturation in the unsaturated zone, causing regions of dry-out below the repository and liquid saturation buildup above. These changes can impact ambient fracture flow, possibly amplifying the effects of natural infiltration in regions of increased liquid saturation and attenuating those effects in regions of dry-out. These changes, along with temperature changes, can alter the intrinsic hydrological, geochemical, and geomechanical properties that influence fluid flow and radionuclide transport in the unsaturated zone. Our analyses[5–8] have indicated that repository-heat-driven changes in the saturation distribution can persist for more than

Natural Infiltration
Affected by repository-heat-driven changes to the • moisture distribution • intrinsic hydrological, geochemical, and geomechanical properties

Buoyant, gas-phase convection and condensate drainage *		Boiling and condensate drainage	
Sub-repository scale	**Mountain scale**	**Sub-repository scale**	**Mountain scale**
Local heating conditions Local Areal Mass Loading Waste package size Waste package spacing	Global heating conditions Areal Mass Loading Repository size Repository location	Local heating conditions Local Areal Mass Loading Waste package size Waste package spacing	Global heating conditions Areal Mass Loading Repository size Repository location
Near-field thermo-hydrological properties	Unsaturated zone-scale thermo-hydrological properties	Near-field thermo-hydrological properties	Unsaturated zone-scale thermo-hydrological properties
t < 1000 yr	1000 < t < 100,000 yr	t < 50 yr for 27 MTU/acre t < 1000 yr for 49 MTU/acre t < 50 yr for 155 MTU/acre	t < 1000 yr t < 100,000 yr for residual effects
Sub-boiling heater tests	Above-boiling heater tests	Marginal-boiling heater tests	Above-boiling heater tests

* *Can occur under both sub-boiling and boiling conditions*

Table I. The various time and length scales involved in how repository heat influences the three major sources of fracture flow.

100,000 yr, even for low Areal Mass Loadings that never drive temperatures close to the boiling point.

Heat-Driven Flow Processes

An important feature of the unsaturated zone at Yucca Mountain is its high fracture density. Moreover, the Topopah Spring tuff, which occurs at the potential repository depth, is one of the most densely fractured hydrostratigraphic units. This is significant because, without fractures, the rock throughout most of the unsaturated zone (including the repository horizon) would be extremely impermeable. In general, repository heat moves moisture by (1) vaporization, (2) driving water vapor from high to low gas-phase pressure, (3) condensation, and (4) gravity- or capillary-driven flow of condensate. Without fractures, the rock would be too impermeable to allow significant vaporization and movement of water vapor. The flow of condensate would also be very slow. A system of connected fractures facilitates significant repository-heat-driven fluid flow as well as natural infiltration.

Heat flow away from the waste packages occurs as heat conduction, the convection of latent and sensible heat, and thermal radiation. Because of the large bulk permeability of fracture networks, gas-phase pressures in the fractures remain very close to atmospheric, even during boiling. Consequently, as temperatures reach the nominal boiling point (≈96°C), boiling first occurs along fractures (Fig. 2) and proceeds into the matrix blocks. Accordingly, dry-out due to boiling is more suppressed in sparsely fractured regions (with large matrix blocks) and less suppressed in intensely fractured regions (with small matrix blocks). As boiling continues, water vapor displaces air away from the waste packages, possibly resulting in the gas phase at the repository becoming 100% water vapor for sufficiently high Areal Mass Loadings. The question of whether (or how long) air is displaced from the repository is important in assessing the impact of oxidation corrosion on waste package integrity.

Most of the water vapor reaching the fracture network is eventually driven away from the emplacement drift by higher gas-phase pressures in the boiling zone to where cooler temperatures cause it to condense along fracture walls (Fig. 2). Buoyant, gas-phase convection can cause more of the vapor flow to be driven upward to where it condenses above the dry-out zone. In general, regardless of where the condensate is generated, there are three things that can happen to it:

(1) It can drain away from the boiling zone.

(2) It can drain back toward the boiling zone.

(3) It can be imbibed by the matrix.

Because the small matrix permeability limits the rate at which the matrix can imbibe the condensate by capillary suction, it can drain for considerable distances down fractures before being completely imbibed by the matrix. Below the boiling zone, condensate drainage is away from the boiling zone (Fig. 2), enhancing the dry-out rate. Above the boiling zone, condensate tends to drain back toward the boiling zone, where it reboils, thereby retarding the net rate of dry-out.

