CNWRA 93-002

THERMO-HYDRO-MECHANICAL COUPLED MODELING:

NEAR FIELD REPOSITORY MODEL, BMT3

DECOVALEX - PHASE II

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-88-005

Prepared by

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

August 1993

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Coupled Modeling: Near-Field
Repository Model, BMT3 DECO

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ABSTRACT

This report presents results of a distinct element analysis for one of the two problems identified for modeling during Phase II activities of the international cooperative project DECOVALEX (acronym for the **DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments in nuclear waste isolation). The analysis was conducted for the benchmark test (BMT) problem identified as the Near-Field Repository Model (BMT3) using the Universal Distinct Element Code (UDEC). This BMT problem was designed to compare modeling results based on both continuum and discontinuum approaches for simulating coupled thermal-hydrological-mechanical (THM) behavior in the near-field repository environment, in which a tunnel and a thermal source are emplaced in a highly fractured rock mass. Future comparison of mechanical stresses, displacements, temperatures, and fluid flowrates will be made among the computer codes and modeling approaches used during Phase II of DECOVALEX.

For the discrete element analysis presented in this report, a vertical plane of symmetry through the tunnel axis was assumed to simplify the model geometry for the BMT3 problem. In addition, two separate cases were run with the UDEC code. The first case modeled a representative fracture distribution only for the immediate region around the tunnel, while the outer region was approximated using equivalent matrix and fracture properties. The second case modeled a representative fracture distribution throughout the 25 × 50 m symmetric region. The second case took substantially longer to run than the first case using a Sun workstation, and thus would be more amenable to running on a Cray computer. Due to the long run time, this second case was analyzed up to the thermal loading period of 1 yr instead of 100 yr, which was done for the first case. The results from these two cases for up to the thermal loading period of 1 yr were not substantially different.

The UDEC results for the BMT3 problem show that the fluid flow into the tunnel is dominated by only a few fractures. This amount of flow is small due to the apertures specified. Based on the given thermal characteristics of the heat source and rock medium, the peak temperature is reached after 4 yr of heating. At this time, the thermal expansion within the rock causes a significant reduction in the flowrate into the tunnel. The flowrate again increases with subsequent decay of the heat released at the source.

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EXECUTIVE SUMMARY

Simulation of the thermal-hydrological-mechanical (THM) behavior of the benchmark test (BMT) problem chosen for modeling during Phase II of DECOVALEX (acronym for the **DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments in nuclear waste isolation) is presented herein. This BMT problem was identified as the Near-Field Repository Model (BMT3) and was simulated using the Universal Distinct Element Code (UDEC). The primary objectives of the DECOVALEX study are to validate coupled THM models believed to be critical to the licensing of a high-level nuclear waste (HLW) repository, as well as to identify the needs for further development of the computer codes based on the importance of the various coupling mechanisms. The DECOVALEX study includes both BMT and test case (TC) problems. The BMT problems are used to compare the results from different computer codes capable of modeling THM behavior. The TC problems are used to compare the computer code results with those from actual experiments that have been designed for the DECOVALEX study. One BMT and one TC problem were chosen by the DECOVALEX Secretariat for the DECOVALEX Phase II study. The Center for Nuclear Waste Regulatory Analyses (CNWRA) research team analyzed only the BMT3 problem for this Phase II study.

The BMT3 problem was formulated for a 50 × 50 m (section) rock block containing a horseshoe-shaped tunnel at its center, with a thermal source at a shallow depth below the tunnel invert. The floor of the tunnel was situated at a depth of 500 m below the ground surface. For the distinct element formulations, mechanical and hydrologic data were provided for the approximately 6,580 random fractures specified for the problem. Due to the large number of fractures and lack of preferred orientation, several assumptions and simplifications were made for the distinct element model using UDEC. The first simplification was to assume vertical symmetry for the two-dimensional (2D) UDEC model based on the symmetrical boundary conditions and random nature of the fracture distribution. The second simplification was to reduce further the number or density of fractures to make the problem computationally feasible. To determine the impact of this simplification, two separate cases were run, each with a different fracture density.

