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COUPLED PROCESSES IN SINGLE FRACTURES, DOUBLE FRACTURES AND FRACTURED POROUS MEDIA

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Abstract

The emplacement of a nuclear waste repository in a fractured porous medium provides a heat source of large dimensions over an extended period of time. It also creates a large cavity in the rock mass, changing significantly the stress field. Such major changes induce various coupled thermohydraulic, hydromechanic and hydrochemical transport processes in the environment around a nuclear waste repository.

The present paper gives, first, a general overview of the coupled processes involving thermal, mechanical, hydrological and chemical effects. Then investigations of a number of specific coupled processes are described in the context of fluid flow and transport in a single fracture, two intersecting fractures and a fractured porous medium near a nuclear waste repository. The results are presented and discussed.

Introduction to Coupled Processes

The assessment of the long-term performance of a nuclear waste repository involves the evaluation of the travel time and rate of transport of radioactive elements from the repository to the accessible environment. This evaluation involves understanding the combined effects of many different processes that may affect such transport. These combined or coupled processes are initiated or induced by the large perturbations to the rock mass due to the emplacement of a nuclear waste repository. The rock mass is perturbed in two ways. First, the nuclear waste repository represents a heat source of large dimensions over an extended period of time. Thermally induced buoyancy and rock expansion effects do not depend directly on the value of temperature rise, but on the integrated heat input into the system. Thus, a relatively low temperature rise over a large volume and a long period of time could cause major buoyancy effects. Second, the repository represents a large cavity constructed out of the rock mass, changing significantly the original stress distribution.

The coupled processes induced by these drastic changes involve mainly four different effects, namely, thermal (T), hydrological (H), mechanical (M) and chemical (C). Among these four, there can be only 11 (i.e., 2^4-5) types of couplings of various levels of importance. These are listed in Table I, which also indicates one example for each of these couplings. It may be useful to draw definite distinctions between different degrees of coupling in order to clarify what we mean by coupled processes. Table II displays schematically several possible connections between processes. The fully uncoupled processes conceptually have negligible influence or effect on one another, so that they can be evaluated independently. The sequential case implies that one process depends on the final state of another so that the order in which they are evaluated becomes important.

The one-way coupled processes demonstrate a continuing effect of one or more processes on the others, so that their mutual influences change over time. The two-way coupling (or feedback coupling) reveals a continuing reciprocal interaction among different processes, and represents in general the most complex form of coupling. In this study, the term coupled processes refers to either the one-way or the two (or more) way couplings among the physical processes considered.

In many studies for the performance assessment of a nuclear waste repository, some of these coupled processes, such as buoyancy flow in a porous medium, have been addressed. However the value of considering these coupled processes in an overall way as suggested by Tsang (1980, 1985) and Tsang and coworkers (1982) lies in the comprehensiveness in the consideration of all possible coupled processes that may occur.

Table I

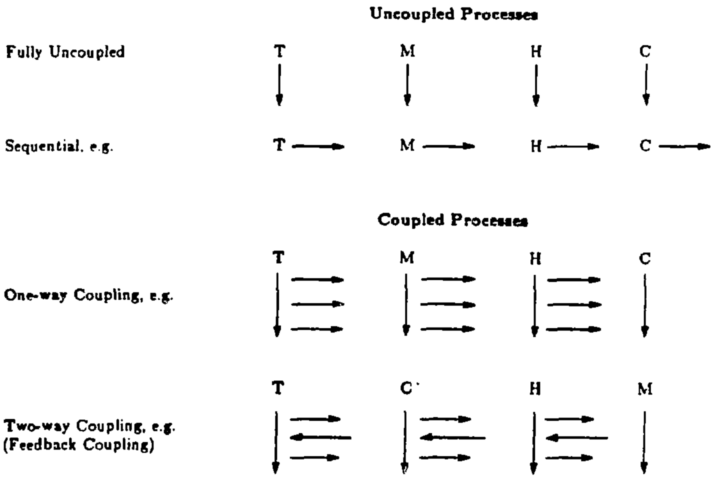
Types of Coupled Processes
(T = Thermal, M = Mechanical, H = Hydrological, C = Chemical;
single line indicates weak coupling, double line, strong coupling)

Type	Examples
T = C	e.g. phase changes
T = H	e.g. buoyancy flow
T = M	e.g. thermally induced fractures
H = C	e.g. solution and precipitation
H = M	e.g. hydraulic fracturing
C — M	e.g. stress corrosion
	e.g. chemical reactions and transport in hydrothermal systems
	e.g. thermomechanical effects with change of mechanical strengths due to thermochemical transformation
	e.g. thermally induced hydromechanical behavior of fractured rocks
	e.g. hydromechanical effects in fractures that may influence chemical transport
	e.g. chemical reactions and transport in fractures under thermal and hydraulic loading