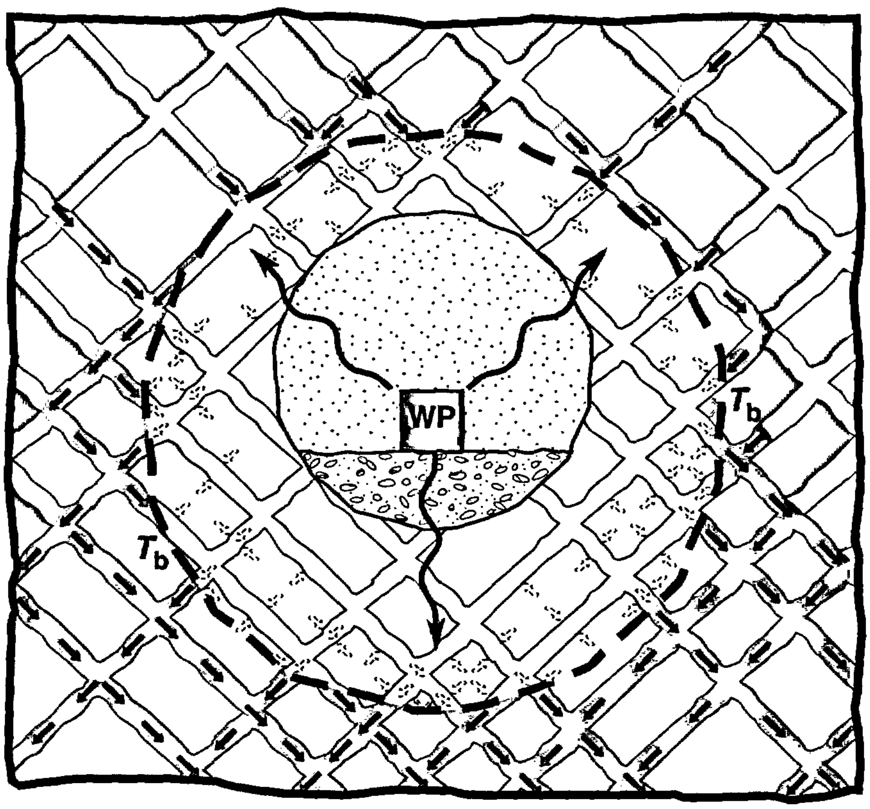

Figure 2. Schematic of hydrothermal flow near the emplacement drift. Rock dry-out occurs as boiling drives water vapor out of the rock matrix. Upon reaching the fracture network, vapor is driven away from the boiling zone to where cooler temperatures cause it to condense along fracture walls. Because the small matrix permeability limits the rate of matrix imbibition, condensate drainage persists for considerable distances down fractures.

The return flow of condensate back toward the heat source causes refluxing, which is the counter-current flow of water vapor and condensate. It is important to note that refluxing does not require boiling conditions.[8] Heat-driven, buoyant gas-phase flow can drive refluxing under sub-boiling conditions. Under boiling conditions, refluxing results in a heat transfer mechanism (driven by the convection of latent heat) called the heat-pipe effect. Given adequately high mass flux rates of water vapor and condensate, heat pipes are capable of sustaining a given heat flux with a much flatter temperature gradient than is associated with heat conduction. Consequently, heat pipes are manifested by a flat temperature profile, with temperatures close to the nominal boiling point. Pruess and others[9,10] were the first to model the heat-pipe effect in the context of thermo-hydrological performance at Yucca Mountain. Depending on the Areal Mass Loading, these effects can occur at the sub-repository-scale or on a mountain scale (Table I).

Thermal Loading Strategies

The extent to which the three major sources of fracture flow may impact waste package integrity, waste-form dissolution, and radionuclide migration is critically dependent on site conditions as well as on the thermal loading strategy that will eventually be adopted for the Mined Geological Disposal System (MGDS) at Yucca Mountain. With respect to repository-heat-driven, thermo-hydrological performance, there are three primary thermal loading strategies (or options). These three strategies are best framed as three fundamental questions:

(1) Can the thermal load be limited and distributed such that it has a negligible impact on hydrological performance?

(2) For intermediate thermal loads, will the impact of thermo-hydrological processes and our understanding of those processes allow us to demonstrate that the MGDS meets regulatory compliance?

