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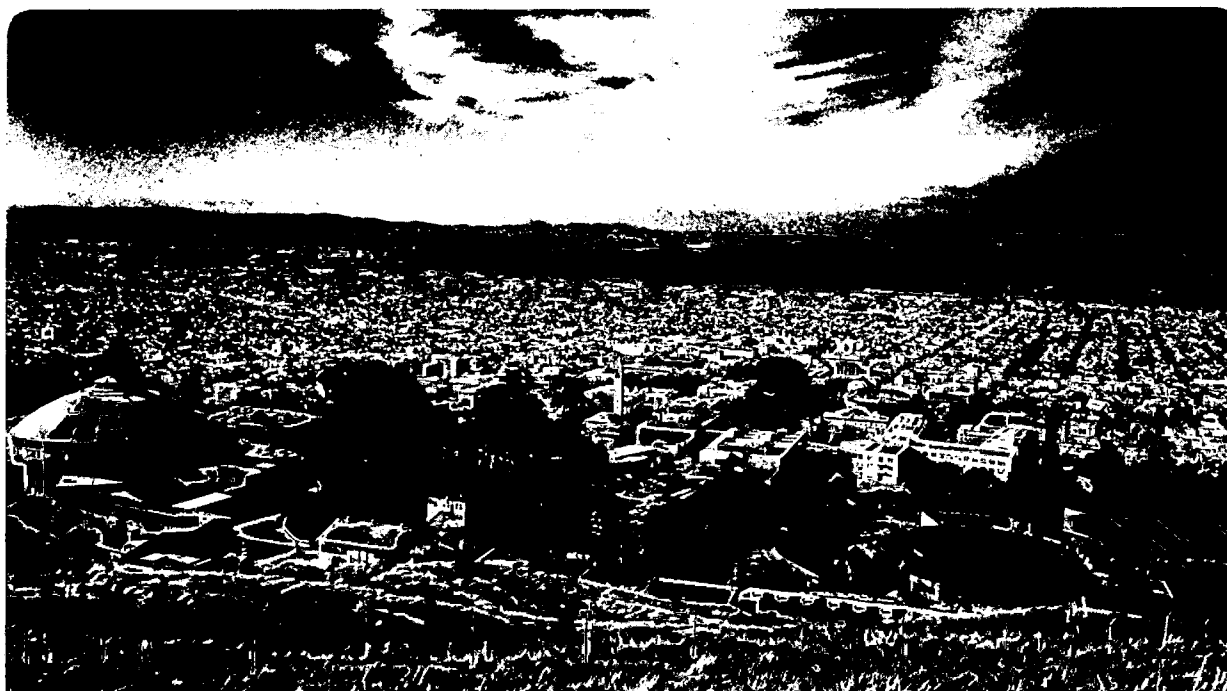
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## Heat Pipe Effects in Nuclear Waste Isolation -- A Review

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## 1. Introduction

The term "heat pipe" is used to describe a variety of man-made or natural systems in which a very efficient heat transfer with small temperature drop is effected by multi-phase convection. The basic ingredients of a heat pipe are (1) a volatile fluid, and (2) a mechanism by which liquid and gas phases can flow in opposite directions, usually capillary action in a porous material (see Figure 1). If heat is injected into such a system, vaporization and pressurization of the gas phase take place, causing gas-phase flow away from the heat source. The gas condenses in cooler regions away from the heat source, depositing its latent heat of vaporization there. This sets up a saturation profile, with liquid phase saturations increasing away from the heat source. In engineered heat pipe systems incorporating porous media, or in drying processes accompanied by heat pipe effects, backflow of the liquid phase towards the heat source is driven by capillary forces. The heat transfer mechanism can be so efficient that effective heat conductivity (ratio of heat flux to temperature gradient) can exceed that of the best metallic heat conductors by factors of several thousand or more [Eastman, 1968].

Heat pipes occur naturally on a large scale (kilometers) in systems known as vapor-dominated geothermal reservoirs [White, Muffler, and Truesdell, 1971; Schubert and Straus, 1979; Pruess, 1985]. In these systems a deep heat source of magmatic origin vaporizes water present in fractured porous rocks. The vapor rises in the fractures, and condenses at shallower depths on the cooler rock surfaces. The downflow of liquid condensate towards the heat source is effected simply by gravitational force. Effective heat conductivity in these systems can be of the order of several hundred  $W/m^{\circ}C$ , whereas heat conductivity of rocks is typically in the range of 1-3  $W/m^{\circ}C$ .

In the context of nuclear waste isolation, heat pipe systems may evolve in the thermal regime near the waste packages. They may have very substantial effects on important aspects of repository performance, including peak temperatures, salinity, and gas content of the fluids near the waste packages, and migration of chemical species.