Thus one hopes that all significant coupled processes will be properly evaluated in the performance assessment. The safety of a nuclear waste repository presents a problem of unusual requirements to the scientific and engineering communities. One is required to make predictions thousands of years into the future and one is also required to predict not just the mean arrival time of radionuclides which may have escaped from the repository, but also the early arrival times at low concentrations. With these extraordinary requirements, coupled processes that may usually be neglected may become of significance. In a panel report devoted to this discussion (LBL, 1084), a few of the often ignored coupled processes were pointed out. One example is the piping effect, i.e., the formation of fluid flow tubes due to pressure induced chemical dissolution and other processes. Such an effect is known in the fields of mining and soil mechanics, but is not much addressed in the nuclear waste storage problem. Another example is the osmotic effects (thermal osmosis and chemical osmosis), which may have significant control of radionuclide transport through clay backfill materials, thus having important impact on the source term for the geosphere transport modeling. A recent international symposium (LBL, 1085) surveyed many of the coupled processes and discussed their significance. Many of the papers in this symposium have been updated and will be a good source of information on this subject (Tsang, 1087).

Table II

Diagrams of Uncoupled and Coupled Processes
(T = Thermal, M = Mechanical, H = Hydrological, C = Chemical)



The present paper will describe results of investigations by the group at Berkeley on a number of coupled processes for the case of a single fracture, two intersecting fractures and fractured porous media. The topics are:

(1) Tracer transport in a single fracture under stress, based on the channel model.

(2) Hydrothermal buoyancy flow in two intersecting fractures.

(3) Modeling of non-isothermal hydrofracturing of a porous reservoir.

(4) Thermohydromechanical process in a fractured porous medium around a heat source.

After the discussion of these results, a few brief conclusions and comments will conclude the paper.

Solute Transport in a Single Fracture Under Stress Based on the Channel Model

In this first example, we shall consider the transport of chemical solute through a water-saturated single fracture under mechanical stress (Tsang and Tsang, 1986). The flow through each fracture is most commonly treated as the flow through a pair of smooth parallel plates separated by a constant aperture, and thus the fluid flowrate varies as the cube of the constant separation. However, a real fracture in rock masses has rough-walled surfaces, and, unlike parallel plates, portions of the fracture may be blocked by filling material or closed when subjected to normal stress. As a matter of fact, it is the blockages or contacts between upper and lower surfaces of a fracture that provide a correlation between normal mechanical stress variations and the fluid flow that is controlled by fracture aperture closure (Tsang and Witherspoon, 1981, 1983).

Theoretical studies (Tsang, 1984) have shown that only at low applied stress, when fracture is essentially open, does the parallel-plate idealization of a rock fracture adequately describe fluid flow. Because of the contact areas between fracture surfaces and constrictions of the fracture subject to stress, flow through a single fracture takes place in a few channels which are tortuous, have variable apertures along their lengths, and which may or may not intersect each other.

Evidence that flow takes place in channels also occurs in field and laboratory experiments. In the field experiments of solute migration in single fractures in the Stripa mine, Sweden (Abelin et al., 1985; Neretnieks, 1985), the observation that the amount and time of tracer returns at two near-by sampling points were very different, and that many of the neighboring collection holes registered no tracer (non-sorbing) return at all lends support to the channel nature of fluid flow within a single fracture.

The laboratory experiments of Pyrak et al., (1985) and the field experiment carried out in a single fracture in Cornwell (Bourke et al., 1985; P.J. Bourke, personal communication, 1986) also demonstrated that flow in a single fracture took place in a limited number of channels.

On the basis of theoretical and experimental observations referred to above, we have studied fluid flow and solute transport in a tight fractured medium in terms of flow through a limited number of tortuous and intersecting channels. These channels have variable apertures, b, along their lengths. Figure 1a shows schematically the channeling effect in a single fracture. Each channel in Figure 1a is represented schematically in Figure 1b. It is defined by the aperture density distribution n(b) along its length. The channel width is assumed to be constant, of the same order as the correlation length, λ, since, by definition, the correlation length is the spatial range within which the apertures have similar values. The channel length does not equal the linear length between two points, but is not expected to vary more than a factor of two to three from the actual linear length. For a given aperture density distribution and correlation length, different realizations of statistically equivalent channels may be generated (Tsang and Tsang, 1986) using geostatistical methods.

