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Hydrological and Thermal Issues Concerning a Nuclear Waste Repository in Fractured Rocks

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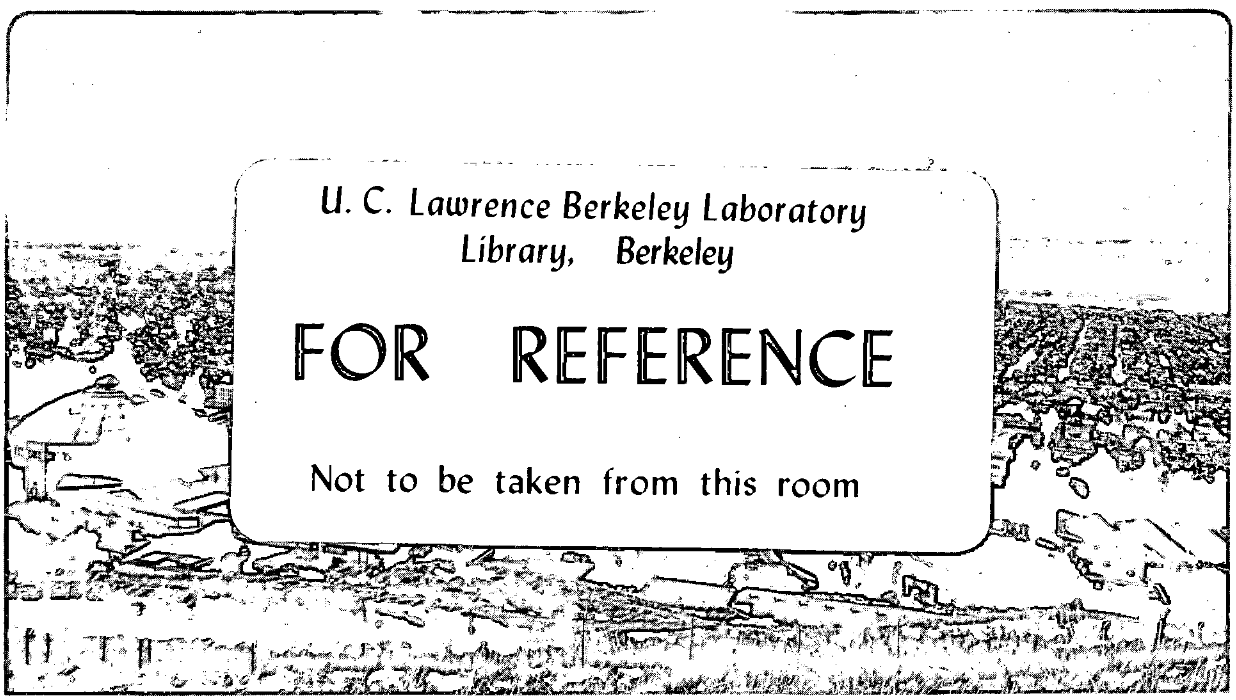

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Abstract

The characterization of the ambient conditions of a potential site and the assessment of the perturbations induced by a nuclear waste repository require hydrological and thermal investigations of the geological formations at different spatial and temporal scales. For high-level wastes, the near-field impacts depend on the heat power of waste packages and the far-field long-term perturbations depend on the cumulative heat released by the emplaced wastes. Surface interim storage of wastes for several decades could lower the near-field impacts but would have relatively small long-term effects if spent fuels were the waste forms for the repository. One major uncertainty in the assessment of repository impacts is from the variation of hydrological properties in heterogeneous media, including the effects of fractures as high-permeability flow paths for contaminant migration. Under stress, a natural fracture cannot be represented by the parallel plate model. The rock surface roughness, the contact area, and the saturation state in the rock matrix could significantly change the fracture flow. In recent years, the concern of fast flow through fractures in saturated media has extended to the unsaturated zones. The interactions at different scales between fractures and matrix, between fractured units and porous units, and between formations and faults are discussed.

Introduction

Site characterization, performance assessment, and repository design for underground disposal of nuclear wastes have motivated many recent studies in earth sciences. Granite, salt, basalt, tuff, and other geological media are being considered in different countries as host formations for nuclear waste repositories. Generic evaluations of the processes and mechanisms and site-specfic investigations of the medium properties and environmental impacts are needed to address scientific and engineering issues associated with geological disposal of nuclear wastes. This paper reviews several hydrological and thermal effects around a repository in fractured rocks. The granite and basalt studies since the late 1970's and the tuff studies in the 1980's have identified fracture flow and transport as one of the major technical challenges in assessing the suitability of hard rock media for nuclear waste repositories.

Thermal Effects

High-level nuclear wastes are composed of two main components: fission products (such as ^{90}Sr and ^{137}Cs) and transuranic actinides (such as Pu, Am, and Cm). For the first few hundred years, the fission products are the principal contributors to the decay heat generation. This fission product activitity is largely independent of the fuel mix and fuel cycle. After the decay of fission products, the relatively long-lived heavy transuranic actinides and their daughters control the heat generation of the wastes. However, the quantities of actinides vary widely according to the fuel cycle. Figure 1 illustrates the sensitivity of the decay heat power on the content of long-lived actinides which depends on different assumptions of fuel mix, reactor burnup, and reprocessing treatment. Spent fuel, with irradiated fuel assemblies treated as wastes after being removed from the reactor, contains both uranium and plutonium as waste components. The uranium-only recycle is from reprocessing of spent fuel to recover most of the uranium and plutonium, with the uranium recycled for further use as fuel. The uranium and plutonium recycle is from reprocessing of fuel assemblies in reactors with a 1:3 blend of mixed oxide (UO_2 and PuO_2) fuel and fresh UO_2 fuel. With effectively more extensive burnup in a mixed oxide cycle, the trace amounts of uranium and plutonium remaining in the reprocessed waste are higher than those in the uranium-only recycle. The wastes in Figure 1 all originate from the same amount of fuel, 1 metric ton of heavy metal U (MTHM), charged to a pressurized water reactor.

The individual spent fuel canister usually contains one fuel assembly. For a pressurized water reactor in the United States, the waste content of one fuel assembly is 0.4614 MTHM. If the canister is stored on the surface for 10 yr before emplacing in a repository, the corresponding heat power is 0.55 kW/canister (Kisner et al., 1978). For a boiling water reactor, the corresponding values are 0.1833 MTHM and 0.18 kW/canister. For reprocessed high-level waste, the waste content in each canister can be controlled in the reprocessing process. Indeed, the maximum canister load is a design parameter that can be determined by a very-near-field thermal criterion. For 10-yr-old wastes, the emplacement heat-power values of 1 to 5 kW/canister have been used in different studies (Callahan et al., 1975; Environmental Protection Agency, 1977; Reference Repository Conditions Interface Working Group, 1984).

Figure 2 illustrates the simulated tempertures in the vicinity of a 3.051 kW canister which is emplaced in fractured tuff under partially saturated conditions (Pruess and Wang, 1987; Pruess et al., 1990). If the vicinity of the waste package dries up and conduction is the dominant heat transfer mechanism, the temperature can reach 250°C. However, the system behavior is completely different if liquid is assumed to be mobile in the fractures. In that case, the liquid condensate in the outer, cooler region can move along fracture walls back toward the heat source. With the establishment of a balanced counterflow, in which outflow of vapor is balanced by backflow of liquid condensate, the vicinity of the waste package will not dry up and the temperature remains near 100°C, the boiling temperature at ambient pressure. These simulation results indicate that the near-field thermal impacts can be sensitive to the relative mobility (permeability) of the fluid phases in fractures under partially saturated conditions.

