LBL-29682

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

Invited paper to be presented at the 1991 International High-Level Radioactive Waste Management Conference, Las Vegas, NV, April 28–May 2, 1991, and to be published in the Proceedings

Advances in the Study of Far-Field Phenomena Affecting Repository Performance

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January 1991

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Advances in the Study of Far-Field Phenomena Affecting Repository Performance

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Engineering and Geosciences Division, and by the Director, Office of Civilian Radioactive Waste Management, Office of Geologic Disposal, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ADVANCES IN THE STUDY OF FAR-FIELD PHENOMENA AFFECTING REPOSITORY PERFORMANCE

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ABSTRACT

Studies of far-field phenomena affecting repository performance have focussed on the role of fractures and other heterogeneities in the potential transport of radioactive solutes from the repository to the biosphere. The present paper summarizes two recent advances in the subject: the channeling model for the understanding and analysis of tracer transport in variable-aperture fractures and the modeling of coupled thermo-hydro-mechanical processes in geologic formation around a repository. The paper concludes with remarks on the need for duality in the approach to performance assessment. One line of the duality is fundamental studies and the other, goal-oriented assessment to satisfy regulatory requirements.

INTRODUCTION

If the rock can be represented by a homogeneous porous medium of very low permeability, any leakage from a potential nuclear waste repository in the rock formation to the biosphere would take a very long time. Then it would be possible to select a good site through careful site characterization and evaluation, and to ensure that the current requirements on the performance of a repository are satisfied with a reasonable safety margin. The uncertainty comes in because of the heterogeneity of the medium and in particular rock fractures in the formation which may have a major role in solute transport.

In this paper we present two highlights of recent advances in our study of the flow and transport phenomena in the far field associated with rock fractures. First is the development of channeling model of transport in fractures and its application to field data. The second is the modeling of coupled thermo-hydro-mechanical process in rock formation under heat loading from a hypothetical nuclear waste repository.

CHANNELING MODEL AND ITS APPLICATION TO FIELD DATA

The concept of flow channels was introduced to the study of fractured rocks by Neretnieks and coworkers (Neretnieks, 1983, 1987; Abelin et al., 1985) based on their experiments in single and multiple fractures in Stripa. Motivated by this, Tsang and Tsang (1987) developed the model in which transport through fractured rocks is controlled by a number of channels, each of which has variable apertures along its length. These variable apertures define an aperture probability distribution function which describes the aperture distribution over the two-dimensional plane of a single fracture. Later, Tsang and Tsang (1989) pointed out that these channels are not physical pipes in the fracture plane, but that they arise directly from the wide range of apertures distributed over each fracture. Figure 1 shows schematically a square section of fracture with a spatial distribution of apertures (Fig. 1a) and the flow channeling that results by imposing a potential difference from left to right (Fig. 1b). In Figure 1b, the thickness of lines is made arbitrarily proportional to the square root of the flow rate along the flow path. Thus flow channeling is manifested by the occurrence of a few tortuous channels, each of which is composed of a number of flow paths of comparable mean velocities.

Flow and transport through a system of fractures can then be envisioned as occurring through these tortuous channels of flow paths from fracture to fracture in the three-dimensional space (Fig. 2). These channels may intersect each other within a fracture plane and also between fractures when fractures intersect in a fracture network. The hydraulic conductivity of each channel is controlled by constrictions along the channel, and which is therefore not directly related to the volume or average aperture value of the channel. Transport in the system is then hypothesized to be dependent on the aperture proba-

bility density distribution with a mean aperture value $\bar{b}$ and a spread or standard deviation σ_b, and on the spatial arrangement of the apertures characterized by the spatial correlation length λ.

In many tracer transport experiments the measuring scale is such that the transport distances cover only a few fracture spacings in a fracture network, in which case transport can be studied as flow through a number of fractures in series. A large number of fractures may be generated by a geostatistical method with a specified aperture probability density distribution and a spatial correlation length, and the local flow rates in each of these fractures may be solved separately (Moreno et al. 1988). Then the fracture may be put in series, satisfying the continuity requirement that the identical total flow rate must occur in each fracture. Particle tracking is then carried out in the series of fractures. This conceptualization of fracture-in-series calculations requires the intersection between two fractures to be an equipotential line, which is a reasonable approximation based on the common observation in mines and drifts that the most conductive zone often occurs at intersection of fractures (Abelin et al., 1987).