## 2. Fluid and Heat Transfer in Heat Pipes

In the simplest case the equation governing the steady state of a heat pipe can be written as

$$\mathbf{F}_l + \mathbf{F}_v = 0 \quad (1)$$

expressing the fact that the fluxes of liquid and vapor phase are equal in magnitude and in opposite direction (balanced counterflow). The heat flux associated with the mass fluxes as given in equation (1) is

$$\mathbf{G} = \mathbf{F}_v h_v + \mathbf{F}_l h_l = \mathbf{F}_v h_{vl} \quad (2)$$

where  $h_{vl} = h_v - h_l$  is the vaporization enthalpy (latent heat) of the volatile fluid in the heat pipe. In the context of nuclear waste isolation the fluid is primarily water, but noncondensable gases and dissolvable solids may also be present and impact on heat transfer. We are particularly interested in the transient thermal response as an initially cold rock mass is subjected to a time-dependent heat input from high-level waste packages. To provide a basis for discussing more general heat pipe conditions, we will therefore write mass- and energy-balance equations in time-dependent form, also allowing for the presence of a noncondensable gas.

The basic mass- and energy-balance equations that govern the flow of fluid and heat in permeable media containing water and a noncondensable gas can be expressed as

$$\frac{d}{dt} \int_V M^{(\kappa)} dV = \int_{\Gamma} \mathbf{F}^{(\kappa)} \cdot \mathbf{n} d\Gamma + \int_V Q^{(\kappa)} dV \quad (3)$$

where  $\kappa=1$ : water;  $\kappa=2$ : noncondensable gas;  $\kappa=3$ : heat. The accumulation term on the left-hand-side is balanced by the flux and source terms, the first and second terms on the right-hand-side, respectively. The mass flux terms ( $\kappa=1$  and 2) contain a sum over liquid and gas phases

$$\mathbf{F}^{(\kappa)} = \sum_{\alpha=l,g} \mathbf{F}_{\alpha}^{(\kappa)} \quad (4)$$

where the flux in each phase is

$$\mathbf{F}_{\alpha}^{(\kappa)} = \frac{-kk_{r\alpha}}{\nu_{\alpha}} X_{\alpha}^{(\kappa)} (\nabla P_{\alpha} - \rho_{\alpha} \mathbf{g}) - \delta_{\alpha g} D_{va} \rho_{\alpha} \nabla X_{\alpha}^{(\kappa)} \quad (5)$$

The first term expresses Darcy's law for laminar flow modified for two-phase conditions. The parameter  $k$  is absolute permeability,  $k_{r\alpha}$  is relative permeability of phase  $\alpha$ ,  $\rho_\alpha$  and  $\nu_\alpha$  are density and kinematic viscosity of phase  $\alpha$ ,  $X_\alpha^{(\kappa)}$  is the mass fraction of component ( $\kappa$ ) in phase  $\alpha$ ,  $P_\alpha = P + P_{c\alpha}$  is the pressure in phase  $\alpha$  (sum of a reference-phase pressure and capillary pressure); and  $\mathbf{g}$  is gravitational acceleration. The second term contributes only for gas-phase flow and represents a binary diffusive flux, with  $D_{va}$  the diffusion coefficient for water vapor in the noncondensable gas.

For the steady-state operation of a heat pipe the net mass flux of each component,  $\mathbf{F}^{(1)}$  and  $\mathbf{F}^{(2)}$ , is zero and the heat flux,  $\mathbf{F}^{(3)}$ , is uniform and constant.

For water ( $\kappa=1$ ) equation (4) becomes

$$\mathbf{F}^{(1)} = \mathbf{F}_l^{(1)} + \mathbf{F}_g^{(1)} = 0 \quad (6)$$

Using equation (5) we get

$$\frac{kk_{rl}}{\nu_l} X_l^{(1)} (\nabla P_l - \rho_l \mathbf{g}) + \frac{kk_{rg}}{\nu_g} X_g^{(1)} (\nabla P_g - \rho_g \mathbf{g}) + D_{va} \rho_g \nabla X_g^{(1)} = 0 \quad (7)$$

When the noncondensable gas is air, its solubility in liquid water is very small, so that  $X_l^{(2)} \approx 0$ , which implies that  $X_l^{(1)} \approx 1$ . The  $\nabla P_g$  term describes movement of the vapor away from the heat source. Liquid-vapor counterflow occurs because  $\nabla P_g$  and  $\nabla P_l$  are of opposite sign, due to the capillary pressure contribution to  $P_l$  ( $P_l = P_g + P_c$ ).

