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Author
Wang, J.S.Y.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA, BERKELEY

EARTH SCIENCES DIVISION

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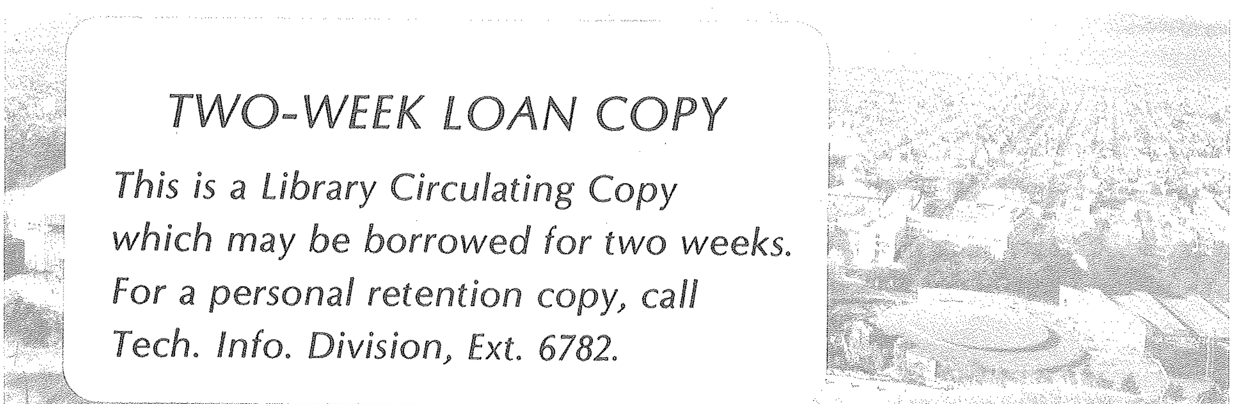

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DISCLAIMER

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J. S. Y. Wang and C. F. Tsang

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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INTRODUCTION

The principal mechanism for underground migration of radionuclides is transport with groundwater. In the selection and assessment of suitable sites as potential repositories of nuclear wastes, it is important to predict the effects of heat generated by the wastes upon the water movement between the repository and the biosphere. With the absence of relevant engineering experience and the limitation on duration of in-situ testings, simulation of global and long-term thermal responses of the rock mass in hypothetical models is the main method for the understanding of the mechanism and the identification of the sensitive parameters controlling groundwater flow. This paper presents results of two sets of calculations: 1) Regional temperature effects are studied for different waste forms, repository dimensions and rock formations. The type of reprocessing treatment and the length of cooling period of the nuclear wastes before emplacement into the repository are found to be two of the more important factors. 2) Thermally induced fluid flow is calculated assuming a simple two-fracture system to make a "worst case" estimate of the transit time of water from repository to ground surface. Recharge capacity from the surrounding formation is found to be a controlling factor.

TEMPERATURE FIELD

To study the long term regional changes in temperature in the rock mass the repository is idealized to be a flat circular disk loaded uniformly with nuclear wastes at time $t=0$. The repository is assumed to be at a depth $D = 500$ m below surface in granite and to have a radius $R = 1500$ m. The principal mode of heat transfer in the rock mass is assumed to be by heat conduction. This has been shown to be a good assumption based on recent Stripa data analysis (Hood, 1979). The temperature rise is calculated by integrating the instantaneous disk source function (Carslaw and Jaeger, 1959) over the heat power function of the nuclear wastes (Kisner et al., 1977). The presence of a boundary of constant temperature at the ground surface is corrected by the method of image. The thermal diffusivity for granite is assumed to be 1.15×10^{-6} m^2/sec and the thermal conductivity is 2.5 W/m/^{o}C.