The channeling model described briefly above is applied to the so-called Stripa-3D data. Details of the Stripa-3D experiment are given by Neretnieks (1987) and Abelin, et al. (1987). The experiment was carried out in the Stripa mine in two drifts in the form of a cross. The longer drift is 75 m long and the shorter intersecting drift is 25 m long. Each drift is 4.5 m in width and 3 m in maximum height. Three vertical boreholes are drilled into the ceilings of the drifts; and in these boreholes nine packered off sections (1 m long) were identified as having large enough local hydraulic conductivity to be suitable for tracer injection. Nine tracers were used and were distributed among the three boreholes. These tracers were collected in over 300 plastic sheets of 1 × 2 m each, covering the ceiling and sides of the drifts. The flow rates at the collection plastic sheets are approximately constant in time, indicating that steady state flow conditions prevail. However, the majority of these sheets did not receive significant flow, and tracer mass tended to concentrate at discrete regions of the drift (see Figure 3).

Only five of the nine tracers are found in significant concentrations in the different plastic collection sheets during the first 30 months of the experiment. These were eosin B, eosin Y, uranine, elbenyl and iodine. The apparent linear transport distances ranged from 10 m to 45 m. Figure 4 shows the injection flow rates as a function of time.

The Stripa-3D data are analyzed based on the insight gained from the variable-aperture channel model. The model suggests that we can consider the tracers to travel along several tortuous channels in a three-dimensional space, each of which is composed of a number of flow paths of comparable but not identical mean velocities, thus giving rise to some kind of dispersion within the 'flow channel'. Of the flow paths which make up the channel, each flow path has variable apertures along its length. No dispersion (Taylor dispersion) is considered within each flow path, and we have ignored possible matrix diffusion and chemical retardation processes with the implicit assumption that the tracers used are conservative over the relatively small travel times (as compared with the time frame of matrix diffusion and chemical retardation processes), so that these are not significant factors. Furthermore, we assume that the travel distances cover only a few fracture spacings so that the 3D fracture network effects are not important. Under all these assumptions, flow velocities and dispersion measures of these 1D channels will be obtained and will be shown to be related to each other and to the basic fracture parameters $\bar{b}$ and σ_b, characterizing the variable-aperture channel model.

Our conceptual model of the Stripa-3D experiment is as follows. Because the underground drift is maintained at atmospheric pressure, it is a major sink for water from the rock around it. The large range of aperture values in the fractures gives rise to flow channeling so that the majority of flow takes place in only selected flow paths of least flow resistance which comprise only a small fraction of the total 3D flow region. When a tracer is injected at a particular location in the flow field, the resultant solution moves downstream along these preferred flow paths toward the drift and emerges in a number of plastic collection sheets. From the experimental measurements we do not have knowledge of the actual flow paths connecting the tracer injection and the particular collection sheet of tracer emergence. However, from the time dependence of the tracer collection, it will be shown below that we can identify channels or groups of flow paths which have comparable residence times.

At Stripa, dilution of the injected tracers is clearly present because the tracer injection flow rate is much smaller than the total exit flow rates at the drift, and also, while the injection flow rate is strongly varying, the collection flow rate is fairly constant over time. Because of the unknown dilution effect of the channel flow, the absolute value of the concentration of the breakthrough curves will not be investigated, and actually this is not needed to obtain the relevant parameters such as mean and standard deviation of aperture values along the flow paths which govern and characterize the advective transport in the fractured medium. In our analysis below, we used the rate of tracer mass accumulation as the observed quantity rather than the more commonly used tracer concentration.

Thus in this conceptual picture, one has a flow channel with emerging flow rate at the collection location while tracer is injected with a given mass per unit time at an upstream location. The tracer mass injected per unit time is proportional to injection flow rate if the injected tracer concentration is constant, as is the case in this experiment. Assuming that the one-dimensional advective-diffusive transport equation holds in the 1D channels, well known analytic solutions are available for the analysis of tracer transport data.

The main complication with the present data set is the strong temporal variation of the tracer injection flow rate (Figure 4). For this a deconvolution method was developed by Tsang et al (1990) who called it the Toeplitz method. The Toeplitz method deconvolutionizes the field data to a_i's which are the tracer breakthrough curves if the tracer injection were a delta function pulse input. All results for the 5 tracers are analyzed and a typical example is shown in Figure 5 for the case of eosin B. This figure with four peaks clearly unveils the multiple channel nature of the tracer transport in the Stripa-3D data. Over the range of distances and observation time periods, eosin-B apparently has four major channels (figure 5), while the other tracers are found to have two channels each. Note that we have defined a channel as a group of nearby flow paths with comparable mean velocities. These results were obtained by applying the Toeplitz analysis to the mean concentration breakthrough curves averaged over all the collection sheets where the tracer arrived. The same analysis was also applied to tracer breakthrough curves for a few specific collection sheets at a single X distance along the experimental drift. Similar results were obtained. Thus the channels do not correspond to different flow tubes arriving at different collection sheets, but rather all sheets appear to display the same multi-channel structure in their respective tracer breakthrough curves.