For air ( $\kappa=2$ ) the steady state condition becomes

$$\mathbf{F}^{(2)} = \mathbf{F}_l^{(2)} + \mathbf{F}_g^{(2)} = 0 \quad (8)$$

The liquid-phase flow  $\mathbf{F}_l^{(2)}$  is negligible because of the small solubility of air in liquid water, so the gas-phase flow  $\mathbf{F}_g^{(2)}$  must be zero:

$$\frac{kk_{rg}}{\nu_g} X_g^{(2)} (\nabla P_g - \rho_g \mathbf{g}) + D_{va} \rho_g \nabla X_g^{(2)} = 0 \quad (9)$$

The first term represents the advection of air due to pressure gradients and gravity. The pressure

gradient  $\nabla P_g$  describes air movement (along with the water vapor) away from the heat source. This is balanced by the second term, representing diffusion of air into water vapor. Thus the air will be concentrated at the cold end of the heat pipe.

The heat flux ( $\kappa=3$ ) has conductive and convective terms

$$\mathbf{F}^{(3)} = -K \nabla T + \sum_{\kappa=1,2} \sum_{\alpha=l,g} \mathbf{F}_{\alpha}^{(\kappa)} h_{\alpha} \quad (10)$$

where  $K$  is thermal conductivity,  $T$  is temperature, and  $h_{\alpha}$  is the enthalpy of the  $\alpha$  phase. Using (6), (8), and (9), this expression simplifies to

$$\mathbf{F}^{(3)} = -K \nabla T + \mathbf{F}_g^{(1)} h_{gl} \quad (11)$$

The convective transport may be quite large and it occurs at nearly constant temperature, creating the large value of effective heat conductivity typical of heat pipe phenomena.

Several heat pipe-related problems of current interest are outlined below.

1. The presence of a noncondensable gas such as air in a heat pipe diminishes the flow of water vapor, thus limiting convective heat transfer, and effectively shortening the length of the heat pipe.
2. In order to obtain good heat transfer characteristics, the permeability of the heat pipe must be high enough to allow ample vapor flow, but pore sizes must be sufficiently small to obtain strong capillary pressures (inversely proportional to pore size) to drive the liquid counterflow. These two requirements are conveniently met by heterogeneous media. In particular, fractured-porous media provide both high permeability pathways for the vapor flow (the fractures) and a porous wick (the matrix blocks) for the liquid counterflow.
3. Mineral redistribution due to solubility variation with temperature and the precipitation or dissolution associated with phase change may significantly alter the rock, gas, and liquid properties throughout the heat pipe region, thus modifying the vapor and liquid flow pattern.



Several analytical solutions have been developed to describe the steady-state operation of an idealized one-dimensional heat pipe. These solutions involve a number of simplifying assumptions about the heat and mass transfer processes, but elucidate heat pipe behavior. *Ogniewicz and Tien* [1979] and *Udell* [1985] analyze heat flow through a homogeneous porous medium consisting of an isothermal convection-dominated two-phase zone bounded on either end by conduction-dominated pure liquid and pure vapor zones, subject to gravity and capillary forces. Boiling and condensation are assumed to occur at the ends of the two-phase zone only. For horizontal heating and in the limit when gravity is negligible, the product of heat flux  $q$  and the length of the two-phase zone  $x_0$ , known as the wick limit, is constant:

$$qx_0 = \frac{\psi(\beta)(k\phi)^{1/2}\sigma h_{el}}{\nu_g} \quad (12)$$

where  $\phi$  is porosity and  $\sigma$  is vapor-liquid interfacial tension. The parameter  $\psi$  is only a function of the viscosity ratio  $\beta = \nu_l / \nu_g$ . Viscosity is temperature-dependent, but since the temperature of the heat pipe remains nearly constant at the saturation temperature,  $\psi$  is a constant (For 100 °C,  $\beta = 1/70$  and  $\psi = .0368$ ). Equation (12) shows that under these conditions, the length of the heat pipe is inversely proportional to the heat flux through it. Furthermore,  $x_0$  increases as the square root of the medium permeability,  $k$ .

With both capillary forces and gravity influencing a vertical heat pipe, *Ogniewicz and Tien* [1979] and *Udell* [1985] introduce a dimensionless parameter  $\omega$ , the ratio of the vapor pressure gradient to the hydrostatic pressure gradient, which indicates the importance of gravity on heat pipe function. The parameter  $\omega$  is defined by

$$\omega = \frac{q \nu_g}{k h_{el} (\rho_l - \rho_g) g} \quad (13)$$

For values of  $\omega$  greater than about 10, gravity has a negligible effect on the heat pipe. For smaller values of  $\omega$ , gravity effects are significant and orientation with respect to the vertical direction influences heat pipe behavior. Capillary forces drive the liquid flow in the direction of decreasing liquid saturation, so that for heating from above, gravity opposes capillary forces,

while for heating from below, gravity and capillary forces act in concert. Relative to the horizontal heating case, where gravity effects are absent, heat transfer is diminished for the top heating case, while it is increased for the bottom heating case. For a given heat flux, the length of the heat pipe is longer for the bottom heating case and shorter for the top heating case.