A repository is expected to have the capacity to receive 70,000 MTHM of wastes which is equivalent to over 150,000 spent fuel canisters from pressurized water reactors. Figure 3 illustrates the dependence of repository temperature rise on rock type, with temperature represents the areally averaged value. The waste density is assumed to be 0.0083 MTHM/m^2, which corresponds to the thermal loading of 10 W/m^2 (40 kW/acre) for 10-yr-old spent fuel. The relative insensitivity of repository temperature rise and far-field temperature field to different rock types has stemmed from the similiarities among the thermal properties (thermal conductivity and especially heat capacity) of different rocks.

Figure 4a illustrates the dependence of the repository temperature rise on the surface cooling period if the spent fuel waste density is held fixed at 0.0083 MTHM/m^2. The waste ages arriving at a repository depend on the repository startup date, the repository receiving capacity, and the backlog of wastes. With repository startup at 2010, most of the spent fuel received by the repository will be much older than 10 yr. Each curve in Figure 4a has several peaks or bumps at different times. The short time features diminish rapidly with longer surface cooling periods. These earlier peaks originate from short-lived radionuclides. The long-lived actinides control the long-term thermal impacts. Although the surface cooling periods change the peak temperature rise, the spent fuel repository will nevertheless have a significant rise above the ambient temperature for over 10^4 yr, even for a surface cooling period of 100 yr. If reprocessed waste instead of spent fuel is stored with the same waste density, the extension of surface cooling period from 10 yr to 100 yr can lower the repository temperature much more effectively, as shown in Figure 4b. Reprocessed waste has most of its long-lived actinides removed, and the repository temperature can therefore return to ambient much faster. Figure 5 compares the cumulative heat released by the wastes with different cooling periods. Wang et al. (1988a) discussed the different loading schemes for aged wastes.

The temperture rise in the rock formation can induce uplift of ground surface and buoyancy flow in the groundwater. The repository represents a heat source of finite size embedded in the host rock. The thermal expansion of the rock matrix could close and open fractures in different regions in the surrounding formations. The mass density contrast between the hot water in the repository vicinity and the ambient cold water away from the repository causes thermally induced convection cells to form. Figure 6 illustrates convective movements of groundwater in an extended vertical fracture through a spent fuel repository 1,000 yr after waste emplacement. The repository is idealized as a disk, 3,000 m in diameter and 500 m below ground surface in a granite formation. Before waste emplacement, the ambient groundwater field is assumed to be nearly horizontal, driven by a regional gradient of 0.001 m/m, as represented by the horizontal vector $\vec{v}_0$ above the ground surface in Figure 6.

The thermally induced buoyancy flow greatly distorts the ambient flow field in this highly idealized model. At 1,000 yr in this model, the sizes of the convection cells are of the same order as the depth of the repository. At much earlier times, the cells are localized in the regions of high temperature gradients in the immediate vicinity of the repository. The buoyancy flow and the convection cells grow as the cumulative heat increases in the rock formation. These thermo-hydrological perturbations will eventually disappear when the heat escapes through the ground surface and the rock returns to its original temperature, tens of thousands of years after waste emplacement. For reprocessed waste, the corresponding long-term perturbations are smaller than those induced by the same amount of spent fuel. If the rock formation is partially saturated, the fractures are the main flow paths for gas flow. The buoyancy-driven gas phase convection could be orders of magnitudes larger than the liquid velocity (Tsang and Pruess, 1987).

Hydrological Problems

The geological formations generally are very heterogeneous, with hydrological properties changing spatially at different scales. Even within a stratigraphic unit, the permeability values of core samples can vary over 2 to 4 orders of magnitude. Between different units, permeability differences over 6 orders of magnitude frequently exist (Wang and Narasimhan, 1991). In this review, we focus on the effects of fractures in hard rock formations with a low permeability matrix. Under saturated conditions, the fractures are the active conduit for flow and transport and the matrix blocks are the passive source and sink for fluid and heat. Under partially saturated conditions, the roles of fracture and matrix may be exchanged. Wang (1991) reviewed some recent progress in the literature on flow and transport in fractured rocks under saturated and partially saturated conditions.

For saturated flow, the most frequently used model for discrete fracture is the parallel plate idealization. With constant aperture between two parallel plates, the laminar flow rate is proportional to the cube of aperture. This cubic law has been shown to be valid for open fractures and for fractures closed under low stresses (Witherspoon et al., 1980). When the fraction of contact area grows under stress and the flow path becomes tortuous, the measured flow rate Q over pressure head Δh first becomes lower than the value predicted by the cubic law, but then approaches a constant, irreducible value while mechanical aperture 2b continues to decrease, as shown in Figure 7. The modifications of the cubic law for fracture flow under stress have been studied by Engelder and Scholz (1981), Raven and Gale (1985), Pyrak-Nolte et al. (1987), Cook et al. (1990), and others.

With aperture between rough surfaces varying over the fracture plane, Tsang and Tsang (1987) showed that the flow was not uniform and solute breakthrough was not regular. These flow and transport channels in the fractures were measured in laboratory and field tests in granite rocks (Moreno et al., 1985; Bourke, 1987; Neretnieks et al., 1987; Abelin et al., 1988). The rough rock surface and the nonuniform aperture field have also been modeled by fractal geometry (Brown 1987; Wang et al. 1988b). Figure 8 illustrates the use of fractal surfaces with different fractal dimensions to represent rock surfaces. The scaling properties of fractal geometry have motivated many studies of fractals for rock and soil surfaces, fracture networks, and fault traces at different scales.

Models of fracture networks can be generated from fracture statistics. Long and Billaux (1987) and Billaux et al. (1989) demonstrated the use of fracture trace data to generate spatially correlated two-dimensional line network and three-dimensional disc network models. Only a small portion of fractures were found to control the flow. A purely statistical approach would not model the fracture hydrology properly if a fault was not taken into account. These models are based on data from the granite studies at Fanay-Augeres, France (Cacas et al., 1990). The fracture network approach has also been extensively used in the international studies at Stripa, Sweden for the interpretations of macropermebility experiment, migration drift experiment, simulated drift experiment, packer and other tests (Rouleau and Gale, 1987; Dverstrop and Andersson, 1989; Long et al., 1990). To improve the network modeling beyond statistical and hydrological approaches, Witherspoon et al. (1987) suggested a combined approach with hydrological tests coupled to geological observations and geophysical imaging (Majer et al., 1989).

Solute moving along a fracture can diffuse into the rock matrix. This matrix diffusion is important for long-term transport (Birgersson and Neretnieks, 1990). In double-porosity and multiple-interacting-continuum models, fractures are treated as a continuum, while matrix blocks embedded in the fracture network control the storage capacities for fluid, heat, and solute (Pruess and Narasimhan, 1985). The flow through the matrix could also be important, especially under partially saturated conditions. Our current understanding of partially saturated systems is based primarily on capillary theory. The capillary pressure is inversely proportional to pore size. Fractures can be desaturated more easily than the matrix if fracture apertures are larger than matrix pore sizes. Under partially saturated conditions with fractures drained, liquid water could flow from one matrix block to another across contact areas, as illustrated in Figure 9 (Wang and Narasimhan, 1985). While we focus mainly on fractured rocks and do not discuss soils with macropores, there are some similiarities between the processes in macropore soils and those in fractured rocks. Heterogeneous soil behavior under partially saturated conditions is of concern for near-surface waste storage and disposal sites, including monitored retrievable storage facilities and low-level nuclear waste trenches.

Figure 10 is the grid used in a study of the interaction between fractured units and a porous unit (Wang and Narasimhan, 1990). These stratigraphic units, the Tiva Canyon welded tuff (TCw), the Paintbrush nonwelded tuff (PTn), and the Topopah Spring welded tuff (TSw), are below the ground surface at Yucca Mountain. Yucca Mountain, on and adjacent to the Nevada Test Site in southern Nevada, U.S.A., is the first potential site chosen by the U.S. Congress for characterization for a high-level nuclear waste repository (Figure 11). The water table at Yucca Mountain lies at more than 500 m below the ground surface. The infiltration of precipitation and snow melt through the unsaturated zone is important to the assessment of flow and transport from the repository to groundwater and biosphere. Preliminary simulations showed that pulse infiltrations, with intensities up to that of 5,000-yr flood, were damped out by the porous PTn unit which separates the fracture-flow-dominated TCw unit on the top and the matrix-flow-dominated TSw unit below.