To quantitatively characterize the channels, we fit the solution of the 1D advective diffusive equation with a delta function tracer injection to each of these peaks in Figure 5. Thus we can obtain the mean tracer velocity v and dispersion coefficient D for each peak and the "channel dispersivity" α is then given by D/v. The results are plotted in Figure 6, which shows the surprising trend of α decreases with the mean travel time $\bar{t} = x/v$, where x is the transport distance of the tracer. Very roughly, the figure appears to show that $\alpha \approx (\bar{t})^{-2}$.

The surprising result that $\alpha \approx 1/\bar{t}^2$ is a direct result of the analysis of the field data. It is in contrast to the case of a porous medium where α is usually assumed to be constant with respect to mean travel time $\bar{t}$. It is also different from the result for flow in a constant-diameter pipe, where the time dependence is given by the Taylor's dispersion, which for small molecular dispersion gives $\alpha \approx x/\bar{t}$. In Stripa 3D data, we find a much stronger $\bar{t}$ dependence for transport through variable-aperture fractures. The basis and implication of this interesting result are yet to be studied. One possible explanation is as follows. Consider the results of deconvolution such as those shown in Figure 5. It can be seen that the standard deviation σ_t of tracer particle arrival times for each of the peaks is about the same with the other peaks in each case, i.e., σ_t appears to be independent of the mean travel times of the peaks. Since the Peclet number for 1D transport along a channel may be expressed (Levenspiel, 1972) as:

$$\alpha = 2x\frac{\sigma_t^2}{\bar{t}^2}$$

then $\alpha \approx (\bar{t})^{-2}$. Now, σ_t is dependent on the variance of fracture apertures or local permeabilities over the 2D fracture plane. For tracer transport along different channels between injection and collection points, this may be approximately the same. However, the mean travel times of these channels may be strongly affected by the local heterogeneity. Thus a local constriction or a relatively large local aperture volume along a flow channel will strongly affect the mean travel times. In other words, for a strongly 2D heterogeneous system as in our case, the mean travel time and the travel time standard deviation may be decoupled. If we extrapolate this line of reasoning, we may conjecture that for the type of system under study, we should not focus on the dispersivity. Rather, we should determine the travel time standard deviations σ_t and mean travel times $\bar{t}$ of the groups of flow paths, or channels. The former, σ_t, is closely correlated to aperture or permeability variance, and can be estimated for the case of Stripa-3D data discussed above. The latter, $\bar{t}$, is strongly affected by the local heterogeneity around the injection location and is not correlated to aperture distribution parameters in our case study. However, if one is able to study the $\bar{t}$ values for a larger number of such transport channels, we expect that the mean of these $\bar{t}$ values can be correlated to the basic aperture probability distribution parameters.

COUPLED THERMO-HYDRO-MECHANICAL BEHAVIOR AROUND A REPOSITORY

Because of radioactive decay of the waste, nuclear waste repository releases considerable energy over thousands of years after its closure. This gives rise to mechanical stress changes and hydrologic buoyancy flow in the geologic formation. To be able to model such coupled thermo-hydro-mechanical (THM) processes in order to carry out repository performance assessment presents a considerable challenge.

Coupled processes around a nuclear waste repository (Tsang, 1987) has been under active research during the last few years. Recently a far-field regional analysis was made, illustrating the advancing state-of-the-art on the subject. The numerical code used is the ROCMAS code (Noorishad, et al, 1984) which has continued to be improved and enhanced since its early development. The code has been verified against a number of known solutions.

A repository is assumed to be located at a depth of 600 m and has a length and width of 3 km. The analysis of the coupled processes is performed on the two dimensional vertical cross section of the rock-repository system which possibly emulates a worse case scenario. The modeled section has a vertical dimension of 2.2 km and a horizontal dimension of 18 km. Figure 7 shows the cross section with the vertical scale exaggerated by 5 times. We placed two major fractures in this section; a horizontal fracture that intercepts the repository in its plane and a vertical fracture that cuts through the repository along its plane of symmetry. Both fractures extend to the model boundaries. A regional hydraulic gradient of 0.1 percent and a geothermal gradient of 30 °C/km were assumed to exist in the model. Material properties assumed are shown in Table 1. The repository is represented by a flat disk, coinciding with the horizontal fracture, and possesses a decaying thermal power output. The power decay curve is adapted from Wang and Tsang (1980) with a 10-year cooled down power output of 14.4 W/m^2 gross thermal loading for the spent fuel. This selected power is chosen in some level of conformity with one of the scenarios of the Atomic Energy of Canada, (Acres, 1978). A study of a modified Raileigh number for a laterally infinite system, with characteristics similar to the waste repository model, indicates a possibility of development of natural thermal circulation pattern in the absence of the regional hydrologic gradient.