For bottom heating, there is a value of  $\omega$  for which gravity-driven liquid flow balances vapor flow. For this value of  $\omega$ , known as  $\omega_{cr}$ , a stable two-phase zone can exist only if capillary forces are zero, implying that the saturation gradient must be zero, and consequently that the two-phase zone is infinitely long. In other words, there is no pure vapor zone at the hot end of the heat pipe. The value of  $\omega_{cr}$  is given by

$$\omega_{cr} = \left( \frac{1}{1+\beta^{1/4}} \right)^4 \quad (14)$$

The corresponding value of  $q_{cr}$  can be found from equation (13), and is known as the critical dry-out flux (the minimum heat flux for which dry-out is possible).

$$q_{cr} = \frac{\omega_{cr} kh_{vl} (\rho_l - \rho_g) g}{\nu_g} = \left( \frac{1}{1+\beta^{1/4}} \right)^4 \frac{kh_{vl} (\rho_l - \rho_g) g}{\nu_g} \quad (15)$$

The functional form of  $\omega_{cr}$  arises from the assumed relative permeability dependence on the third power of saturation. *Hardee and Nilson* [1977] and *Bau and Torrance* [1982] consider similar models, but do not include capillary forces and assume that the relative permeability dependence on saturation is linear. They derive a value of  $\omega_{cr}$  given by

$$\omega_{cr} = \left( \frac{1}{1+\beta^{1/2}} \right)^2 \quad (16)$$

Because capillary forces are not included, for heat flow above the critical dry-out flux a two-phase zone cannot exist, and it is replaced by a dry steam zone. In related studies, *Dhir and Catton* [1977] assume that liquid relative permeability is one and that the vapor is inviscid ( $\nu_g = 0$ ). They obtain a value of  $q_{cr}$  given by

$$q_{cr} = 0.01 \frac{kh_{vl} (\rho_l - \rho_g) g}{\nu_l} \quad (17)$$

The factor of 0.01 is determined empirically.

Studies by *Jennings and Udell* [1985] consider a heterogeneous medium composed of two porous media in parallel with different permeabilities. The two media are assumed to be in local thermodynamic equilibrium, so the capillary pressure at a given location is the same in each medium. Capillary pressure is inversely proportional to effective meniscus radius, resulting in the separation of liquid and vapor into the low and high porosity regions, respectively. The corresponding enhancement of liquid and vapor relative permeabilities allows larger flow rates and thus more efficient heat transfer. Due to the increased complexity of the heterogeneous problem, closed-form solutions for the wick limit  $qx_0$  and the critical dry-out flux  $q_{cr}$  cannot be obtained. However, these parameters can be calculated numerically for specific cases, and are found to be substantially higher than those for a homogeneous system composed entirely of the lower permeability medium.

*Udell and Fitch* [1985] have extended the model of a homogeneous system to include advection and diffusion of a noncondensable gas and thermal conduction. A local Nusselt number, defined as the ratio of the total heat flux to the conductive heat flux, is derived through the use of Kelvin's equation for vapor-pressure lowering and the Clausius-Clapeyron equation, which together define the thermodynamic equilibrium conditions for a liquid-wetting porous medium under two-phase conditions. When the Nusselt number is large, convective heat flow arising from two-phase liquid-vapor counterflow is significant, and nearly isothermal conditions exist. When the Nusselt number decreases to near one, conduction is the dominant heat transfer mechanism, requiring a large temperature gradient. Given a heat flux, gravitational orientation, and system properties, the model predicts the spatial distribution of liquid saturation, temperature, vapor pressure, and molar fraction of the noncondensable gas.

Noncondensable gases are advected toward the cold end of the heat pipe, where molecular diffusion balances advection, as predicted by the form of equation (9). The influence of the noncondensable gases is localized in this region. In the limit of negligible noncondensable gas molar

fractions, the local Nusselt number is proportional to the medium permeability. Conduction must be considered when noncondensable gases are present or for medium permeabilities less than  $10^{-12} \text{ m}^2$ . In general, conduction increases the length of the two-phase zone. When heat conduction or temperature-dependent fluid properties are taken into account, then boiling and condensation will not only occur at the ends of the two-phase zone, but will be distributed throughout. Gravitational forces have a negligible effect on the noncondensable gas distribution.