The first UDEC model (Case A) for the BMT3 problem contained 211 fractures, forming 337 distinct element blocks and 1,540 finite difference zones. This model contained essentially two regions. The inner region around the tunnel contained a fairly dense set of fractures as simplified from the original problem by including only those fractures longer than 2 m. The outer region extending to the model boundaries contained a uniform set of evenly spaced horizontal and vertical joints with an assumed spacing of 5 m. These outer joints were necessary primarily to allow connectivity of the flow from the top boundary where a constant fluid pressure was applied to the inner region containing the tunnel, since UDEC considers fluid flow through fractures only. Appropriate mechanical and hydrologic properties were developed for the rock mass in this outer region to represent the original problem.

The second UDEC model for the BMT3 problem (Case B) assumed again vertical symmetry; however, the dense fracturing extended from the tunnel boundary to the outer model boundaries. This model still did not incorporate all the fractures specified in the original reference fracture pattern. Only those fractures longer than 1.5 m were included in the model. Thus, this second model contained 1,799 fractures forming 2,497 discrete element blocks. These blocks were discretized into 6,001 finite difference zones.

Distinct element results from UDEC are given for the stresses, displacements, fracture flowrates, and temperatures at specified points and regions in the vicinity of the tunnel, for the following stages: (i) initial hydromechanical equilibrium without the tunnel, (ii) hydromechanical equilibrium after excavation of the tunnel, and (iii) various periods of thermal loading. The discrete element results showed that the majority of the flow into the tunnel occurs along one or two dominant fractures. The water pressures within the fractures were near zero within a small region extending approximately 5 to 10 m from the tunnel boundary due to the zero pressure boundary condition specified along this tunnel boundary after excavation. Beyond this region, the pore pressures increased rapidly to their initial *in situ* values. Also, due to the orientation of the fractures around the tunnel, the immediate wall and floor of the tunnel became destressed, and larger inward displacements occurred. For the given thermal properties of the source and surrounding media, the peak temperature was reached after 4 yr of heating. At this peak thermal output time, a significant decrease in the total flowrate across the excavation boundary was seen as a result of thermal expansion and closure of fracture apertures. At longer thermal times, the flowrate into the tunnel gradually increased again. The computer run time for the more detailed UDEC model (Case B) was substantially longer than that for Case A, and consequently was analyzed up to the thermal loading period of 1 yr. The results between the two cases, however, were not substantially different. There was no closed-form solution to this problem, so comparisons of results for the BMT3 problem obtained from the different research teams involved in DECOVALEX Phase II study will be conducted, and a final report will be issued by the DECOVALEX Project Secretariat upon completion of the Phase II modeling activities.

1 INTRODUCTION

1.1 BACKGROUND

DECOVALEX (acronym for the **DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments in nuclear waste isolation) is an international cooperative project to support the development of mathematical models of coupled processes in the geosphere and their applications and validation against experiments in the field of nuclear waste isolation. The DECOVALEX project has been organized to increase the understanding of three processes, thermal-hydrological-mechanical (THM), for rock mass stability and radionuclide release and transport from a repository to the biosphere and to assess how they can be described by mathematical models. The state-of-the-art and possible directions of future research in the field of coupled processes can be found in the literature (Tsang, 1991; Manteufel et al., 1992). The DECOVALEX project was started in 1991. The first DECOVALEX workshop was held in Stockholm, Sweden, on May 18–20, 1992, to present, discuss, and compare the results of DECOVALEX Phase I study (Jing et al., 1993). The Phase I study included three problems: (i) Far-Field THM Model, BMT1; (ii) Multiple Fracture Model, BMT2; and (iii) Coupled Stress-Flow Model, TC1. Eleven research teams, including the Center for Nuclear Waste Regulatory Analyses (CNWRA), were participants in the DECOVALEX Phase I study. For the Phase I study, the CNWRA research team conducted coupled analysis on two of the three problems: (i) Multiple Fracture Model, BMT2; and (ii) Coupled Stress-Flow Model, TC1 (Ahola et al., 1992). These two problems were analyzed using the Universal Distinct Element Code (UDEC) developed by Itasca Consulting Group, Inc. (Itasca, 1992).