Simulation times of interest for performance assessment of a repository range to thousands of years. This immediately brings out the difficulty of obtaining a time marched solution of the THM processes occurring in the host geologic system. There is a large discrepancy in the time constants of the heat transport and the mass flow phenomena since the flow processes take place rather fast compared to the slowly changing temperature field. Following an approach used by Runchal [1980], for investigation of the role of convection in the evolution of temperature field around a repository, we adapted a snapshot approach for the solution of the fluid flow part of the THM processes. Within this strategy, the evolution of the quasi-static thermomechanical processes was followed by a time marched simulation of the THM phenomena which uses a steady-state solution of the coupled flow-deformation equations at each time increment. This approach not only provides a reasonably correct picture of the thermohydromechanical state of the problem, it also saves very effectively on the computation cost.

The nonlinearity introduced in the model is that of the two extensive fractures which span the model. The results reveal noticeable effects. We present here an example of the thermal, flow and stress patterns 1000 years after repository closure. Figure 8 gives the temperature contours. Far away from the repository, the temperature field follows the initial geothermal gradient. The presence of the repository is accompanied by a local high temperature region. Figure 9 shows the distribution of fluid flow directions which includes the initial regional flow from left to right and the induced bouyancy flow due to the thermal output from the repository. The buoyancy flow velocity is generally larger in magnitude in the fractures. However, the quantity of water involved is small and is thus not noticed in this figure. The principal stresses at 1000 years is shown in Figure 10. Originally they are parallel to r and z directions increasing in magnitude as a function of depth. The influence of heating from the repository and of the presence of the major horizontal and vertical fracture can be seen in this figure. The normal stress changes along the vertical fracture from the repository to land surface ranges over two orders of magnitude, resulting in aperture increases near the surface and decreases near the repository.

These results are shown to demonstrate the advancing capability of performing more realistic calculations. Further studies are underway to apply these capabilities to repository performance assessment, and to identify critical phenomena involved, important parameters to be measured and key elements that may impact repository safety.

CONCLUDING REMARKS

Advances are continued to be made in the study of far field phenomena that may impact nuclear waste repository performance. This paper highlights two of these advances. In this context, we would like to make the following remarks.

The performance assessment of a nuclear waste repository is an endeavor that is "first of its kind". How well it is done depends strongly on the state-of-the-art. New understanding of processes may have significant impact on how performance assessment is done. For example, this paper introduces new understanding of channeled flow and questions the meaning of channel dispersivity. It also points out the coupled effects of thermo-hydro-mechanical processes. On the other hand, performance assessment of a nuclear waste repository does not require the capability of being able to quantita-

tively evaluate all physical and chemical factors affecting a repository. The requirement is only that sufficient confidence is obtained whether or not repository performance satisfies regulatory requirements. Thus our view is that a responsible performance assessment program should include two lines of work. The first line is fundamental studies of various scientific and technical issues related to a geologic repository to improve the general scientific understanding and calculational capability. This should be maintained continually with a second line, which is to carry out goal-oriented and perhaps hierarchically-structured performance assessment. The latter includes only the elements required to determine whether the repository performance satisfies regulatory requirements. However, new advances on the first line may strongly affect the execution of the second line. To carry out proper performance assessment of a nuclear waste repository both lines are equally needed.

ACKNOWLEDGMENTS

The paper covers work done in cooperation with F.V. Hale, J. Noorishad and Y.W. Tsang, whose contributions are gratefully acknowledged. Work is jointly supported by the Director of Office of Energy Research, Office of Basic Energy Sciences, Engineering and Geosciences Division, and by the Director, Office of Civilian Radioactive Waste Management, Office of Geologic Disposal of the U. S. Department of Energy under contract No. DE-AC03-76SF00098.