An alternative conceptual model for the steady state behavior of a one-dimensional porous heat pipe has been developed by *Gomaa* [1973], in conjunction with experimental studies. In this model evaporation and condensation rates are prescribed along the length of the heat pipe, rather than arising as a result of the calculation as in the previous model. The evaporation rate decreases linearly from a maximum value at the hot end of the heat pipe to zero at the middle, while the condensation rate increases linearly from zero at the middle, to the same maximum value at the cold end. The entire length of the heat pipe is partially saturated with both liquid and vapor phases, and the two end temperatures of the heat pipe are held fixed. The key result of the experimental studies is the component of the effective thermal conductivity arising from the heat pipe effect, known as  $K_{hp}$ , which is given by

$$K_{hp} = \frac{\bar{F} h_{sl} x_0}{\Delta T (1 - \phi \bar{S}_v)} \quad (18)$$

where  $\bar{F}$  is the average mass flow rate of vapor or liquid over the length of the heat pipe ( $x_0$ ),  $\Delta T$  is the temperature difference between the hot and cold ends of the heat pipe, and  $\bar{S}_v$  is the average vapor saturation. The experimental measurement of  $K_{hp}$ , and use of equation (18) determine  $\bar{F}$ , which depends on the relative permeability and capillary pressure functions. A statistical analysis of the experimental results indicates that  $K_{hp}$  depends, in decreasing order of importance, on the following parameters

1)  $k$  and  $\phi$  or  $(k \phi)$

2)  $h_{vl}$

3)  $\bar{S}_l$  (average liquid saturation)

4)  $\sqrt{\frac{k_{rl} k_{rv}}{\nu_l \nu_v}}$

5)  $\frac{dP_c}{dS_l}$

6)  $\sin \theta$  ( $\theta$  is the angle of the heat pipe with respect to the vertical)

Numerical models can be used to complement the analytical solutions by studying the transient development of heat pipes, as well as examining the impact of the simplifying assumptions used in the analytical solutions. At present there are several sophisticated numerical models that consider the thermohydrological processes taking place in porous heat pipes [Travis, 1983; Pruess, 1984; Bizler, 1985], and other models that consider mineral redistribution [Braithwaite and Nimick, 1984; Verma and Pruess, 1985], but the complete coupling of all processes occurring in a porous heat pipe has yet to be implemented in a single mathematical model.

### 3. Issues in Nuclear Waste Isolation

The heat generated by a nuclear waste repository provides a potential energy source for a heat pipe and saturated or partially saturated, possibly fractured rock surrounding the repository may be an appropriate heat pipe medium. Whether or not a heat pipe is likely to develop for given repository conditions is of major importance in predicting the overall behavior of the repository. The wick limit and critical dry-out flux can give a general indication of the likelihood of heat pipe development in a specific repository environment, but for detailed predictions mathematical models which can represent fluid and formation properties in more realistic detail are needed.

Studies of vapor-dominated geothermal reservoirs [Pruess, 1985] indicate that several geological conditions are necessary for the existence of a heat pipe. If the heat pipe region lies below the water table, it must be sealed laterally to prevent the inflow of liquid water from surrounding higher pressure regions. The presence of fractures is necessary to provide high permeability paths for vapor flow. If the matrix permeability is too low to allow sufficient liquid flow through the matrix to balance vapor flow, then the liquid in the fractures must be mobile, requiring that liquid saturation in the matrix be high enough (and capillary forces correspondingly low), to allow sufficient liquid to remain in the fractures to be mobile.

We do not expect heat pipe effects to play a role in nuclear waste repositories in saturated rock. Studies by *Pruess and Bodvarsson* [1982] for the Basalt Waste Isolation Project have indicated that boiling conditions with two-phase flow are confined to the immediate vicinity (a few centimeters) of the waste package emplacement hole. No heat pipe mechanism was observed in this study, because of the absence of a driving force for vapor away from the heat source. Ambient pore pressure was high (130 bars), so that flow of both liquid and vapor phases was toward the low-pressure region around the canisters (assumed to have been emplaced open-hole at  $P=1$  bar). It appears that, generally speaking, ambient pore pressures in repository host formations below the water table will exceed the maximum vapor pressures expected near the waste packages. Therefore, zones with boiling conditions will be of very limited extent, if they form at all. Furthermore, prior to resaturation vapor will tend to flow towards the pressure sinks at the waste packages rather than away from the them, precluding development of a two-phase counterflow pattern.

The situation is entirely different for a waste repository in partially saturated rock, where ambient pore pressure is near 1 bar. Under these conditions, heat pipe development is quite probable, and has been observed in a number of studies (see Section 4).