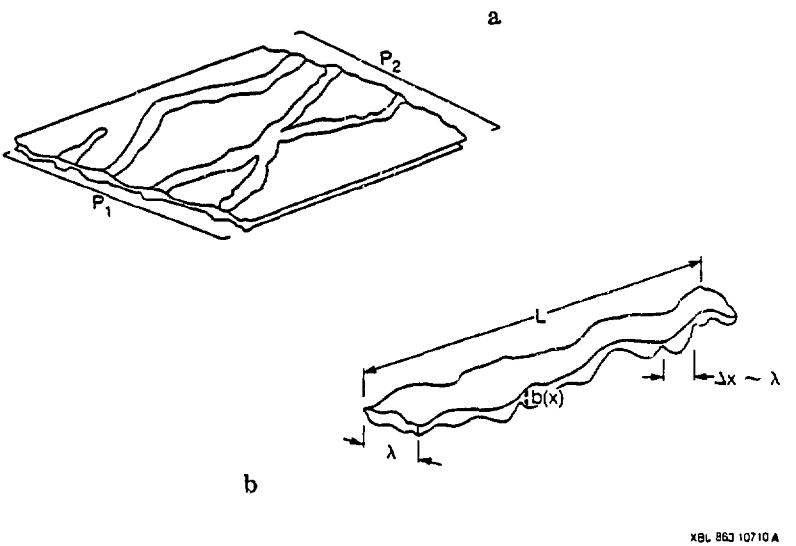


Figure 1. (a) Schematic diagram of the channel representation of fluid flow in a single fracture.
(b) Schematic sketch for one channel.

When a pressure difference is applied between two ends of a single fracture, flow takes place along a number, M, of these channels in the fracture plane. If we assume that a step function input of chemical solute (tracer) at constant concentration be injected at the high pressure end, we can calculate the tracer concentration breakthrough curves at the exit end. Figures 2a through 2d show the tracer concentration breakthrough curves as a function of time for M = 32, 16, 11 and 8, respectively. We note a rather steep rise in the concentration curves in the early times, then some "stair-step" structure due to the finite delay for the solute carried in the next channel to breakthrough. The early arrivals correspond to flow in fast channels, those with few very small aperture constrictions. The steep rise therefore indicates that a large proportion of the total flow is in fast channels. In Figures 3a through 3d we reproduce the breakthrough curves from laboratory experiments (Moreno, et al., 1985) performed on a single fracture in a 18.5 cm core. Careful examination of Figures 2 and 3 indicates that the prominent features in the theoretical curve based on the channel model are also evident in the observed curves. These features (such as the steep rise in tracer returns and the stair-step structures) are not found in the conventional advection-dispersion curves. We are aware of the fact that there are data measurement errors in the laboratory breakthrough data, hence raising a question made over the claim that the stair-step structure in the experimental breakthrough curve arises from the channel nature of the flow. Discussions with Eriksen (private communication, 1986) who performed the experiments as shown in Figure 3 about the precision of the measurements led us to believe that the stair-step structures are not merely data scatter.

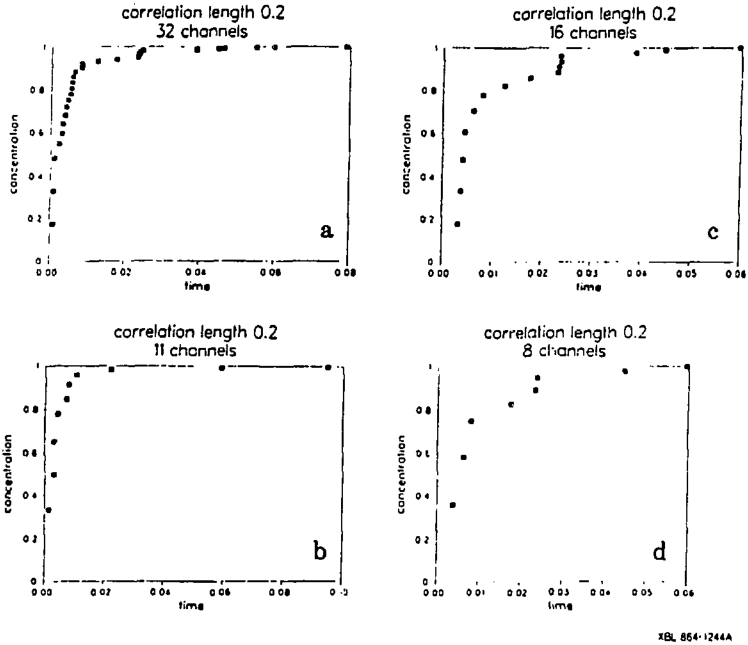


Figure 2. (a) - (d) Theoretical tracer concentration breakthrough curves for a set of M channels with common end point pressures P_1 and P_2, with M = 32, 16, 11 and 8 respectively.