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— Table 1. Material Properties Used for Various Runs with ROCMAS

Material	Parameter	Laboratory/Field* Data	Modeling Data
Fluid:	Mass density, ρ_l		997 kg/m^3
	Compressibility, β_p		5.13×10^{-1} GPa^{-1}
	Dynamic viscosity at 20°C, n_l		1×10^{-3} N–sec/m^2
	Thermal expansion coefficient		3.17×10^{-4} °C^{-1}
	Specific heat		1.0 kcal/kg
Rock:	Young's modulus, E_s	80 GPa	35 GPa
	Poisson's ratio, ν_s	0.25	0.25
	Mass density, ρ_s	2.9×10^3 kg/m^2	2.9 times10^3 kg/m^3
	Porosity, ε		0.015
	Intrinsic permeability, k		10^{-20} m^2
	Biot's constant, M		130 GPa
	Biot's constant, α		1.0
	Thermal expansion coeficient		1.1×10^{-5} °C^{-1}
	Specific heat		2×10^{-1} kcal/kg
	Solid-fluid thermal conductivity		6.9×10^{-4} kcal/m · sec · °C
Fracture:	Initial normal stiffness, K_n	1620 GPa/m	1620 GPa/m
	Initial tangential stiffness, K_s		3 GPa/m
	Initial aperture, b	17 microns	17 microns
	Porosity, ε		1.0
	Biot's constant, M		2 GPa
	Biot's constant, α		1.0
	Radius, r		1.2 m
	Initial normal stress, σ_0	10.2 MPa	8.6 mpa

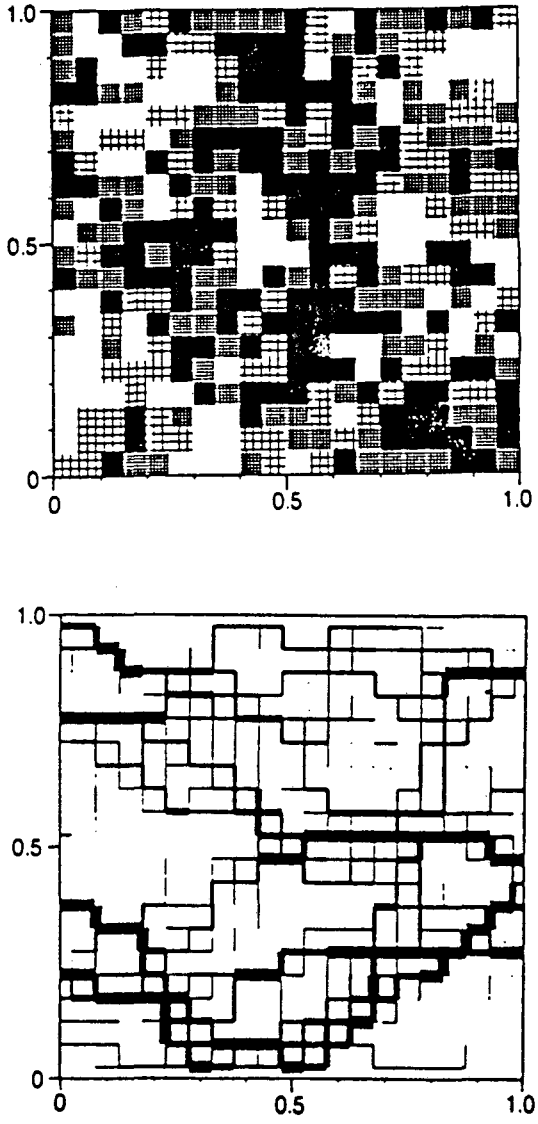

Figure 1. A discretized representation of apertures in a fracture plane is shown above. The magnitudes of the apertures are indicated by shading, with lighter shading corresponding to larger apertures. Relative flow rates for the apertures are shown below, assuming constant pressure boundaries on the left side of the first fracture and the right side of the second fracture. Flow is from left to right with upper and lower boundaries closed. Thicker lines indicate larger flow rates.

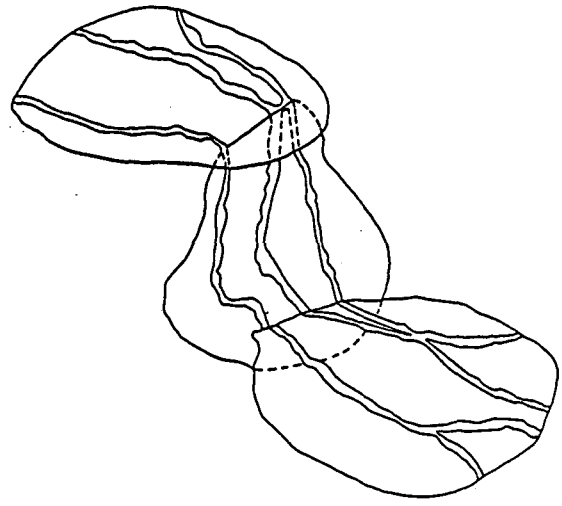

Figure 2. Conceptual model of flow channeling through three fractures in series.