Yucca Mountain is approximately 2,000 m wide. A minor fault, the Ghost Dance Fault (see Figure 11), will be a major hydrological concern if fault flow is an important transport mechanism there. The stratigraphic units at Yucca Mountain generally tilt eastward at an average of 6°. The tilting of the units could divert water laterally, especially through the nonwelded porous units (Montazer and Wilson, 1984). Two-dimensional simulations have shown that the flow distribution is sensitive to boundary conditions and to hydrological properties of the unsaturated units (Rulon et al., 1986; Prindle, 1989; Wang and Narasimhan, 1990). If the fault-formation boundary is treated as a seepage face, Figure 12 shows that the equal potential lines are nearly horizontal and the fluid flow direction is therefore nearly vertical in the interior of the tuff formations with tilted alternating units. This simulation is for the case with uniform infiltration of 0.1 mm/yr on the upper surface. More information on the unsaturated characteristics of fault zone material and more detailed models are needed to assess the impacts of faults in flow and transport through the unsaturated zone.

Concluding Remarks

This review is mainly on the flow field in fractured rock formations in the preemplacement conditions and in the postemplacement conditions surrounding a high-level nuclear waste repository. The hydrological and thermal studies, together with geochemical transport and mechanical stability studies, are needed to quantify the impacts of disposing nuclear wastes underground. A natural geological system is intrinsically heterogeneous. The heterogeneities are difficult to characterize and considerable uncertainty exists. The time scale of required prediction over thousands of years is far beyond the experience of traditional engineering practice. It is therefore essential that the models for prediction could also be used to understand the hydrogeological evolution of a system over the past thousands to millions of years. "The past is the key to the future". We need to feel confident about the models before we address "To bury, or not to bury? That is the question". The multiple barrier approach, systematic long-term monitoring, progressive validation, and waste retrievability are integral parts of a solution to manage nuclear wastes (Narasimhan and Wang, 1991). Hopefully the active exchange of information and collaborations among scientists and engineers from different countries can resolve many technical problems in this sociopolitically sensitive issue of nuclear waste disposal.

Acknowledgements

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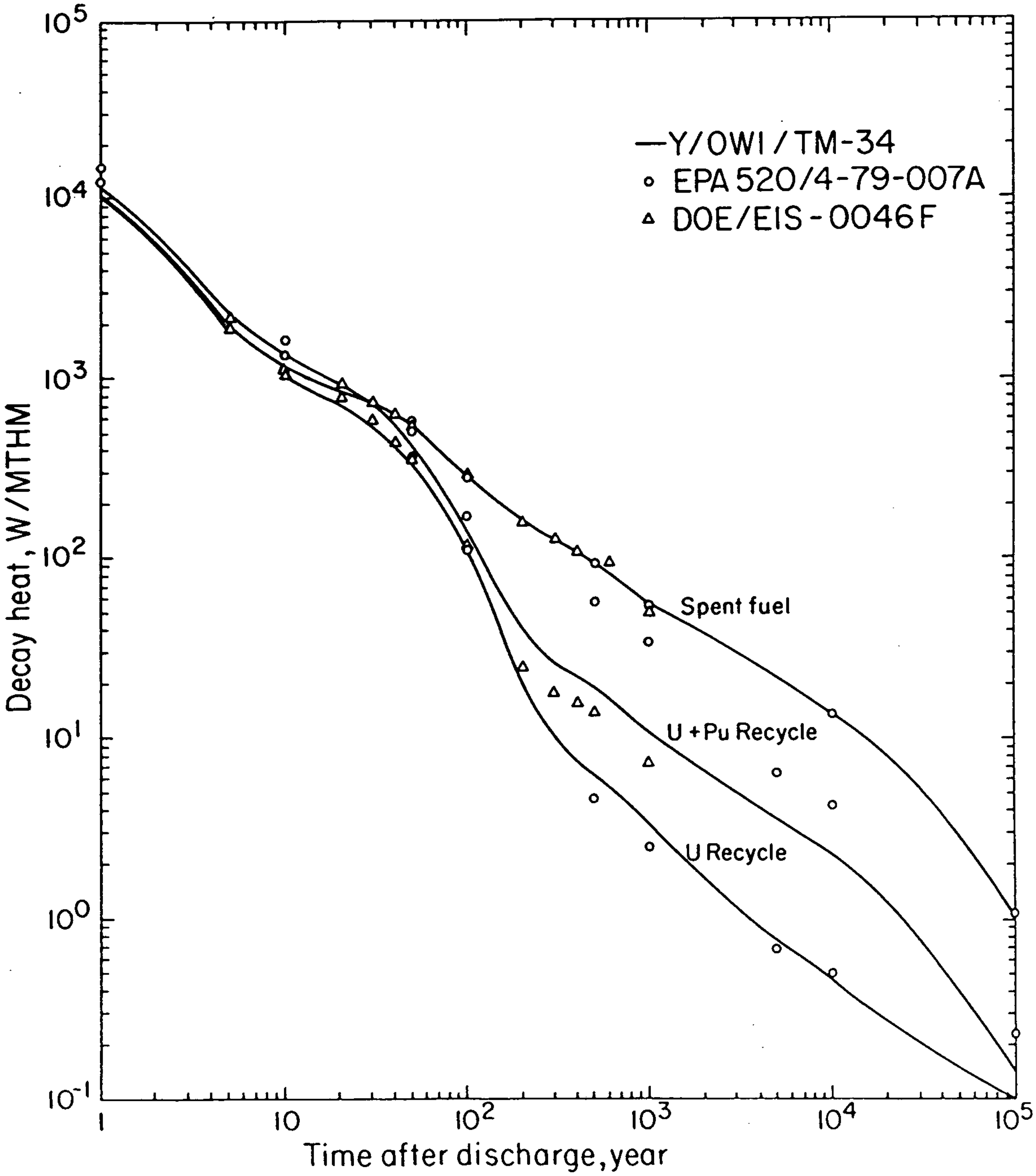


Figure 1. Decay heat power from 1 MTHM of a pressurized water reactor for three different nuclear fuel cycles.