The temperature changes are proportional to the waste density, or equivalently the initial power density with which the repository is loaded. Besides this simple proportionality, the temperature field, especially the long term behavior, is sensitive to the decay characteristics of the heat power functions of the wastes. The time dependence in power is determined by the waste composition. The nuclear wastes contain short-lived fission products and the long-lived actinides. The fission products generate most of the heat at early life of the wastes and decay rapidly after discharge from the reactor. Accordingly, the effects of a period of near surface cooling of the wastes before burial in a repository may be expected to be significant. Figure 1 illustrates the effects of pre-emplacement surface-cooling times of spent fuel discharged from a pressurized water reactor on the repository temperatures. Although the temperature rises are calculated on a uniformly loaded model, it can be concluded from these results that the period for which the wastes are cooled before emplacement is an important factor in determining the thermal effects.

Figure 1 also indicates that the temperature at the repository reaches a maximum after a period of less than 100 years and thereafter decays very slowly over a period of thousands of years. After 100 years, most of the fission products have decayed and the actinides and their daughters are the main heat source. Therefore, the reprocessing treatment of spent fuel to recover the uranium and plutonium may affect the long term thermal field significantly. To study the far field effects and, in particular, those at the surface, the maximum temperature gradient at the epicenter above the repository has been calcualted for a variety of conditions (Wang et al., 1979). Figure 2 shows the large differences in surface gradient between the spent fuel and the reprocessed wastes for a number of different rock formations. Either form of the wastes is assumed to be buried 10 years after discharge from the reactor at an initial loading density in the repository of 10 W/m^2. With the same initial power density, the accumulated heat generated by the spent fuel is much larger than the reprocessed wastes. From Figure 2, it can also be seen that very different thermal fields are expected for different rock formations.

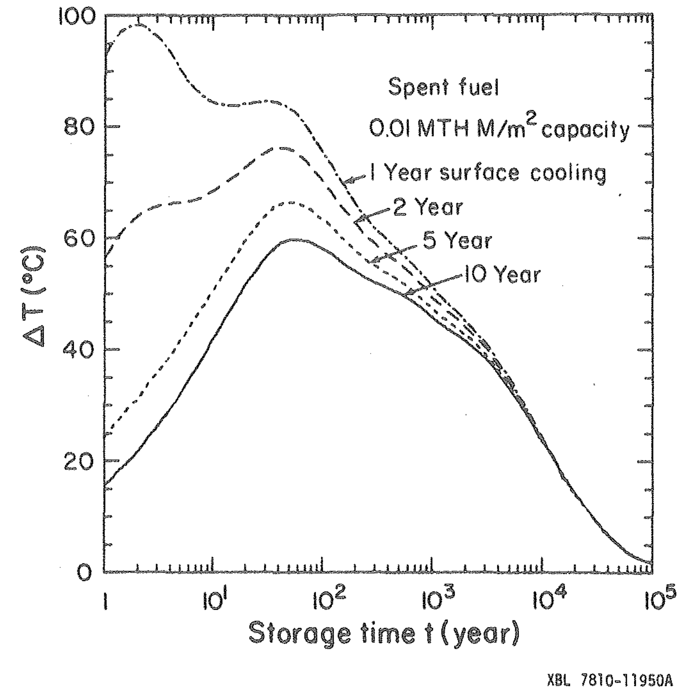

Figure 1. Effects of Surface Cooling on the Repository Temperature with Waste Density of 0.01 Metric Ton of Uranium per m^2.