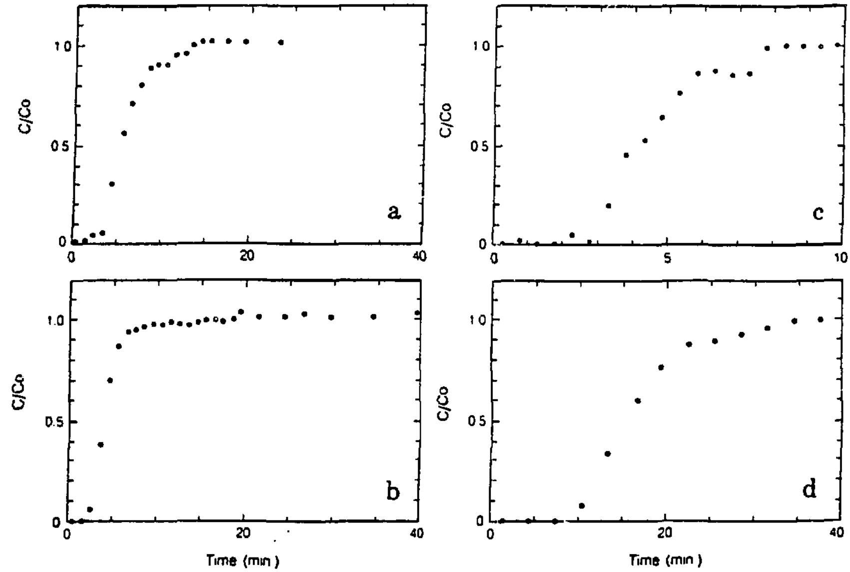


Figure 3. (a) - (d) Tracer concentration breakthrough data from laboratory measurements on a single fracture in a granitic core 18.5 cm in height and 10 cm in diameter (Moreno et al., 1085). The four curves correspond to different runs involving different injection flowrates and different tracers (NaLS or I).

When the normal stress across a fracture is increased, the reduction in channel apertures affects the tracer breakthrough curves. One may start with the experimental concentration breakthrough data such as in Figure 3c and interpret them in terms of our conceptual channel model. Making the assumption that all the apertures in the fracture are reduced by 6% due to the mechanical stress, a new tracer breakthrough curve may be derived (Fig. 4). This figure indicates that even with a small change in the mean fracture aperture (6% reduction), a large change in the breakthrough curve resulted. The reason is that the small change affects significantly the constricted part of the channels, which controls the flow rates. Thus the signature of channeling in fracture is in the stair-step structure of the breakthrough curves and their sensitivity to stress applied across the fracture. These suggested possible coupled hydromechanical laboratory experiments which may be performed in order to further investigate the channel nature of fluid flow in fractures. Note that these hydromechanical effects would not be expected if flow through fractures were approximated by flow between smooth parallel plates.

Buoyancy Flow in a Two-Fracture Model

The coupling of heat and fluid flow in porous media around a nuclear waste repository is studied by a number of authors. We made a study of such a coupled process in two intersecting fractures. These two fractures may be either one horizontal and one vertical (Wang et al., 1980; Wang et al., 1979) or both vertical (Wang and Tsang, 1980). Recent buoyancy flow studies (Tsang and Pruess, 1986; Pruess, et al., 1985) also considered two-phase flow in a highly fractured porous medium, in which water vapor and air may also

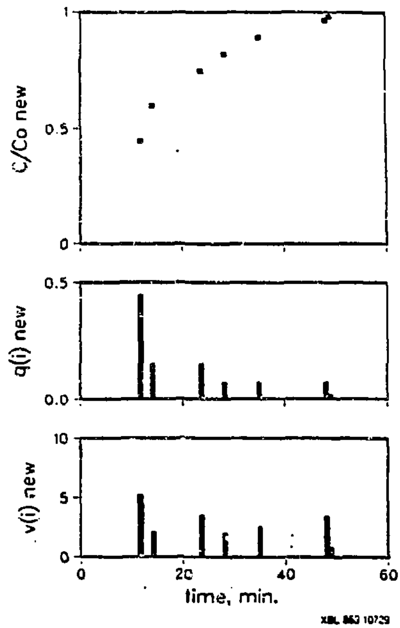


Figure 4. Predicted tracer concentration breakthrough curves for flow through a single fracture subject to normal stress, based on the laboratory data shown in Figure 3c.

be present. In this case, for example, water may evaporate into vapor near heat source at the repository and condense as the vapor moves up away from it. For our present illustration of coupled buoyancy flow we shall present the simple case of single phase flow in a system of one horizontal and one vertical fracture.