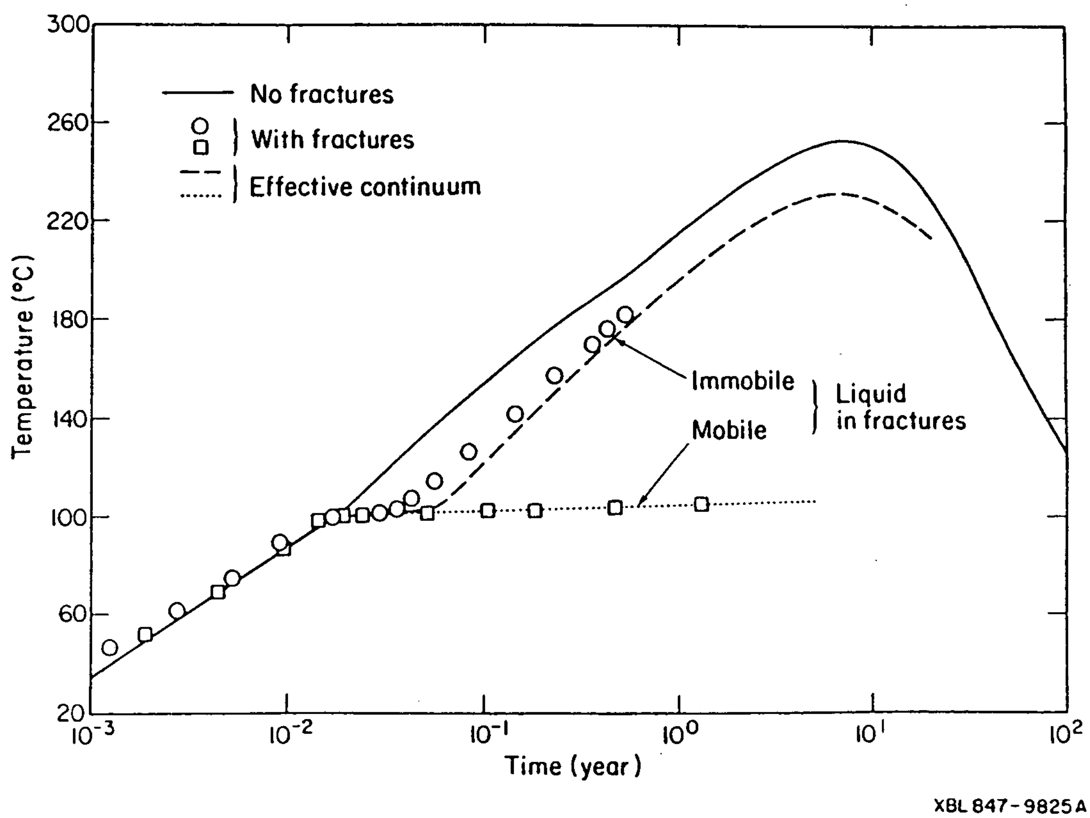


Figure 2. Simulated temperatures at a distance of 0.34 m from the centerline of an array of 3.051 kW waste canisters.

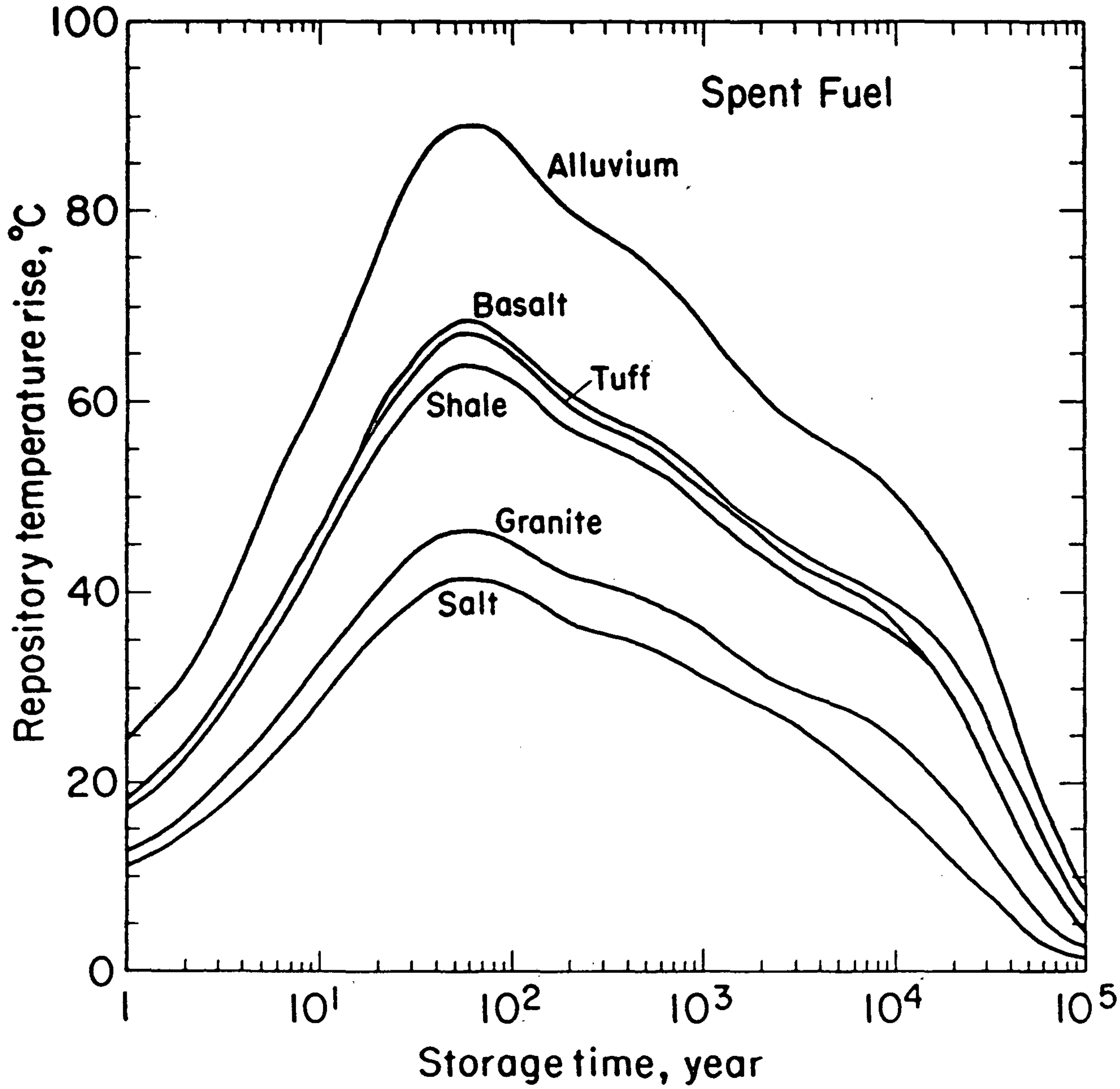
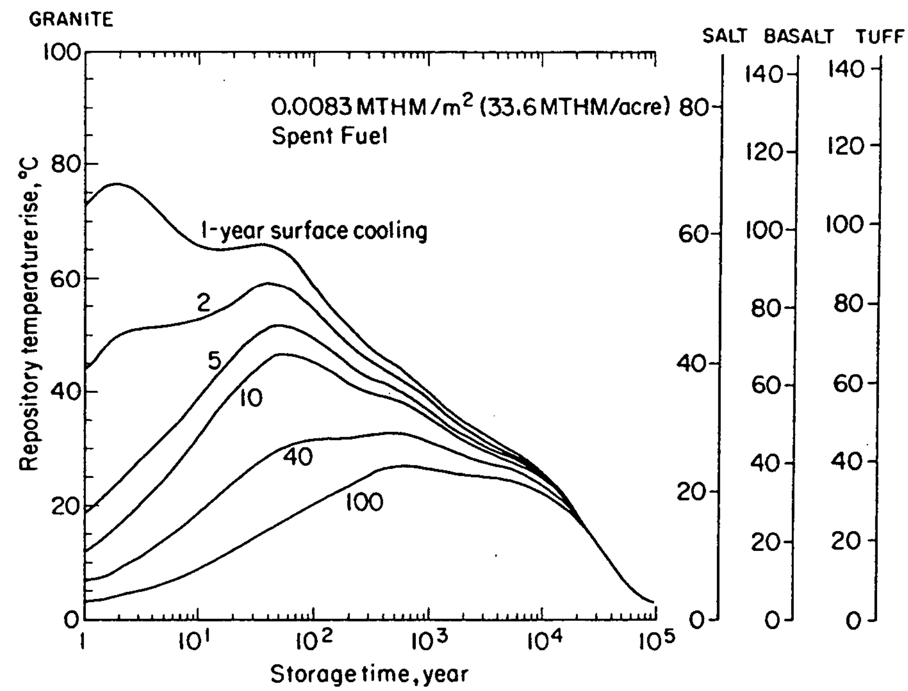


Figure 3. Average temperature rises of spent fuel repository in six different rock types.