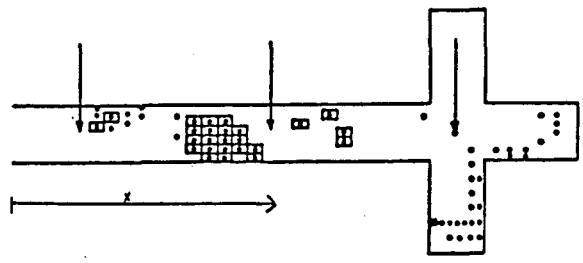

Figure 3. A diagram showing tracer emergence distribution in the Stripa 3D test site. The arrows indicate the positions of the injection holes; dots indicate sheets with significant water flow; and squares indicate sheets where tracers were collected.

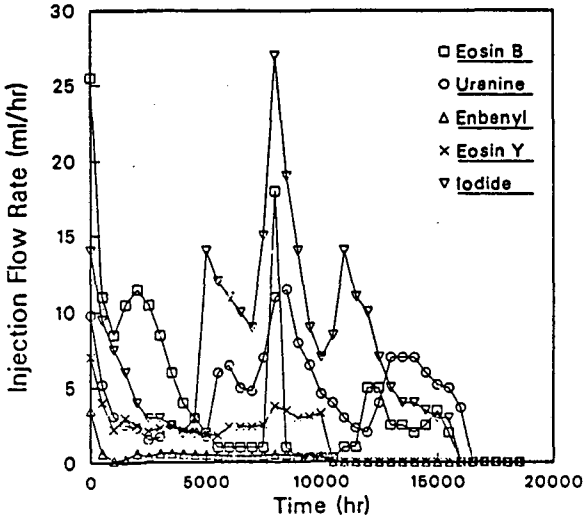

Figure 4. Injection flow rates in ml/hr for the five tracers; points are estimates for average flow rates over 500 hour intervals.

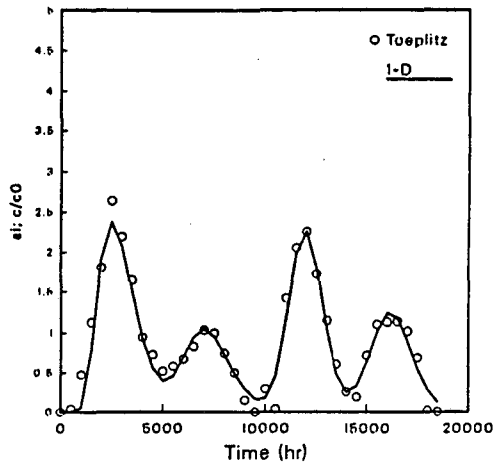

Figure 5. Results of Toeplitz analysis method for Eosin B. The circles are the normalized results of the Toeplitz analysis, and the solid line is the fit of the 1D advection-diffusion equation to the normalized results, separated into distinct peaks.

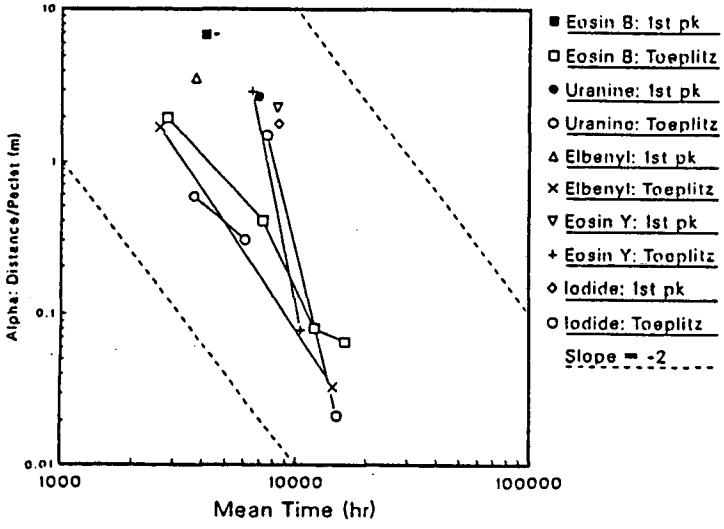

Figure 6. Log-log plot of $\alpha = D/v$ versus mean arrival time of each channel. The broken lines indicate a slope of -2.