It is well known that 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. The model used is comprised of 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 the horizontal fracture is intercepted by a vertical fracture from the center of the repository to the surface as shown in Figure 5. 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 buoyancy forces.

The repository is assumed to have a radius, R, of 1500 m and is positioned at D = 500 m or 1000 m below the land surface. The temperature rise is calculated by a heat conduction model assuming an instant emplacement of nuclear waste with a heat output density of 10 W/m^2. The heat power output variations with time are assumed to be given by $P(t) \propto 10(t/to)^{-3/4}$ This corresponds approximately to the power output curve for spent fuel (Wang et al., 1979). The thermal diffusivity for the rock formation (granite) is assumed to be 15 x 10^{-6} m^2/sec and the thermal conductivity is 2.5 W/m/°C. The recharge and discharge zones are assumed to be far away from the repository and maintained at normal hydrostatic pressure and ambient temperature. Before the emplacement of wastes, 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. In Figure 6, 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 6, 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 assume to have the same aperture $b_z = b_x = 1\mu m$.

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 (Lamb, 1932; Witherspoon et al., 1980) is assumed 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 7, the results of a constant horizontal aperture $b_x = 1\mu m$ and with a range of vertical apertures $b_z = 10\ \mu m$, $1\ \mu m$ and $0.1\ \mu m$ 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 large 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.

Although the thermohydrological model used for the analysis above is very simple, it possesses 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 estimation. 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.

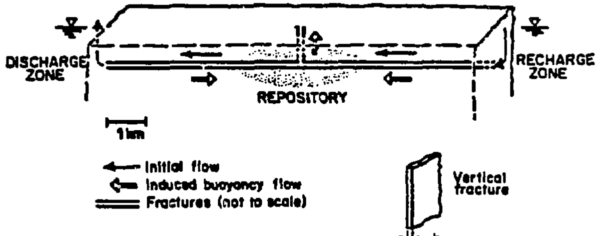


Figure 5. Two-fracture model for simulating buoyant flow.

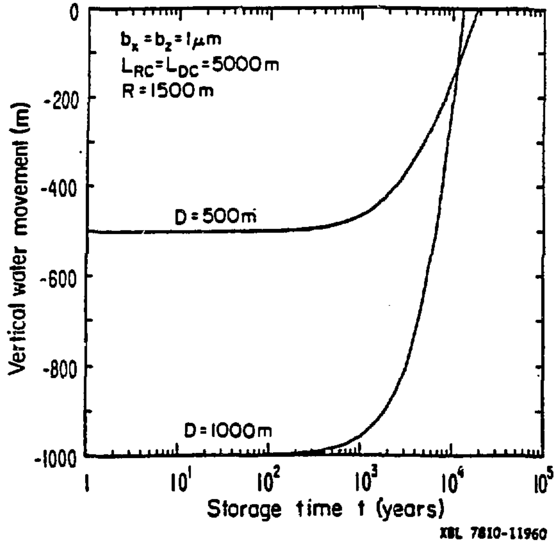


Figure 6. Effects of repository depths on the water movement along the vertical fracture.

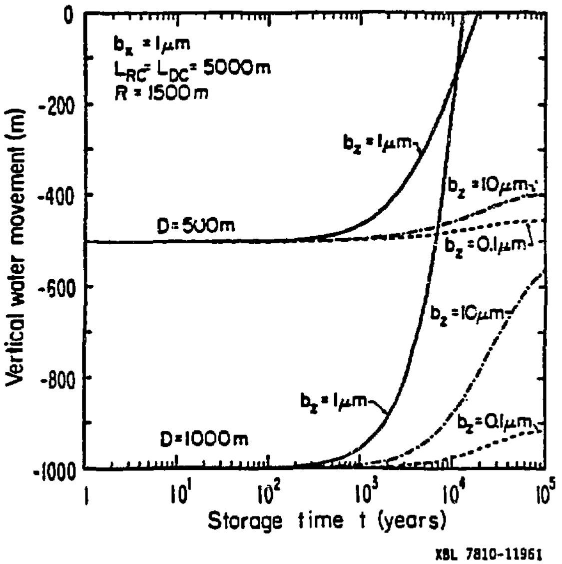


Figure 7. Effects of vertical fracture apertures on the water movement along the vertical fracture.