The primary desirable effect of a heat pipe region around a repository is the great amount of heat that can be transferred away from the vicinity of the repository without a large temperature

increase. The temperature of a heat pipe remains near the saturation temperature for the prevailing pressure. For a repository in a partially saturated formation with "sufficient" gas phase permeability this condition is atmospheric pressure and 100°C. A low maximum temperature, as well as a small temperature gradient, helps maintain the integrity of the rock surrounding the waste canister by minimizing thermal expansion effects. In general, canister corrosion proceeds more slowly at lower temperature. Additionally, some relevant material properties and thermodynamic data are poorly known for the high temperatures that may develop around a repository with conduction-dominated heat transfer, but are well known at lower temperatures, allowing more confident predictions to be made for repository behavior. The concentration of air and liquid water at the cold end of the heat pipe, away from the canisters, lessens the likelihood of corrosion. The liquid flow toward the canister further inhibits outward transport of liquid-dissolved wastes (e.g., actinides), although the gas phase may transport droplets of liquid as an aerosol and volatile components of the waste (e.g.,  $^{14}\text{C}$ ,  $^3\text{H}$ ,  $^{85}\text{Kr}$ ,  $^{129}\text{I}$ ) away from the repository [Evans, 1983].

If a dry steam zone develops at the hot end of the heat pipe, it is accompanied by a large temperature increase as conduction becomes the dominant mode of heat transfer. The absence of liquid water changes the chemical environment of the waste packages. In particular, corrosion of canisters is greatly lessened. In addition to ordinary diffusion, gaseous ionized waste components may be transported through a dry steam zone by forced diffusion, due to an electric field created via the Compton effect by gamma radiation [Green *et al.*, 1985].

Mineral redistribution can play a major role in the development of a heat pipe around a repository. Evaporation at the hot end of the heat pipe causes precipitation of dissolved minerals, while condensation at the cold end causes dissolution of minerals. The temperature, salinity, and pH dependences of mineral solubility may reinforce or counteract this process. Laboratory experiments by Bau and Torrance [1982] exhibited formation of a dry steam zone with temperature up to 120°C adjacent to the heat source when a low permeability zone developed due to  $\text{CaSO}_4$  and

CaCO<sub>3</sub> precipitation. By adding a buffering solution of pH 7, precipitation was eliminated, no dry steam zone formed, and system temperature did not exceed 100 ° C.

Extensive dissolution of rock minerals may threaten the structural integrity of the rock. Extensive precipitation may also be hazardous, decreasing permeability to the point where steam cannot flow away from the repository, leading to pressure increases and possible hydrofracturing of the rock. Precipitation adjacent to the canisters may inhibit corrosion. The effect of precipitation on porosity is straightforward given the mass and density of the precipitate, but the relationship between porosity and permeability is complex, and differs greatly between fractures and porous media [Verma and Pruess, 1985]. Experimental results on granite [Vaughan, 1985] show that for a porosity decrease of 8%, permeability decreases 96%, while uniform deposition of silica predicts a decrease of only 26%. Furthermore, not only are the equilibrium solubilities of minerals necessary for understanding heat pipe behavior, but reaction kinetics may be important as well. Thus the net effect of mineral redistribution is difficult to anticipate without detailed modeling studies.

Knowledge of a number of relevant physical and chemical properties of fractured rocks is far from complete. Laboratory experiments have been done to determine relative permeability and capillary pressure variations with liquid saturation, and kinetics of silica dissolution and precipitation, but the extrapolation from laboratory experiments involving small-scale samples to field settings is definitely nontrivial.

#### **4. Heat Pipe Studies in Nuclear Waste Isolation**

Most often, nuclear waste isolation studies only consider conductive heat transfer. A number of authors do include convective heat transfer, but only allow liquid-phase flow. In a few cases, vapor is present but liquid is assumed to be immobile or absent, or capillary forces are ignored. None of these scenarios is conducive to the development of a heat pipe around a repository. A few recent papers have considered heat pipe effects specifically in nuclear waste isolation



modeling studies. Several other authors have studied heat pipes theoretically or experimentally, and some of their findings have interesting applications to nuclear waste isolation.

*Pruess and Wang [1984]* have employed a numerical model for nonisothermal flow of water, vapor, and air in permeable media to study the thermohydrological conditions in the near vicinity of high-level nuclear waste packages emplaced in a partially saturated porous medium. The study specifically addresses the question of whether or not the waste canister environment will dry up. In the basic calculation using typical parameters, a dry environment develops around the canister. Parameter sensitivity studies show that a stronger capillary pressure force or a higher intrinsic permeability creates a wet environment, in which a dry steam zone does not develop. A high intrinsic permeability with a low relative liquid permeability results in a dry environment. Of critical importance for the drying behavior are capillary pressures and relative permeabilities in the vicinity of the residual liquid saturation, which are poorly known at present. Laboratory and field experimentation is needed to quantify these parameters. The vaporization process taking place near the canisters purges air from the canister vicinity, creating an environment free of gaseous oxygen.