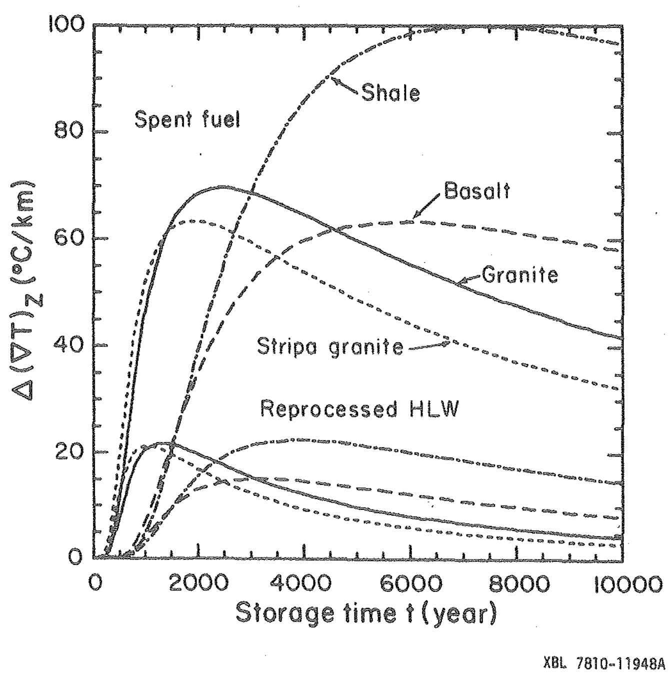

Figure 2. Effects of Waste Types and Rock Formations on the Ground Surface Thermal Grandient with Initial Power Density of 10 W/m^2.

BUOYANT FLOW IN TWO-FRACTURE MODEL

Variations in the temperature of the rock mass cause changes in the density and viscosity of water in the rock fracture system and induce buoyant flows. The permeability of many crystalline and argillaceous rocks arises mainly from the hydraulic conductivity of fractures. The concern on fracture flow is related to the important question of the possibility of waste components being carried by the fracture water from the repository to the surface. Porous medium models representing fractured rock mass with multiple fracture sets have been used in generic studies of granitic formation (e.g., KBS, 1977). For this paper, a simple model is used that comprises a horizontal fracture at the depth of repository connecting a recharge zone to the repository, which is also connected to a discharge zone in the opposite direction, and intersecting a vertical fracture from the center of the repository to the surface as shown in Figure 3. Before the repository is loaded and the rock mass subjected to changes in temperature, it is assumed that the original groundwater flow is horizontal from recharge zone to discharge zone. As the rock temperature increases, the water initially at the depth of the repository will move upward in the vertical fracture by the buoyancy forces.

From Darcy's law and Boussinesq approximation, the one-dimensional flows within the fractures can be derived (Wang et al.,1979). The recharge and discharge zones are assumed to be far away from the repository and they are maintained at normal hydrostatic pressure and ambient temperature. Before the emplacement of wastes,