Non-isothermal Hydrofracturing of a Porous Medium

In this example of coupled process, we consider fluid injection into a fracture embedded in a permeable porous medium (Noorishad and Tsang, 1987). In general, the deformation of fractured rocks in response to fluid pressurization (e.g., by fluid injection) is a well-known phenomenon. Repressurization of hydraulically induced fractures in hydrofracturing experiments is commonly used to obtain better estimates of in situ stresses. In this procedure the compressive stress in the fracture is neutralized by the pressure of the injected fluid, resulting in an increase in fracture aperture. The deformation process, both in the rock as a whole and in the fracture specifically, is a coupled phenomenon. Thus far, realistic simulation of fluid injection has not been possible because of the lack of data and the complexity of analysis. These limitations are even greater if one considers nonisothermal injection, which is used in hot-dry-rock experiments or cold-water flooding of oil reservoirs. Cold-water flooding entails a triply coupled thermohydromechanical (THM) process among the flow of heat, the flow of fluid, and the host medium deformability. Theoretical developments of Nowacki (1962) and other observations (e.g., Stephens and Voight, 1982) have pointed to the important role of thermal stress in the process of fracture deformation. Even though the scarcity of data and complexity of the processes prevent the realistic simulation of THM phenomena, the availability of numerical procedures (Noorishad et al., 1984) does allow a scoping analysis of some observations to be made. This calculation is intended to explain the observations made for the case of cold-water flooding of an oil reservoir.

Field equations of THM phenomena, the general setup of a THM initial boundary value problem, and a numerical solution approach are given in Noorishad et al. (1984). That work also provides a basis for an understanding of the role of the thermal stresses in the THM phenomena through inspection of the stress-strain relationships. To investigate the role of thermal stresses in circumstances where transport of energy is enhanced by fluid flow, as well as in conjunction with the mechanical aspect of the flow of fluids, numerical techniques such as the code ROCMAS (Noorishad et al., 1984) must be used.

The numerical simulation in this work is based on semi-quantitative data on cold-water flooding experiments provided by an oil company. In these experiments, it was noticed that hydrofracturing and/or reopening of existing fractures in the warm reservoir consistently took place at pressure gradients that were about 1.5 x 10^{-3} MPa/m less than the expected values. For a reservoir at a depth of about 3000 m, the above reduction in gradient implies a shut-in pressure reduction of about 5 MPa. Using the code ROCMAS we constructed a hypothetical two-dimensional (x-y) model of the reservoir to study this problem. Figure 8 shows a sketch of the geometry and the initial and boundary data. In the field experiments, water is injected at constant rates until well pressure stabilizes; the rate is then increased by a constant amount, and the procedure continues for a period of a day or more, during which one or two hydrofacturing episodes is observed. A realistic simulation of the experiment is not possible; instead we seek a crude approximation. We do this by

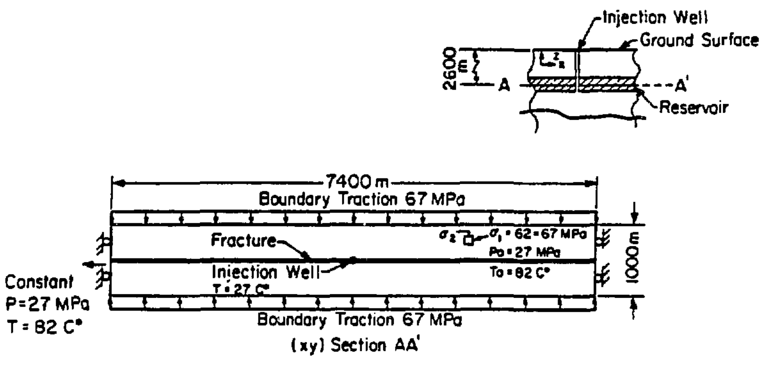


Figure 8. Schematic geometry of the non-isothermal fracturing model and initial and boundary conditions.

obtaining a THM response of the model though a series of steady-state HM calculations that use the results of a coupled transient thermal analysis. The approximation is justified because of the large difference between the time constants for fluid flow and heat flow. The fracture in the model is regarded to be closed initially (with aperture 10^{-7} m). Pressurization of the reservoir opens the fracture elastically against sustained compressive stresses. This increase in the aperture allows further penetration of the pressure front until the fracture goes into a tension state and hydrofracturing takes place. In the simulations, the occurrence of hydrofracturing is marked by instability of the system in the numerical solution. The presence of thermal stresses accelerates this phenomenon. Figure 9 show the results of an isothermal (HM) calculation and nonisothermal (THM) calculation of the model. As can be observed in the figure, the system become unstable at an injection pressure close to one order of magnitude less than that of isothermal injection calculations. Figure 10 depicts the advancement of the thermal front in the fracture, and Figure 11 displays the calculated TH and THM pressure distributions in the fracture as they separate from each other with the advancement of time.