(3) For higher thermal loads with the potential of generating extended-dry conditions, will the impact of thermo-hydrological processes and our understanding of those processes allow us to demonstrate that the MGDS meets regulatory compliance?

The goal of the first thermal loading strategy is to minimize the hydrological impact of repository heat so that the primary concern in assessing hydrological performance is the ambient hydrological system. Therefore, this strategy requires that (1) we demonstrate that repository heat has a negligible impact on hydrological performance, and (2) the behavior of the ambient hydrological system and our understanding of that behavior are sufficient to demonstrate that the MGDS meets regulatory compliance. The motivation for this strategy is to avoid any potentially adverse effects of repository heat.

The goal of the third thermal loading strategy is to demonstrate that, for some period of time, repository heat is capable of dominating the ambient system with above-boiling conditions surrounding the repository. Ideally, this would result in (1) the absence of liquid water in the vicinity of the waste packages as long as boiling persists, and (2) the continuation of sub-ambient liquid saturation conditions for some time following the above-boiling period without incurring adverse effects that may offset the benefits of dry-out. The primary motivations for this strategy are to (a) minimize the sensitivity of repository performance to hydrological variability, (b) extend the period of radionuclide containment in the engineered barrier system, and, (c) during the period of radionuclide migration, reduce two factors: the probability of water contacting waste packages, and the flow rates associated with transport. Another important motivation is to delay the period of significant radionuclide migration until the inventory of radionuclides has been substantially diminished by radioactive decay.

The second thermal loading strategy falls between the first and third strategies. All three strategies require an adequate understanding of both the ambient hydrological system and how heat perturbs fluid flow in that system.

It is important to note that what effectively constitutes a "cold," ambient-system-dominated repository or a "hot" extended-dry repository is not well understood. Presently, we lack adequate knowledge of ambient site conditions to define where the transitions from cold to intermediate or from intermediate to hot thermal loads occur. We have analyzed how site conditions will influence the determination of these transitions.[8] In particular, the influence of buoyant, gas-phase convection and how hydrogeological heterogeneity may focus vapor and condensate flow are critical to determining what thermal loads are sufficiently "cold" to render hydrothermal impacts of repository heat as negligible. The influence of these processes will also largely determine what thermal loads are sufficiently "hot" (or whether any such thermal loads exist) to allow us to demonstrate that extended-dry conditions will prevail for some time in the vicinity of waste packages.

Generally speaking, site conditions that are beneficial to a "cold" repository also benefit the performance of a "hot" repository. If we find that the bulk permeability is too small to promote significant buoyant, gas-phase flow and that heterogeneity does not result in significant focusing of vapor flow and condensate drainage, it may be possible to demonstrate that a sub-boiling repository has a negligible impact on the ambient hydrological system. These same site conditions are also beneficial for extending the period of above-boiling temperatures and, during that time, minimizing the presence of mobile liquid water in the vicinity of waste packages.

Buoyant, Gas-Phase Convection

Sub-repository-scale, buoyant, gas-phase convection occurs within fracture networks having a connectivity with length-scale comparable to the distance between the hot and cold regions of the repository (Fig. 1a). Buoyant, gas-phase convection cells develop as the warmer, less dense column of gas within the footprint of the waste packages is displaced by the cooler, denser column of gas in the adjacent areas. As the initially cooler gas is heated up, its relative humidity is lowered, causing it to evaporate water from the rock matrix below hot regions of the repository. This warm moist air is convected upward to where it cools above the waste packages, generating condensate that drains down fractures back toward the repository and/or is imbibed by the matrix, causing a saturation buildup above the waste packages.

Mountain-scale, buoyant, gas-phase convection occurs within fracture networks having a connectivity with length scale comparable to the unsaturated zone thickness and repository width (Fig. 1b). Buoyant, gas-phase convection cells develop as the warmer, less dense column of gas within the footprint of the repository is displaced by the cooler, denser column of gas outside. As the initially cooler gas is heated up, its relative humidity is lowered, causing it to evaporate water from the rock matrix below the repository. This warm moist air is convected upward to where it cools above the repository, generating condensate that drains down fractures back toward the repository and/or is imbibed by the matrix, causing a saturation buildup above the repository. Because water removed below the repository may be replenished by water imbibed from the saturated zone, this process can result in a net saturation buildup in the unsaturated zone. High Areal Mass Loadings result in a large zone of above-boiling temperatures that suppresses the effects of buoyant vapor flow, both on the mountain and sub-repository scales.[8]