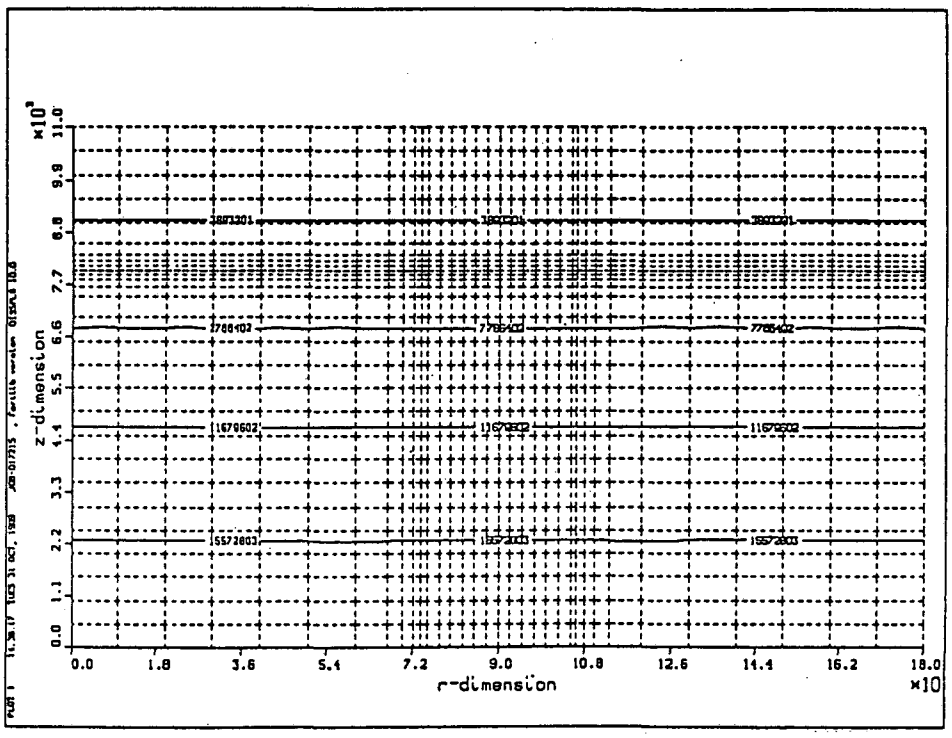

Figure 7. Model sketch with vertical scale exagerated five times. This sketch is used in the rest of the figures.

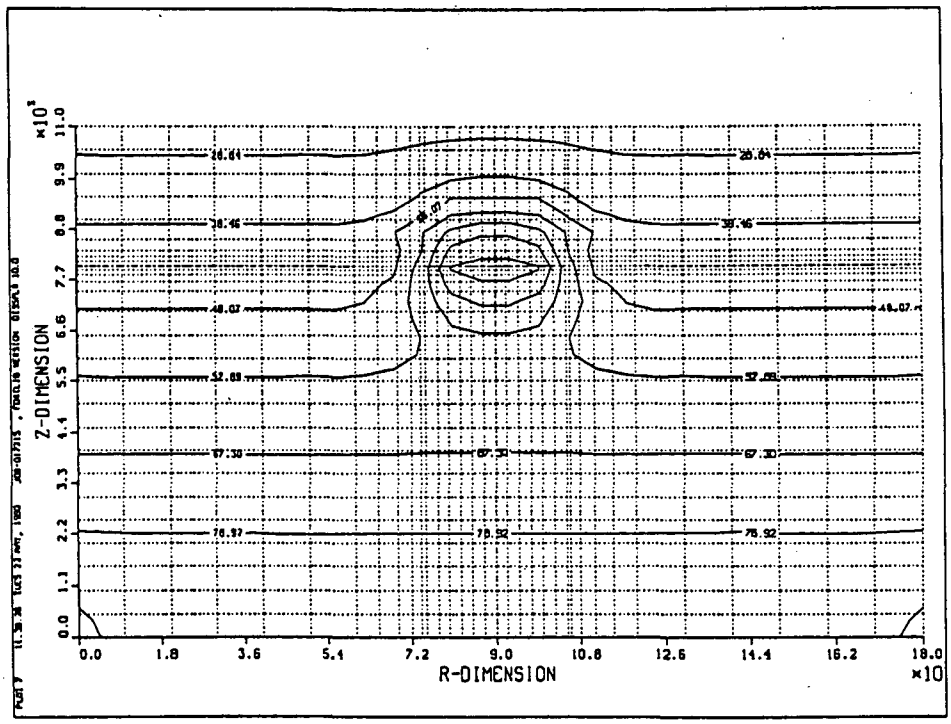

Figure 8. Temperature contours at 1,000 yrs.