(a)



(b)

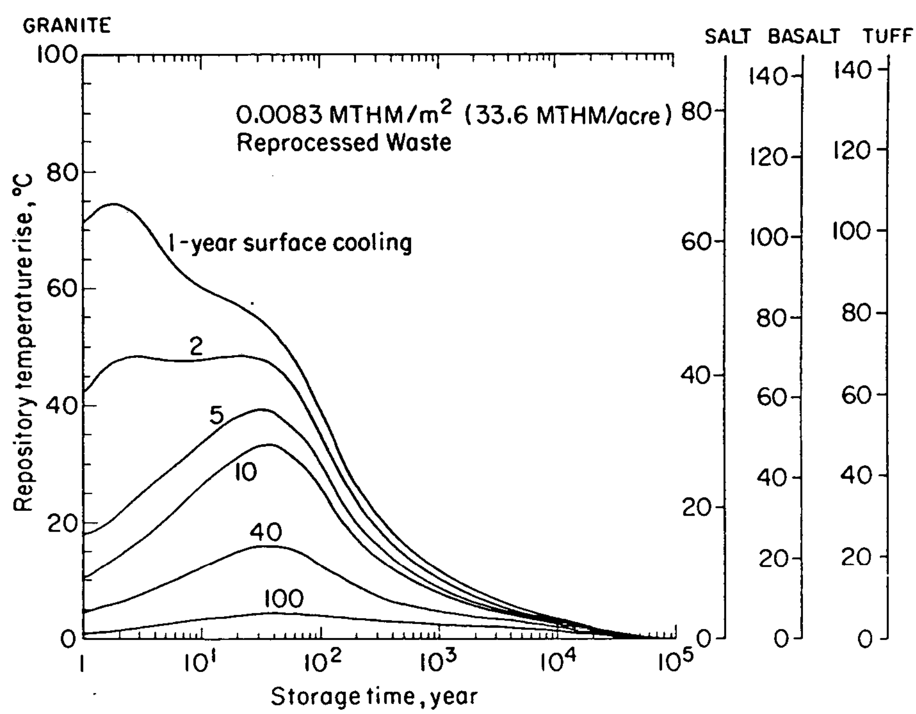


Figure 4. Average temperature rises of (a) spent fuel and (b) reprocessed high-level waste repository with different surface cooling periods.

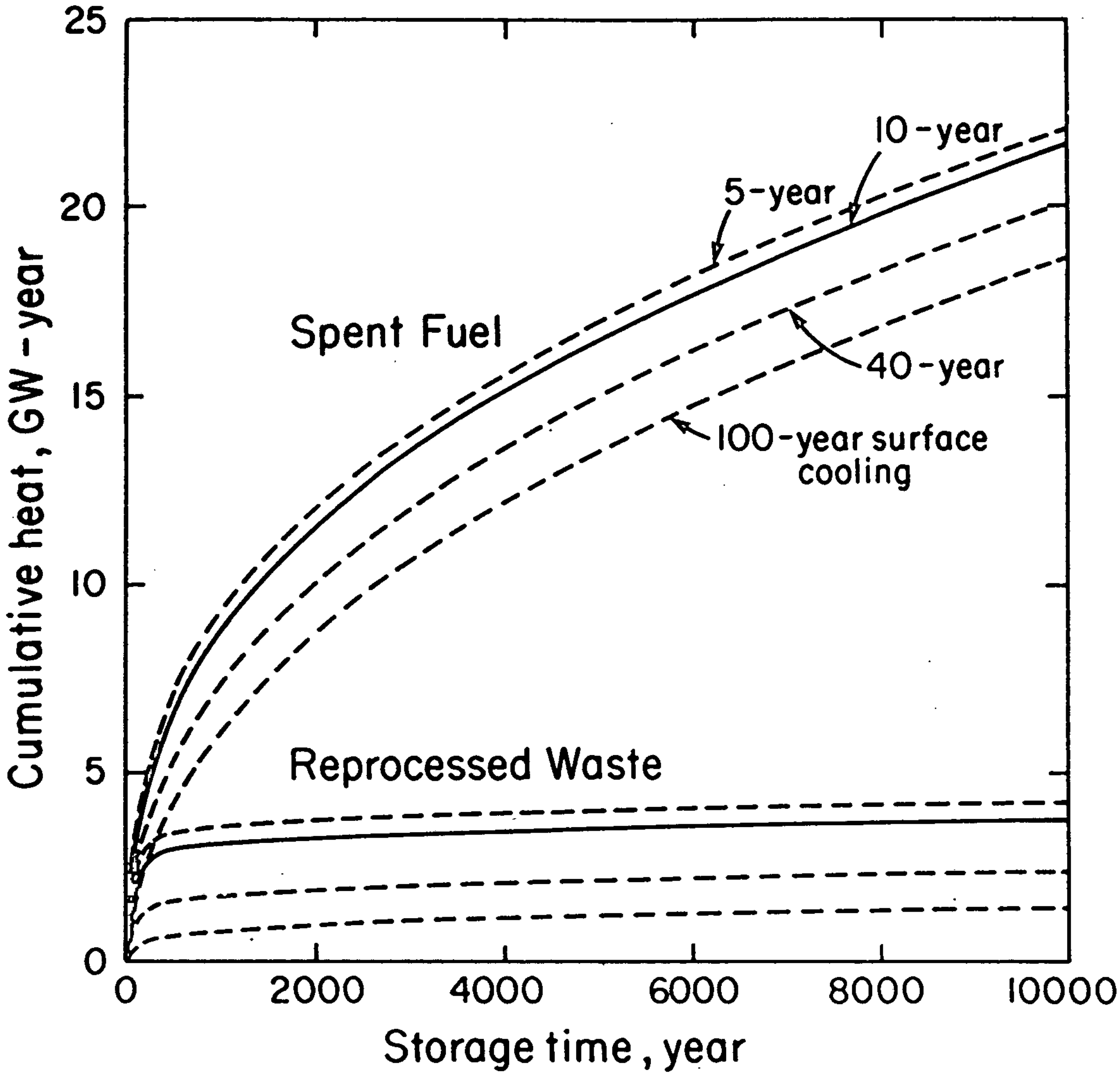


Figure 5. Cumulative heat released by spent fuel and reprocessed waste with different surface cooling periods.

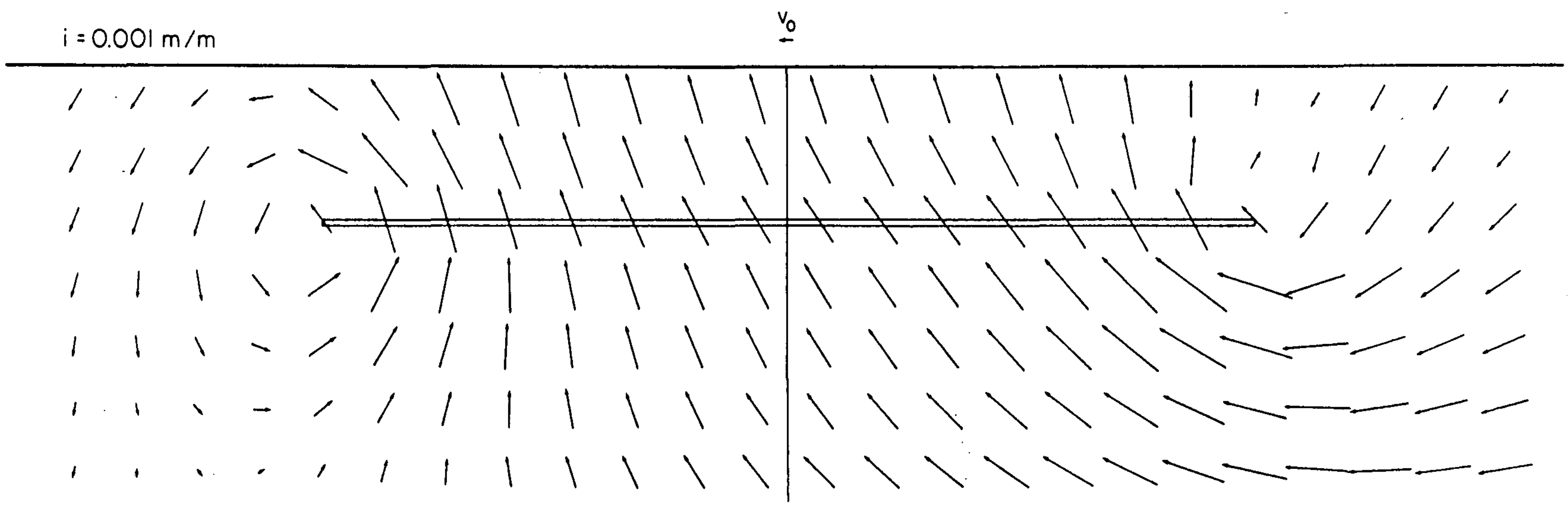


Figure 6. Distortion of ambient groundwater flow $\vec{v}_o$ by convection cells induced by a spent fuel repository, 1,000 yr after waste emplacement.