Depending on the Areal Mass Loading, we identified a threshold bulk permeability at which buoyant, gas-phase convection begins to dominate moisture movement.[8] At 10 times this threshold, buoyant, gas-phase convection begins to dominate thermal behavior. Given adequately large bulk permeability, mountain-scale, buoyant, gas-phase convection can dominate moisture movement in the unsaturated zone on the order of 100,000 yr (Table I). Sub-repository-scale, buoyant, gas-phase convection continues as long as significant temperature differences persist within the repository. We find that it can dominate moisture movement for up to 1000 yr for the drift spacing described in the Site Characterization Plan–Conceptual Design Report (SCP–CDR).[11] More recently, there has been considerable momentum toward the use of the multi-purpose container (MPC), which, compared with the waste packages described in the SCP–CDR, is much larger, contains more assemblies, and therefore has a higher thermal output per waste package. The larger drift spacing that is consistent with the use of larger waste packages will result in temperature differences within the repository persisting longer. Consequently, the effects of sub-repository-scale, buoyant vapor flow will also be more persistent, possibly lasting thousands of years.

Focused Vapor and Condensate Flow

Refluxing, or the heat-pipe effect, is important to consider because it can affect repository performance in two ways. First, refluxing maintains local temperatures near the boiling point, making it more difficult to dry the rock out. Consequently, the relative humidity may remain high, increasing the likelihood of a liquid film on waste package surfaces. Second, refluxing can bring mobile liquid water in contact with waste packages, affecting waste-form dissolution and radionuclide transport.

To investigate the impact of heterogeneity on the focusing of vapor flow and condensate drainage (and how that focusing affects the development of heat pipes), we considered the situation in which a vertically contiguous zone, with bulk permeability much greater than the nominally fractured rock, intersects the waste package (Fig. 1c).[8] Effectively, the high-permeability zones are competing for a finite quantity of vapor flow and condensate generation. Consequently, there is a trade-off between the duration of refluxing and the number of locations where it can occur in the repository. If there are too many such zones, focusing will not be sufficient to cause persistent refluxing in the repository. The degree of focusing necessary to cause persistent refluxing limits the number of locations where it can occur. Therefore, it is unlikely that refluxing can dominate overall thermal behavior in the repository.

Figure 3 summarizes the effect of focused vapor flow and condensate drainage for a high and intermediate Areal Mass Loading (154.7 and 49.2 MTU/acre). For both cases, high-permeability zones are aligned along the axis of the waste packages and separated by low-permeability zones. The gas-phase pressure differential between these zones drives water vapor back toward the drift and into the high-permeability zone (Figs. 1c and 3). Water vapor flows up the high-permeability zone until it condenses and drains back down. If enough water vapor enters and condenses in this zone, the condensate drainage flux will be large enough to maintain refluxing in the repository. The resulting heat-pipe effect enables the temperature at the top of the drift to remain at the nominal boiling point, causing a depression in the dry-out zone (Figs.