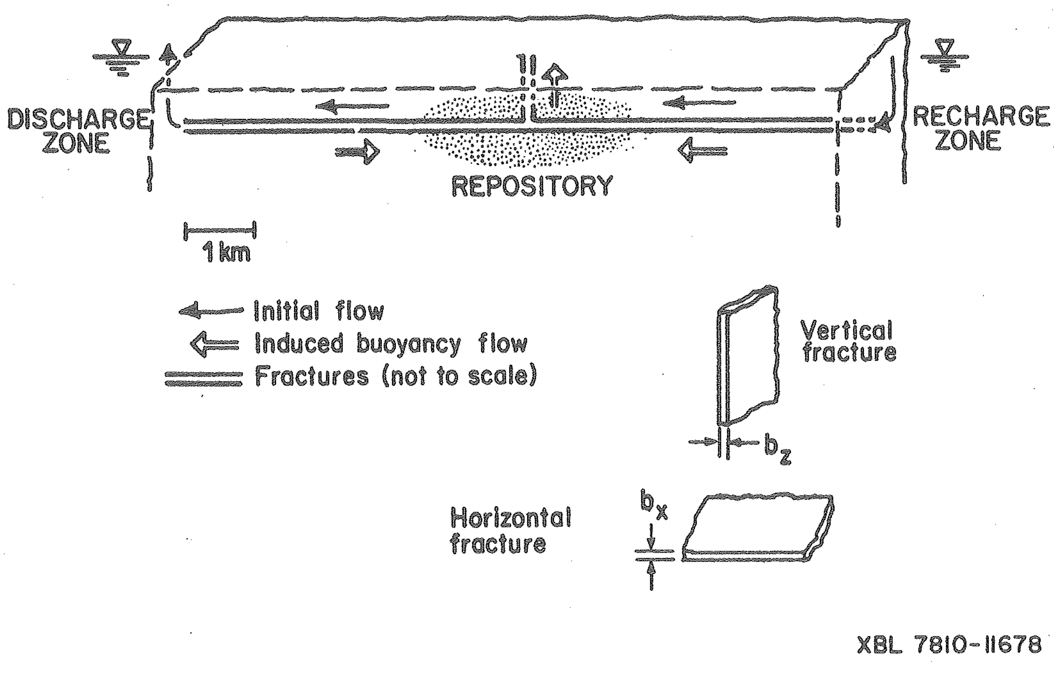

Figure 3. Two-Fracture Model for Simulating Buoyant Flow.

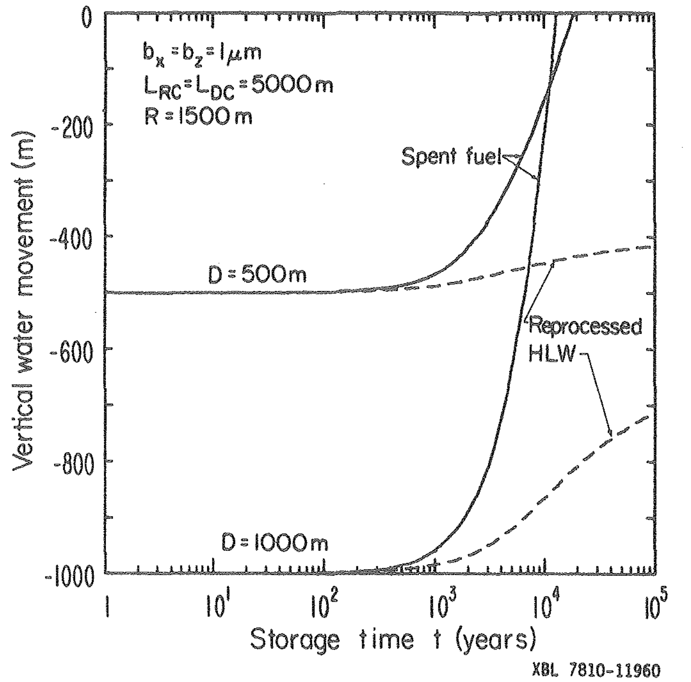

Figure 4. Effects of Waste Types and Repository Depths on the Water Movement along the Vertical Fracture.

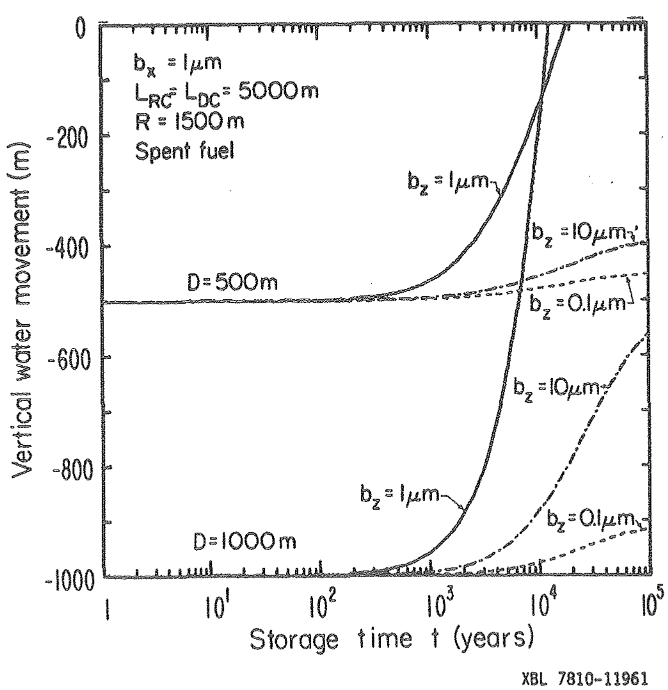

Figure 5. Effects of Vertical Fracture Apertures on the Water Movement along the Vertical Fracture.