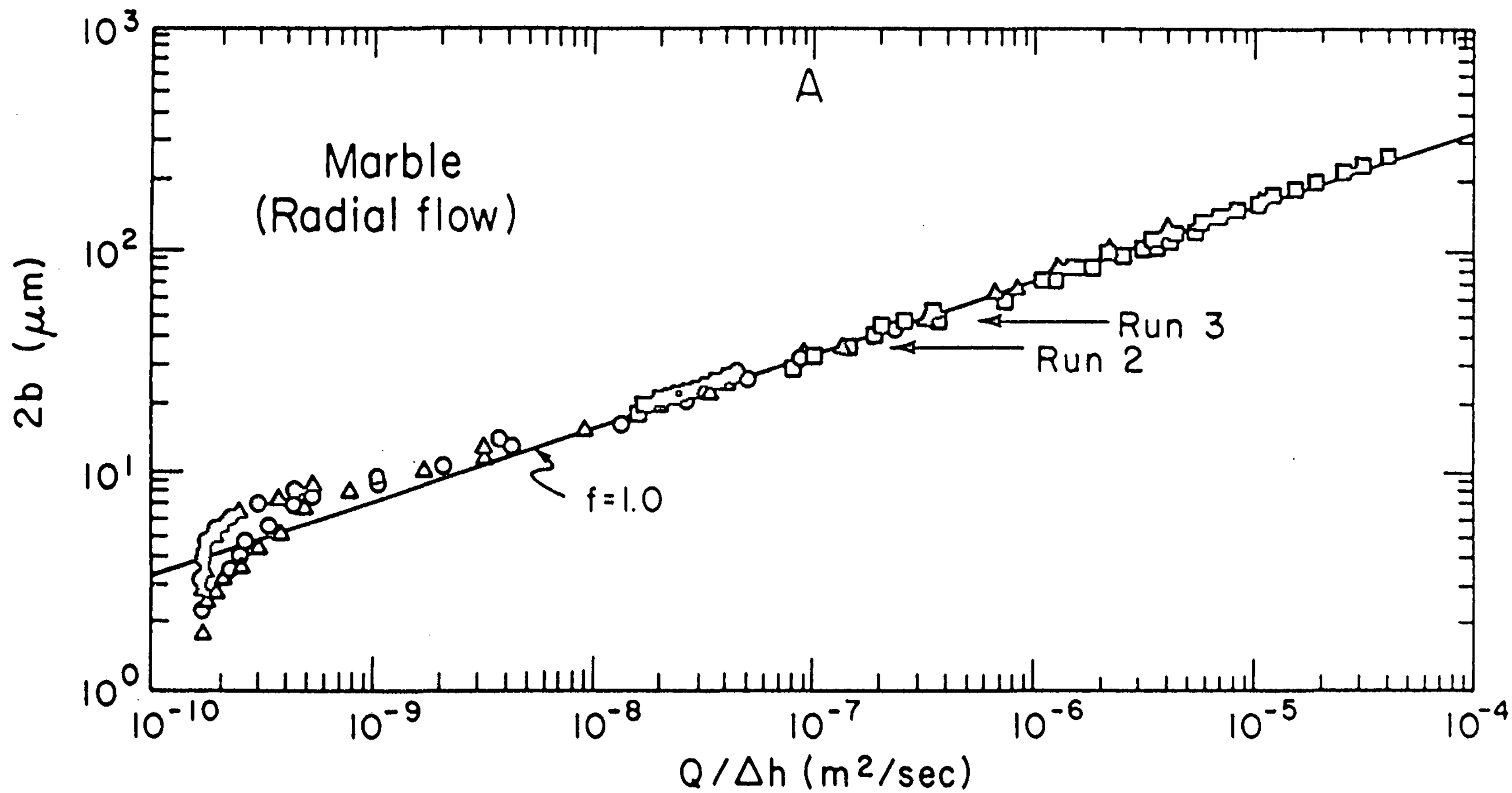


Figure 7. Comparison of experimental results with cubic law for radial flow through a tension fracture in marble.

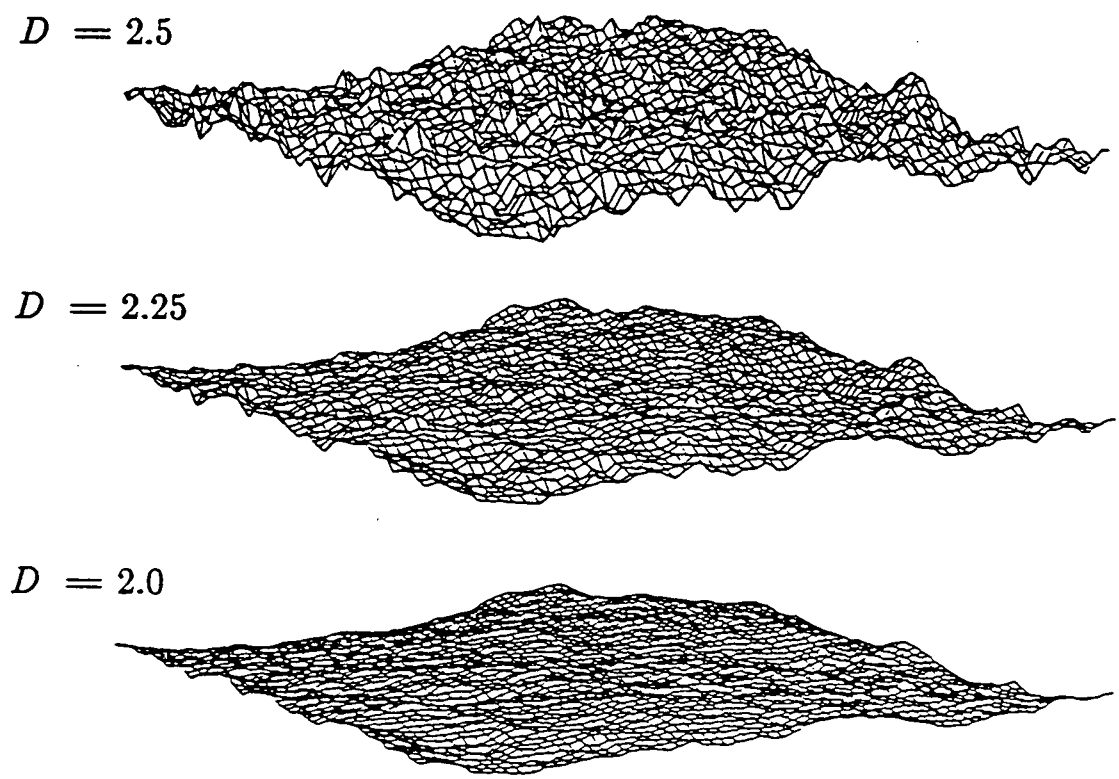


Figure 8. Representation of rough fractures with fractal surfaces.