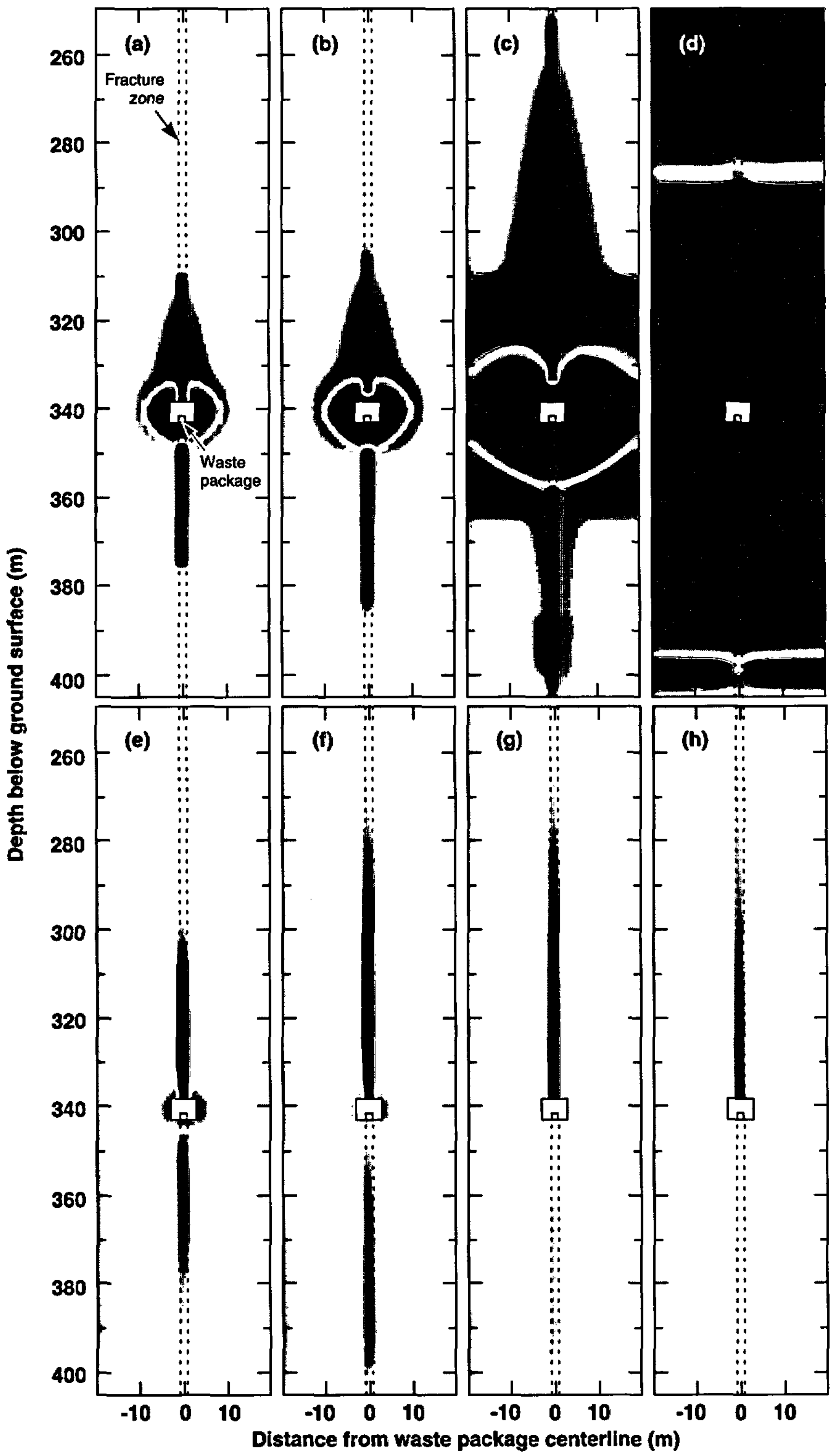

Figure 3. Dimensionless liquid saturation distribution orthogonal to an emplacement drift containing spent nuclear fuel (SNF). Distributions are shown for 30-yr-old SNF, an AML of 154.7 MTU/acre, and an APD of 114 kW/acre at *t* of (a) 8, (b) 10, (c) 30, and (d) 200 yr. Distributions are also shown for 20-yr-old SNF, an AML of 49.2 MTU/acre, and an APD of 43.7 kW/acre at *t* of (e) 159, (f) 661, (g) 1575, and (h) 2534 yr. Within the 1.6-m-wide fracture zone, k_b = 84 darcy; otherwise, k_b = 10 millidarcy. The medium-shaded area surrounding the drift corresponds to a region that is drier than ambient (dry-out zone). The dark-shaded areas correspond to regions that are wetter than ambient (condensation zones). The lighter shading surrounding the dark-shaded areas corresponds to a decreasing buildup in saturation (outer edges of condensation zones). No shading indicates no change in saturation. Note that the transition from drier to wetter conditions is shown as a white ring at early time which becomes a white band at later time.

3a, b, and e). In spite of persistent refluxing, the temperature along most of the remainder of the drift wall, the air in the drift, and the waste package itself is well above the boiling point. Therefore, although liquid water may be dripping in the drift, the relative humidity around the waste package can still be low.

The heat-pipe zone attracts heat flow (mainly by conduction) from the neighboring rock. In effect, the heat-pipe zone functions as a "cooling fin" that is manifested by an elongated region of liquid saturation buildup (Fig. 3). The process of gas-phase focusing into the heat-pipe zone develops more quickly than the process of attracting heat from the neighboring rock. Within 8.5 yr, enough heat is being conducted into the heat-pipe zone for the high Areal Mass Loading case to overwhelm the heat pipe, causing the top of the drift to begin to dry out (Figs. 3a and b). Preferential heat conduction into the heat-pipe zone continues to dry it out (Fig. 3c). Notice that the effect of focused condensate drainage is no longer evident at 200 yr (Fig. 3d).