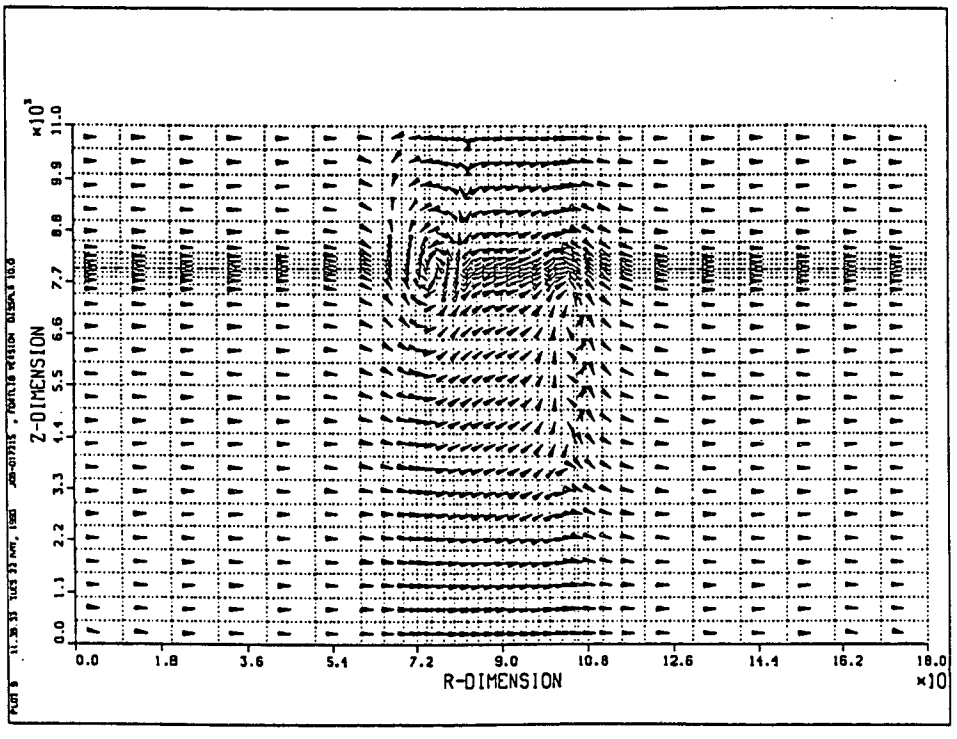

Figure 9. Flow direction at 1,000 yrs.

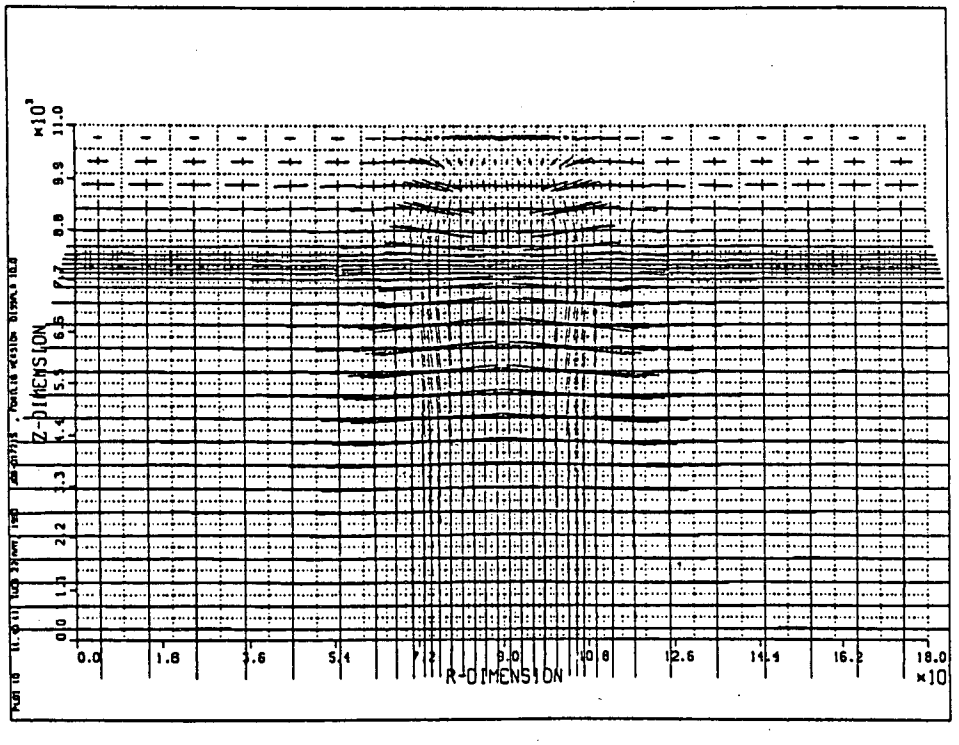

Figure 10. Principal stresses at 1,000 yrs.

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