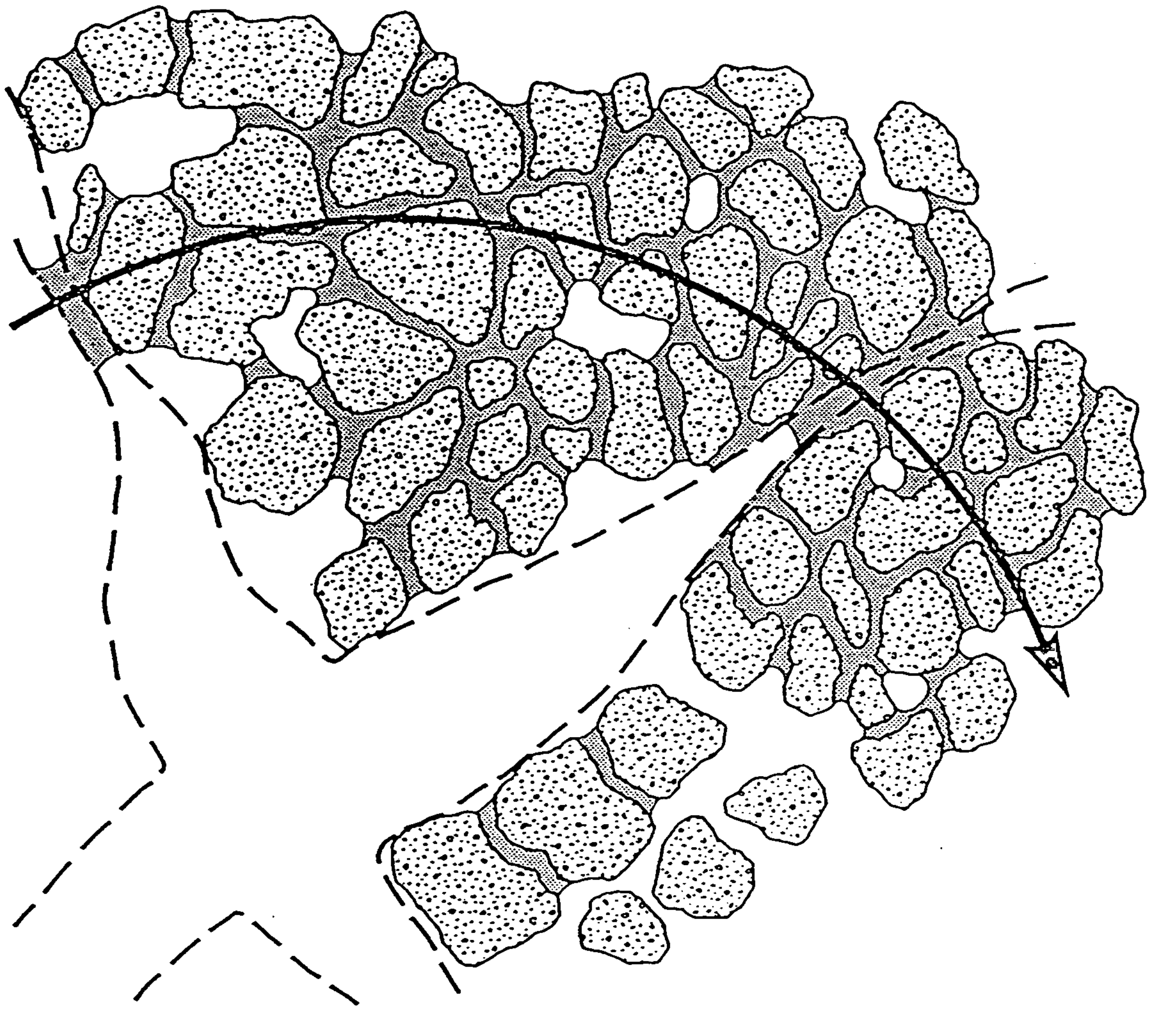


Figure 9. Schematic representation of water flow in a fractured porous medium under partially saturated condition.

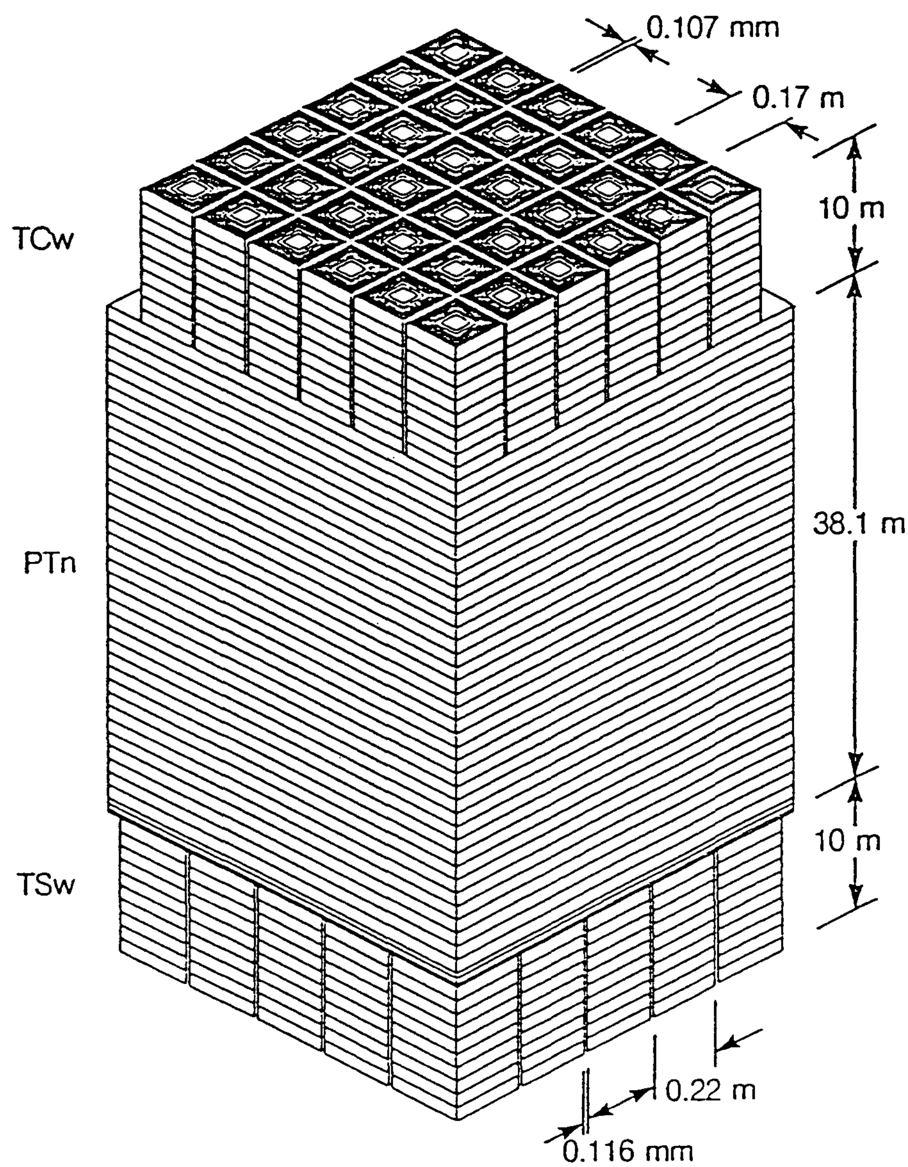


Figure 10. Computational mesh used for studying the responses of alternating welded and nonwelded tuff units to extreme infiltration pulses.