For the intermediate Areal Mass Loading case, which is the reference thermal load in the SCP–CDR,[11] focused vapor flow causes persistent refluxing in the high-permeability zone (Figs. 3e–h). This thermal load generates marginal boiling conditions, which last only 160 yr, and is insufficient to coalesce the dry-out zones between neighboring drifts. There is also not enough heat to overwhelm the heat pipe and dry out the rock at the top of the drift. Refluxing persists at the top of the drift for several thousand years (Figs. 3e–h), long after the end of the boiling period. Diagnosing the potential for these repository-heat-driven effects to impact waste package integrity and radionuclide migration will require *in situ* heater tests conducted under sub-boiling as well as above-boiling conditions.[12,13]

Extended-Dry Repository Concept

Much of the preceding discussion has emphasized repository-heat-driven processes that may increase the likelihood or quantity of liquid water contacting a waste package and driving radionuclide transport. However, depending on the thermal loading conditions, repository heat may also be instrumental in reducing the likelihood and quantity of liquid water reaching the repository for a considerable period of time. The Site Characterization Plan[11] includes the concept of a (300 to 1000 yr) period of "substantially complete containment" of radionuclides in waste packages. This concept was developed largely on the basis of the assumption that, for the reference thermal loading conditions, a region of above-boiling temperatures surrounding waste packages would keep them dry for 300 to 1000 yr. The "extended-dry" or "hot" repository is simply an extension of this concept.

Our model studies[5–7] show that the duration of boiling conditions is primarily dependent on the Areal Mass Loading of the repository and less sensitive to fuel age. For an Areal Mass Loading of 154.7 MTU/acre, we calculated the duration of the boiling period to be 11,500 yr at the center of the repository and about 4000 yr at the outer edge. We also found that boiling can result in a dry-out zone extending 300 m vertically (200 m above and 100 m below the repository horizon), with re-wetting of the repository horizon back to ambient conditions requiring 160,000 yr, long after boiling has ceased. Many of the calculations assumed averaged thermal loading conditions and did not represent how heterogeneity might cause focused vapor flow and condensate drainage. However, more recent calculations, which address the impact of heterogeneity and spatially varying thermal loading conditions, have yielded similar results for high thermal loads.[8]

It is important to point out that the calculations for the extended-dry repository (or for any other thermal load) have been conducted with idealized models that have not been validated and with limited data. The process of building confidence in our ability to *conservatively* predict performance is greatly facilitated by the use of hypothesis tests.[8] For the extended-dry repository, the critical questions involve how confidently we can predict the extent of above-boiling temperatures, whether such conditions correspond to the absence of mobile liquid water near waste packages, and how long the dry-out zone persists after the end of the boiling period. The only conclusive means of addressing these issues is through long-term, *in situ* heater tests[12,13] and long-term monitoring of the thermo-hydrological behavior of the repository system.

Conclusions

The radioactive heat-of-decay from spent nuclear fuel will play a dominant role in the performance of a potential repository at Yucca Mountain. Coupled hydrothermal-geochemical processes can strongly affect the composition and flow rates of gas and liquid around the waste packages. Waste package degradation, waste-form dissolution, and radionuclide release will critically depend on these processes. Repository heat will also play a dominant role in the evolution of the flow field that will drive gas-phase and liquid-phase transport. In addition, coupled hydrothermal-geochemical phenomena may significantly affect the performance of natural barriers underlying the repository. Depending on the thermal-loading management strategy (which will affect the design and operation of the repository) and site conditions, repository heat may either substantially increase the likelihood of water contacting waste packages and the magnitude of release and transport of radionuclides or preclude, or at least minimize, these effects for some period of time.

In our modeling studies, our approach has been to identify conditions that could potentially generate adverse performance. Accordingly, we have considered a wide range in bulk permeability and examples of heterogeneity that may be extreme. This work provides a context for understanding the relative importance of various hydrogeological properties and features that will be determined during site characterization. This work also shows that the challenge of adequately understanding repository-heat-driven, vapor and condensate flow is at least as formidable for sub-boiling conditions as it is for above-boiling conditions. Long-term *in situ* heater tests, conducted under both sub-boiling and boiling conditions, are required to determine the potential for the major repository-heat-driven sources of fracture flow to impact waste package performance and radionuclide transport.