During this first DECOVALEX workshop, one benchmark test (BMT) and one test case (TC) problem were selected for modeling in Phase II of DECOVALEX. The BMT problem — Near-Field Repository Model, BMT3 — is a new problem formulated for DECOVALEX Phase II study. The TC problem — Coupled Stress-Flow Model, TC1:2 — is a revision of the Coupled Stress-Flow Model, TC1, modeled during Phase I, with additional features and modifications to aid in overcoming some modeling problems encountered during Phase I. This report presents the analysis results of DECOVALEX Phase II study conducted by the CNWRA research team using Version 1.8 of UDEC (Itasca, 1992).

1.2 DECOVALEX PROBLEMS: PHASE II

The two problems chosen for modeling during Phase II of DECOVALEX are briefly discussed below.

- Near-Field Repository Model, BMT3. This BMT was designed to simulate the THM processes in fractured rock in the near-field repository environment. The model had dimensions of 50 × 50 m and contained 6,580 fractures forming a complicated fracture pattern within the model. The center of the model contained a horseshoe-shaped tunnel, with invert located 500 m below the ground surface. A decaying heat source was located at a shallow depth (2.5 m) below the tunnel invert. The water table was assumed to be located at the ground surface. The modeling sequences consisted of: (i) establishing initial hydromechanical equilibrium, (ii) excavating the tunnel and establishing a new hydromechanical equilibrium, and (iii) thermal loading with convection boundary condition on the tunnel surface. The BMT was proposed and formulated by research teams from France (ANDRA, CEA/DMT, and INERIS), United Kingdom [AEA Technology Decommissioning and Radwaste (AEA D+R)], and Norway [Norwegian Geotechnical

Institute (NGI)]. Detailed specifications of this problem are given in DECOVALEX Doc 92/112 (1992b).

- Coupled Stress-Flow Test, TC1:2. This TC problem, TC1:2, was a Phase I problem TC1 (DECOVALEX Doc 91/105, 1991) that was revised for Phase II of DECOVALEX. The new TC1:2 was specified with different joint properties and a more detailed description of the testing equipment and procedures. The TC problem was designed to compare modeling results with experimental test data. The experimental testing apparatus was designed and built by the NGI to quantify the effects of joint displacement and joint conductivity. With this experimental apparatus, joints can be closed and sheared under stress-controlled conditions while fluid is flushed through the joint. Displacements and stresses are recorded simultaneously. The joint properties are specified by NGI in accordance with the Barton-Bandis joint model. The Coupled Stress-Flow Model has been prepared by N. Barton of NGI. The specifications of this problem are given in DECOVALEX Doc 92/111 (1992a).

1.3 COMPUTER PROGRAMS FOR THM PROCESSES

Currently, few codes are capable of solving coupled three-dimensional (3D) THM problems in fractured rock masses (Manteufel et al., 1992; Kana et al., 1991). Some of the two-dimensional (2D) and 3D computer programs with various degrees of THM-coupled modeling capabilities being used or considered by DECOVALEX research teams from several countries include: ROCMAS I, II (Noorishad and Tsang, 1989), GENASYS (Wijesinghe, 1989), THAMES 3D (Ohnishi et al., 1985), FEHMS (Kelkar and Zyvoloski, 1990), UDEC (Board, 1989a), 3DEC (Hart et al., 1988), FLAC (Board, 1989b), JOBFEM (Stille et al., 1982), MOTIF (Jing et al., 1993), ADINA-T (Bathe, 1981), JRTEMP (Halonen, 1989), and the three code set of VIPLEF, CHEF, and HYDREF (Tijani, 1991). The CNWRA research team has selected UDEC for DECOVALEX Phases I and II analyses. The selection of UDEC is based on the findings of the code qualification study of the CNWRA Seismic Rock Mechanics Research project (Brady et al., 1990a) and the degree of THM-coupled modeling capability of UDEC.