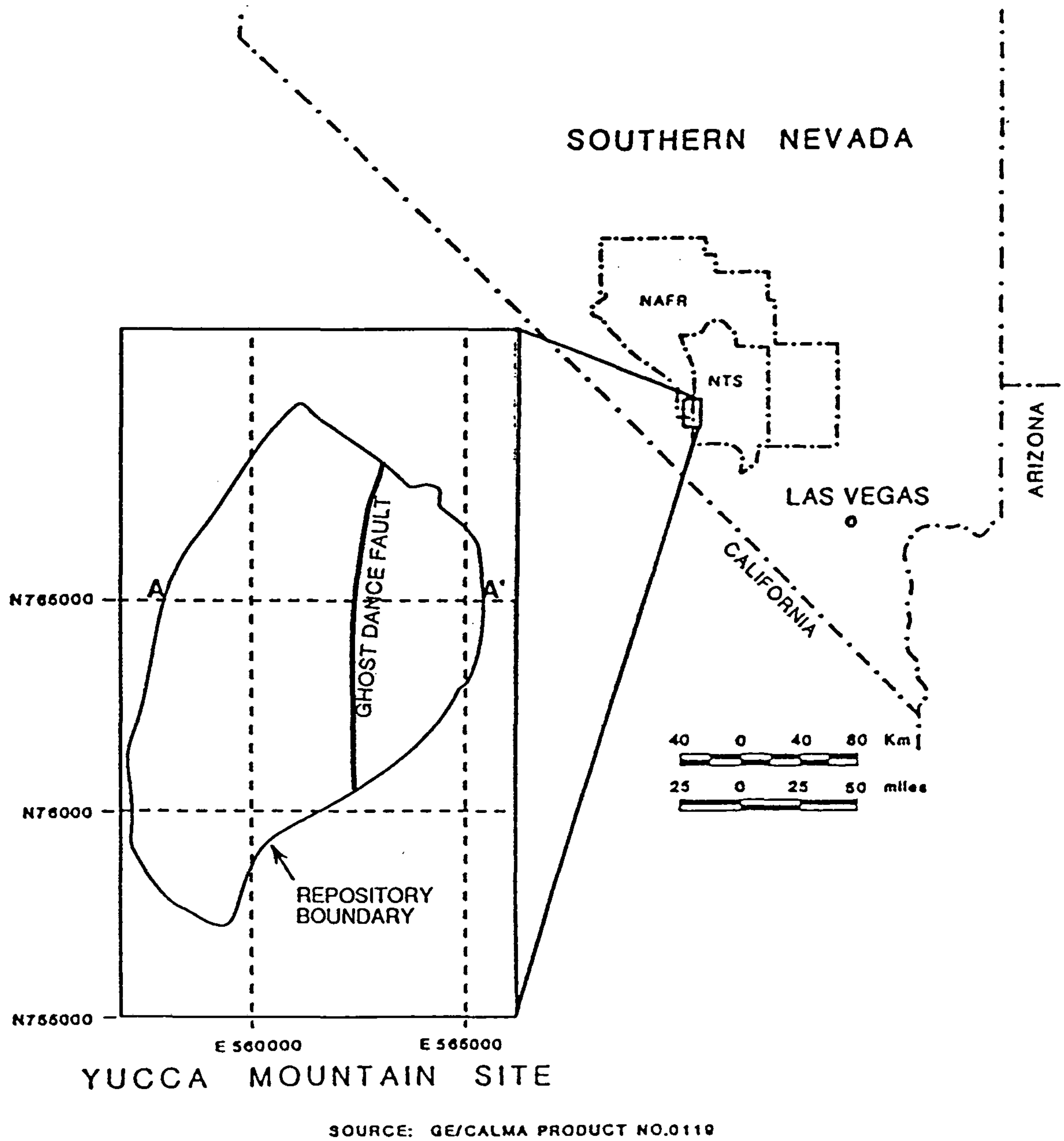


Figure 11. Location map of the Yucca Mountain site, Nevada for a potential high-level nuclear waste repository.

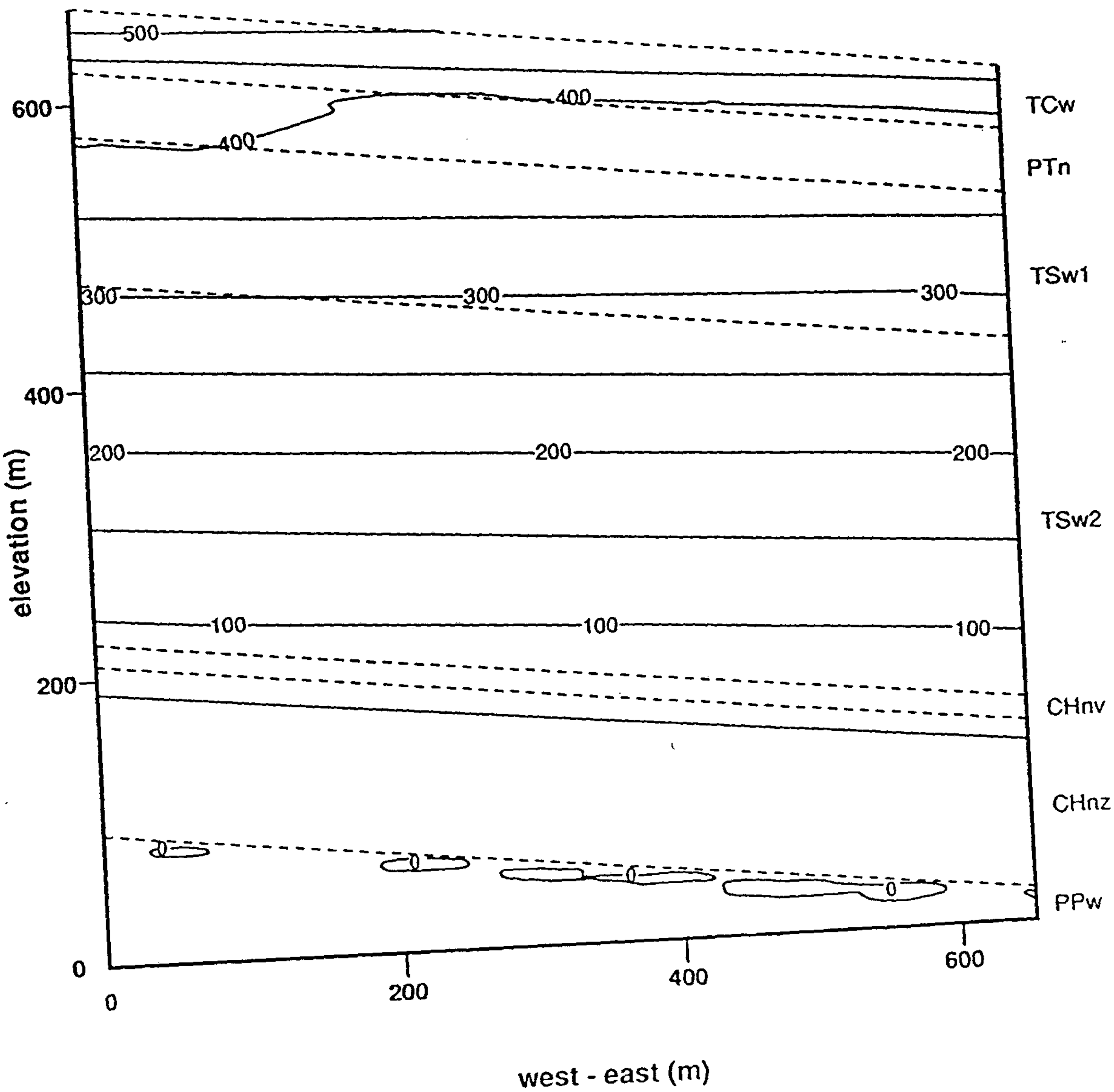


Figure 12. Potential distribution in a 645-m section west of the Ghost Dance Fault.

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