Thermohydromechanical Process in a Fractured Porous Medium Around a Heat Source

In this last example, we present the results, based on the numerical code ROCMAS used for the problem in the last section, of thermohydromechanical behavior of a fractured porous medium around a nuclear waste canister hole (Noorishad et al., 1984). The nuclear waste canister is represented by a 5-kW heater located at a depth of 350 m in granite. A horizontal fracture is assumed to lie 3 m below the heater mid-plane and to extend from the heater borehole to a hydrostatic boundary at a radial distance of 20 m from the borehole. The properties of rock and fractures are given in Noorishad et al. (1984) and the two-dimensional axisymmetric (r,z) finite-element grid is shown in Figure 12. The heater drift, approximated by cylinderical hatched

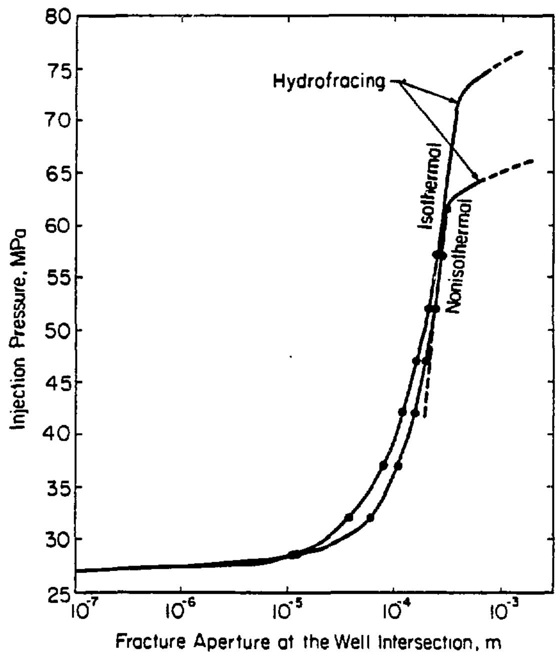


Figure 9. Variation of fracture aperture in response to pressurization.

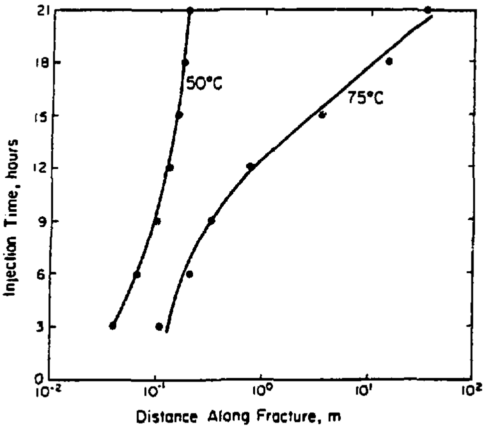


Figure 10. Thermal front advancement in the fracture.

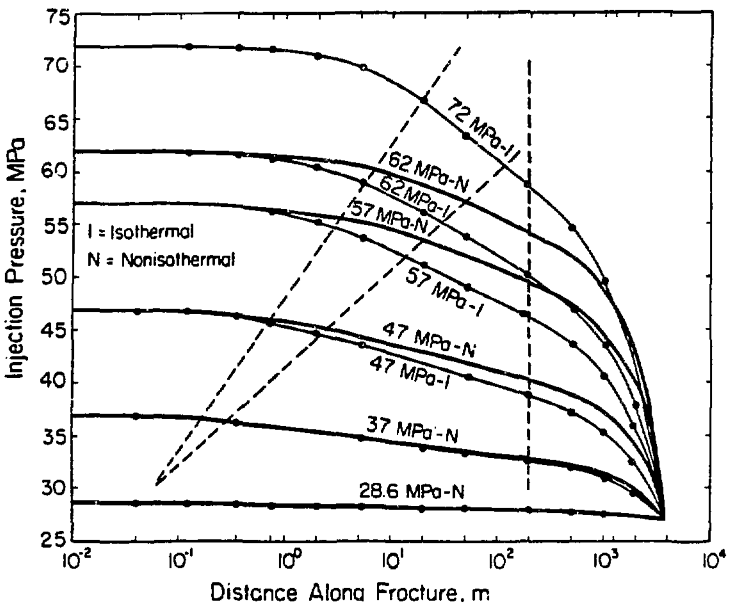


Figure 11. Pressure profile in the fracture for isothermal and nonisothermal injection episodes.