*Pruess, Tsang, and Wang [1984]* have done numerical modeling studies of high-level nuclear waste packages emplaced in partially saturated fractured tuff. The studies are generic rather than site-specific, but use material properties typical of those at the Nevada Test Site. Both discrete fractures and the porous matrix are modeled, and the sensitivity of the system to the relative permeability function is studied. The initial state of the system when the canisters are emplaced includes a high liquid saturation (80%) in the porous matrix, and a low liquid saturation (1 to 3%) in the fractures. A key feature determining system behavior is whether the liquid in the fractures is initially mobile or not. If the liquid in the fractures is initially immobile, outflow of vapor in the fractures exceeds inflow of liquid. A transient heat pipe process is observed, with very large effective heat conductivity across a zone of vapor-liquid counterflow. However, because the counterflow is not balanced, the rock near the waste package dries up while the counterflow

region expands to larger distance. As time progresses the heat pipe region moves outward from the waste packages. If the liquid in the fractures is initially mobile, outflow of vapor can be balanced by inflow of liquid, resulting in a stable heat pipe, with no dry steam zone around the waste canister.

Additionally, an equivalent continuum model is developed which makes use of a generalized relative permeability concept to account for fracture effects. This results in a substantial simplification of the flow problem which makes larger scale modeling of complicated systems feasible. However, only certain aspects of the thermohydrologic response can be modeled with the continuum model. The temperature, pressure, saturation, and fluid flow fields can be represented. However a single continuum gives only a single velocity field, which will either underestimate flow velocities in the fractures or overestimate flow velocities in the matrix. Furthermore, no description of interflow between fractures and matrix is made in the single continuum model.

Both the above studies and the various analytical formulations referred to in Section 2 show the importance of relative permeability and capillary pressure dependence on saturation, and indicate the present uncertainty in the values appropriate for repository media. Laboratory experiments are planned [Eaton *et al.*, 1985] to examine these material properties for samples of welded tuff from the Topopah Spring formation at the Nevada Test Site. Numerical modeling using the code NORIA [Bixler, 1985] has been done to aid in determination of optimal experimental conditions. Results of the modeling studies show that heat pipe characteristics such as saturation distribution (including dry-out) and length of transient period are strongly dependent on the initial saturation of the sample and the imposed temperature difference.

## 5. Conclusions

From the above discussion, it is apparent that the existence of fractures favors heat pipe development, as does a partially saturated medium. A number of geologic media are being considered as potential repository sites. Tuff is partially saturated and fractured, basalt and granite

are saturated and fractured, salt is unfractured and saturated. Thus the most likely conditions for heat pipe formation occur in tuff while the least likely occur in salt. The relative permeability and capillary pressure dependences on saturation are of critical importance for predicting thermohydraulic behavior around a repository. Mineral redistribution in heat pipe systems near high-level waste packages emplaced in partially saturated formations may significantly affect fluid flow and heat transfer processes, and the chemical environment of the packages. We believe that a combined laboratory, field, and theoretical effort will be needed to identify the relevant physical and chemical processes, and the specific parameters applicable to a particular site.

## 6. Nomenclature

$D_{va}$	Binary diffusion coefficient for water vapor and air ( $m^2/s$ )
$F$	Mass flux ( $kg/m^2s$ )
$\bar{F}$	Average mass flux ( $kg/m^2s$ )
$G$	Convective heat flux ( $W/m^2$ )
$g$	Gravitational acceleration ( $m/s^2$ )
$h_{vl}$	Vaporization enthalpy ( $J/kg$ )
$K$	Thermal conductivity ( $W/mK$ )
$K_{hp}$	Thermal conductivity due to heat pipe effect ( $W/mK$ )
$k$	Intrinsic permeability ( $m^2$ )
$k_{r\alpha}$	Relative permeability of phase $\alpha$
$P$	Pressure ( $N/m^2$ )
$P_c$	Capillary pressure ( $N/m^2$ )
$q$	Heat flux ( $W/m^2$ )
$q_{cr}$	Critical heat flux corresponding to $\omega_{cr}$ ( $W/m^2$ )
$S$	Saturation
$\bar{S}$	Average saturation