an ambient temperature field of 20°C at ground surface and a normal geothermal gradient of 30°C/km is assumed. The buoyancy force is proportional to the density contrast between the heated water in the vertical fracture and the cooled water in the recharge and discharge zones. The large difference in the long-term temperature fields between spent fuel and reprocessed waste results in large difference in the vertical flow as illustrated in Figure 4. In Figure 4, the upward movement of water initially at the depth of the repository is plotted as a function of time. The results in two cases, one with the repository at a depth of 500 m and the other at a depth of 1000 m are compared. There is little difference due to the change in depth. Essentially the flow of water as a result of buoyancy depends upon the average temperature of the water throughout the length of the vertical fracture. The more important factor affecting the buoyant flow of groundwater is the ratio between the distance L from repository to the recharge zone and the depth D of the repository. For the particular case illustrated in Figure 4, the repository is assumed to be located a distance, L = 5000 m, midway between the recharge and distance zone. The vertical and horizontal fractures are assumed to have the same aperture $b_z = b_x = 1$ μm.

In addition to the temperature change and hydrologic connecting distances L and D, the buoyant flow depends sensitively on the apertures and permeabilities of the fractures. For a fracture with aperture b, the permeability $k = b^2/12$ for laminar fracture flow is assumed (Lamb, 1932; Witherspoon et al., 1979) in the calculation. If the horizontal fracture representing the recharge path from the surrounding formation has a given finite aperture, the dependence of the buoyant flow on the vertical aperture is of great interest. In Figure 5, the results with a constant horizontal aperture b_x = 1 μm and with a range of vertical apertures b_z = 10 μm, 1 μm and 0.1 μm are shown. The movement of the groundwater in the vertical fracture is significantly slower both for the case of $b_z = 10\ b_x$ and of $b_z = 0.1\ b_x$ than with $b_z = b_x$. For nonzero distance L and a finite horizontal aperture b_x, the buoyant flow does not become infinite as the vertical fracture aperture b_z increases. On the contrary, the buoyancy flow decreases as b_z increases. This can be easily explained by the fact that a large vertical fracture with storage capacity reduces fluid flow velocity. Thus the buoyant flow in the vertical fracture is controlled by the finite recharge capacity through the horizontal fracture.

DISCUSSION AND CONCLUSION

Although the thermo-hydrologic models used for the analysis presented in this paper are very simple, they should possess the same physical behavior as that of the more complex repository systems. Accordingly, it should provide a good insight into the dynamics of the thermally-induced groundwater flow, and illustrate the sensitivity of this flow to various parameters. The actual numerical results should be considered as no more than an order of magnitude estimations. It must be pointed out also that the transport of nuclides does not take place at the same rate as that of the groundwater. Nuclide transport is retarded in a certain degree by various physical and chemical processes, such as sorption.

The calculations reported in this paper suggest that the magnitude of the thermally-induced buoyant groundwater flow carrying toxic wastes from a repository to the biosphere depends upon many factors. Of these, the aggregate increase in the temperature of the rock mass containing the repository is one of the most important. This temperature is affected by the design of the repository, the kind of nuclear waste buried in it and the period for which this waste has been cooled near surface before burial. Significant differences exist between reprocessed waste and spent fuel in respect of the degree to which the rock mass is heated and hence the time taken for groundwater to reach the surface by buoyant flow. The thermal conductivity of different kinds of rocks has a significant effect on buoyant groundwater flow also. Finally, the bouyant groundwater flow also depends strongly upon the ratio of the hydraulic transmissivities of the vertical and horizontal fractures.

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