area, is simulated by assigning a very low value of Young's modulus to the elements. Before the heater raises the temperature of a large volume of rock, the flow from the hydrostatic outer boundary to the atmospheric ("zero" hydraulic pressure) borehole is high. Later in time, with the heated rock above the fracture expanding and the fracture aperture near the heater borehole closing, the flow decreases sharply, as shown in Figure 13. The evolution of the fracture aperture profile, together with the variations of the pressure and temperature distributions, are shown in Figure 14. As may be seen in the pressure-distance graph of this figure, before the tapping of the fracture at 0-day, full hydrostatic pressure prevails in the fracture. This pressure diminishes rapidly at 0.25-day before a major development of the thermal front. However, as thermal stresses are established, the fracture starts closing. As a result the pressure inside the fracture starts rising, thus leading to the establishment of full pressure in the fracture at 14-day, similar to the situation at 0-day. These results may provide a better understanding of some of the observations made in the in situ heater experiments in the Stripa granite. The delayed responses of the extensometers in these experiments (Witherspoon et al., 1981) may be explained by the closing of the fracture. Similarly, gradual stoppage of the water inflow into the heater borehole (Nelson et al., 1981) can be explained by the same phenomena.

The above example indicates a case ("one-way coupling," Table I) where thermo-hydro-mechanical changes take place in the field near a heat source. Such changes are hard to calculate if one considers the three phenomena T, H, M independently.

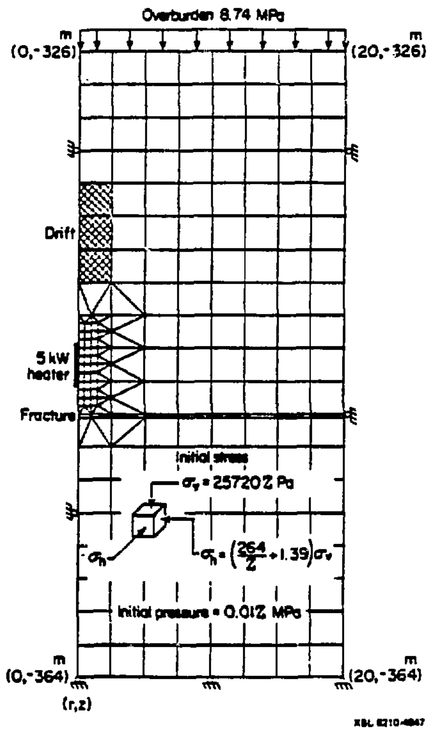


Figure 12. Finite-element model of an heat source environment.

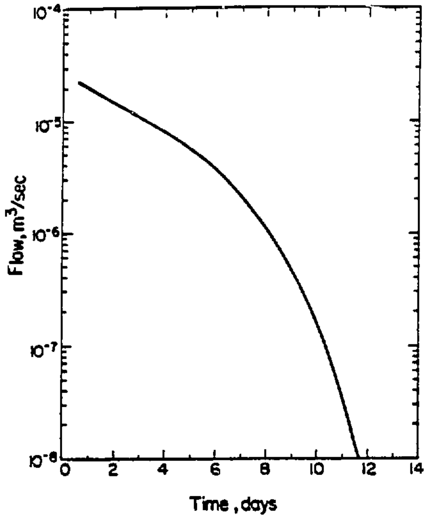


Figure 13. Variation of fluid inflow to the heater borehole as a function of time.

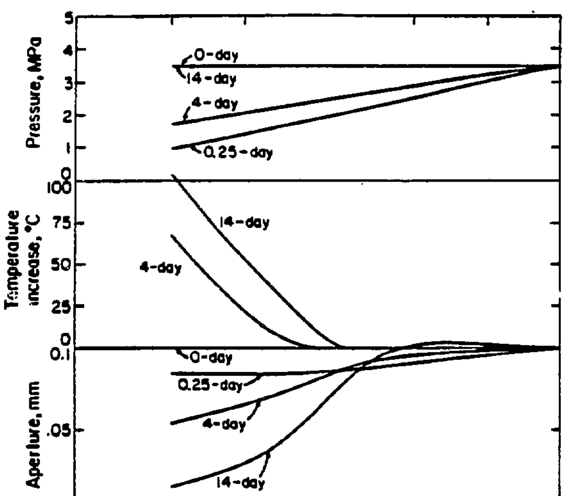


Figure 14. Pressure and aperture profiles in the fracture for various durations and temperature profiles along the heater midplane.

Concluding Comments

The performance assessment of a nuclear waste geologic repository requires a capability to make predictions of transport of low concentrations of radionuclides in the geologic formation for thousands of years. This represents a major challenge. The consideration of coupled processes provides a convenient framework to survey and address major elements that need to be evaluated or modelled in order to perform a proper safety assessment. Such a consideration has opened up new areas of research, such as combined effects of heat transfer, fluid pressure and mechanical stress-displacements in fractured rock masses. Chemical dissolution and precipitation accompanied with temperature gradients and steam-water flows are also new areas of research currently underway.

The present paper attempts to introduce the coupled processes framework, to describe four examples of specific coupled processes in fractured media and to provide references for further study.

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