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References

1. Montazer, P., and W.E. Wilson, "Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada," Water Resources Investigation Report 84-4345, U.S. Geological Survey (1984).

2. Klavetter, E.A., and R.R. Peters, "Estimation of Hydrologic Properties of an Unsaturated Fracture Rock Mass," *SAND84-2642*, Sandia National Laboratories, Albuquerque, NM (1986).

3. Buscheck, T.A., J.J. Nitao, and D.A. Chesnut, "The Impact of Episodic Nonequilibrium Fracture-Matrix Flow on Geological Repository Performance," *Proceedings American Nuclear Society Topical Meeting on Nuclear Waste Packaging (Focus 91)*, Las Vegas, NV, Sept. 30–Oct. 2, 1991. Also, *UCRL-JC-106759*, Lawrence Livermore National Laboratory, Livermore, CA (1991).

4. Nitao, J.J., T.A. Buscheck, and D.A. Chesnut, "The Implications of Episodic Nonequilibrium Fracture-Matrix Flow on Repository Performance," *Nuclear Technology*, Vol. 104, No. 3, pp. 385-402 (1993).

5. Buscheck, T.A., and J.J. Nitao, "The Impact of Thermal Loading on Repository Performance at Yucca Mountain," American Nuclear Society, *Proceedings Third International High-Level Radioactive Waste Management Conference*, Las Vegas, NV, April 12–16, 1992. Also, *UCRL-JC-109232*, Lawrence Livermore National Laboratory, Livermore, CA (1992).

6. Buscheck, T.A., and J.J. Nitao, "The Impact of Repository-Heat-Driven Hydrothermal Flow on Hydrological Performance at Yucca Mountain," American Nuclear Society, *Proceedings Fourth International High-Level Radioactive Waste Management Conference*, Las Vegas, NV, April 1993. Also, *UCRL-JC-112444*, Lawrence Livermore National Laboratory, Livermore, CA (1993).

7. Buscheck, T.A., and J.J. Nitao, "Repository-Heat-Driven Hydrothermal Flow at Yucca Mountain, Part I: Modeling and Analysis," *Nuclear Technology*, Vol. 104, No. 3, pp. 418–448 (1993).

8. Buscheck, T.A., and J.J. Nitao, "The Impact of Repository Heat on Thermo-Hydrological Performance at Yucca Mountain," *Proceedings American Nuclear Society Topical Meeting on Site Characterization and Model Validation (Focus 93)*, Las Vegas, NV, Sept. 26–30, 1993.

9. Pruess, K., Y.W. Tsang, and J.S.Y. Wang, "Numerical Studies of Fluid and Heat Flow Near High-Level Nuclear Waste Packages Emplaced in Partially Saturated Fractured Tuff," *LBL-18552*, Lawrence Berkeley Laboratory, Berkeley, CA (1984).

10. Pruess, K., J.S.Y. Wang, and Y.W. Tsang, "On Thermohydrologic Conditions Near High-Level Nuclear Wastes Emplaced in Partially Saturated Fractured Tuff, Part 1: Simulation Studies With Explicit Consideration of Fracture Effects," *Water Resources Research*, Vol. 26, No. 6, pp. 1235–1248 (1990).

11. SNL (Sandia National Laboratories), "Site Characterization Plan–Conceptual Design Report," *SAND84-2641*, Sandia National Laboratories, Albuquerque, NM (1987).

12. Buscheck, T.A., D.G. Wilder, and J.J. Nitao, "Large-Scale In Situ Heater Tests for the Characterization of Hydrothermal Flow at Yucca Mountain," American Nuclear Society, *Proceedings Fourth International High-Level Radioactive Waste Management Conference*, Las Vegas, NV, April 1993. Also, *UCRL-JC-112445*, Lawrence Livermore National Laboratory, Livermore, CA (1993).

13. Buscheck, T.A., D.G. Wilder, and J.J. Nitao, "Repository-Heat-Driven Hydrothermal Flow at Yucca Mountain, Part II: Large-Scale In Situ Heater Tests," *Nuclear Technology*, Vol. 104, No. 3, pp. 449–471 (1993).

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