- $T$  Temperature (K)
- $\Delta T$  Temperature difference (K)
- $t$  time (s)
- $X$  Mass fraction
- $x_0$  Length of two-phase (heat pipe) zone (m)
- $\beta$  Liquid-gas viscosity ratio
- $\theta$  Angle of heat pipe with respect to vertical (rad)
- $\nu$  Kinematic viscosity ( $\text{m}^2/\text{s}$ )
- $\rho$  Density ( $\text{kg}/\text{m}^3$ )
- $\sigma$  Vapor-liquid interfacial tension (N/m)
- $\phi$  Porosity
- $\psi$  Parameter in wick limit
- $\omega$  Parameter indicating the importance of gravity in heat pipe behavior
- $\omega_{cr}$  Critical value of  $\omega$  below which no two-phase zone forms

**Subscripts**

- $l$  Liquid
- $g$  Gas
- $v$  Vapor
- $\alpha$  Phase

**Superscripts**

- ( $\kappa$ ) Component
- (1) Water
- (2) Air
- (3) Heat

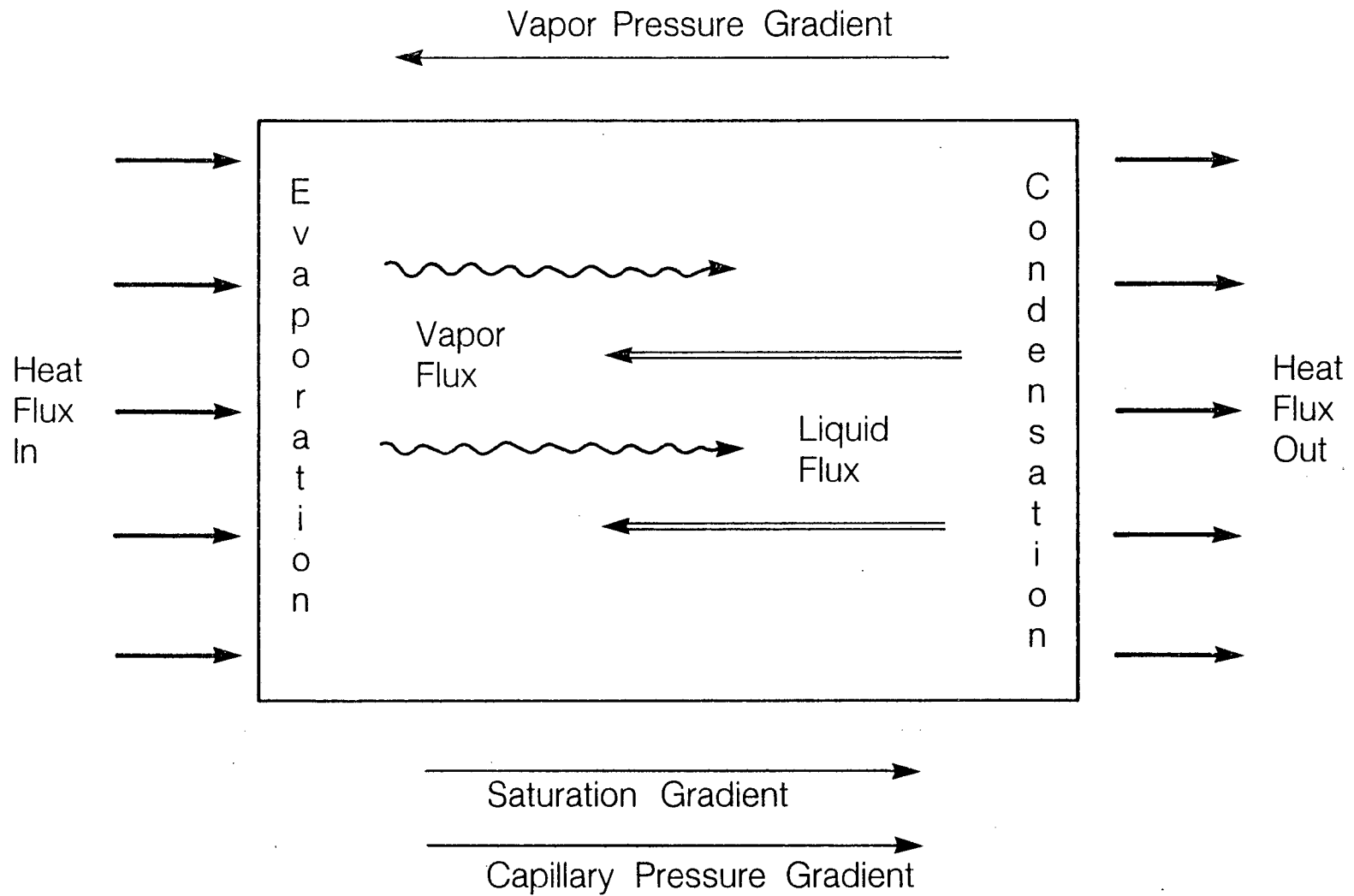
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Figure 1. Schematic diagram of a porous heat pipe, after *Jennings* [1984].

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