1.4 OBJECTIVE AND STRUCTURE OF THE REPORT

The CNWRA research team has conducted THM-coupled analysis on one problem in the second phase of DECOVALEX. This problem — the Near-Field Repository Model, BMT3 — was analyzed using the distinct element computer program UDEC. This report presents the analysis results of this problem in a format suggested by the DECOVALEX Project Secretariat. Section 2 gives a brief mathematical description of UDEC along with problems encountered with the code during the Phase I studies. Section 3 gives a description as well as chronology of development of UDEC. Comments on the given specifications for the BMT3 problem are given in Section 4, and Section 5 briefly describes the BMT3 problem as well as the UDEC modeling approach. Sections 6 and 7 give the results and follow-up discussion of the results, respectively. Recommendations for future modeling of this BMT problem are given in Section 8. Finally, summary and conclusions are discussed in Section 9.

2 MATHEMATICAL BACKGROUND OF THE UDEC CODE

2.1 BRIEF MATHEMATICAL BACKGROUND OF THE UDEC CODE

A brief mathematical background of UDEC has been provided in the DECOVALEX Phase I reports (Ahola et al., 1992; Jing et al., 1993). This computer code can be used to model the THM processes with fluid flow through the fractures, that is, in cases where the rock matrix may be assumed to be impermeable. UDEC is based on the distinct element method in which a rock mass is represented as an assemblage of discrete blocks. Joints are viewed as interfaces between the discrete bodies. A fully coupled mechanical-hydraulic analysis is performed in which fracture conductivity is dependent on mechanical deformation and, also, joint water pressure affects the mechanical behavior. The heat transfer in UDEC is based on conductive transfer within the medium with the provision for constant temperature, constant flux, convective, or radiative boundaries. One-way thermal to mechanical coupling behavior is provided in UDEC.

2.2 MODELING DIFFICULTIES ENCOUNTERED IN UDEC DURING DECOVALEX PHASE I STUDY

During the first phase of DECOVALEX, UDEC was used by several research teams (Jing et al., 1993) to model BMT1 (Far-Field THM Model), BMT2 (Multiple Fracture Model), and TC1 (Coupled Stress-Flow Model) problems. In general, for the two benchmark problems, no modeling difficulties were encountered with UDEC, nor were any problems with the code found. Comparison of UDEC results with other finite element codes for these two benchmark problems, as presented in the final report on DECOVALEX Phase I (Jing et al., 1993), shows fairly good agreement. For Coupled Stress-Flow Model (TC1), some problems were identified with the Barton-Bandis nonlinear joint model in UDEC. More specifically, the code was found to be unable to accurately represent the changes in joint behavior (e.g., dilation, aperture, and flowrate) upon reversal of the shear loading, even though the shear stress loading history appeared to be correct. Also, the characteristic hysteresis during normal loading and unloading of the joint for TC1 did not appear to be correctly modeled using the Barton-Bandis model. Continuation of the modeling of TC1 into DECOVALEX Phase II by other research teams using UDEC, and further comparison with the experimental results obtained by NGI, will help to further identify and resolve these problems with the formulation of the Barton-Bandis model in UDEC.

3 DESCRIPTION OF UDEC

Formulation and development of the distinct element method have progressed for over 20 yr, beginning with the initial presentation by Cundall (1971). The method was developed originally as a 2D representation of a jointed rock mass, but has been extended to applications in particle flow research (Walton, 1980), studies on micromechanics of granular media (Cundall and Strack, 1983), and crack development in rocks and concrete (Plesha and Aifantis, 1983; Lorig and Cundall, 1987). The most recent 2D program, UDEC, was developed in 1980 (Cundall, 1980; Lemos et al., 1985) to combine into one code a formulation capable of representing both rigid and deformable blocks separated by discontinuities. The chronology of development of the distinct element method, and UDEC in particular, is shown in Figure 3-1.

Over the years, the performance of UDEC has been verified for specific problems through numerous studies (Board, 1989a; Brady et al., 1990a, b; Lemos and Lorig, 1990; Itasca, 1992). These verification studies have shown reasonable agreement with analytical solutions or results obtained using other codes. UDEC has also been used to analyze the results of field tests (Brady et al., 1985; Hart et al., 1985) and to predict the results of laboratory tests. UDEC simulations of jointed rock problems involving response to storage of high-level nuclear waste (HLW) have been conducted by many investigators (e.g., Johansson et al., 1991a, b; Board, 1989a; Christianson, 1989; Lorig and Dasgupta, 1989).

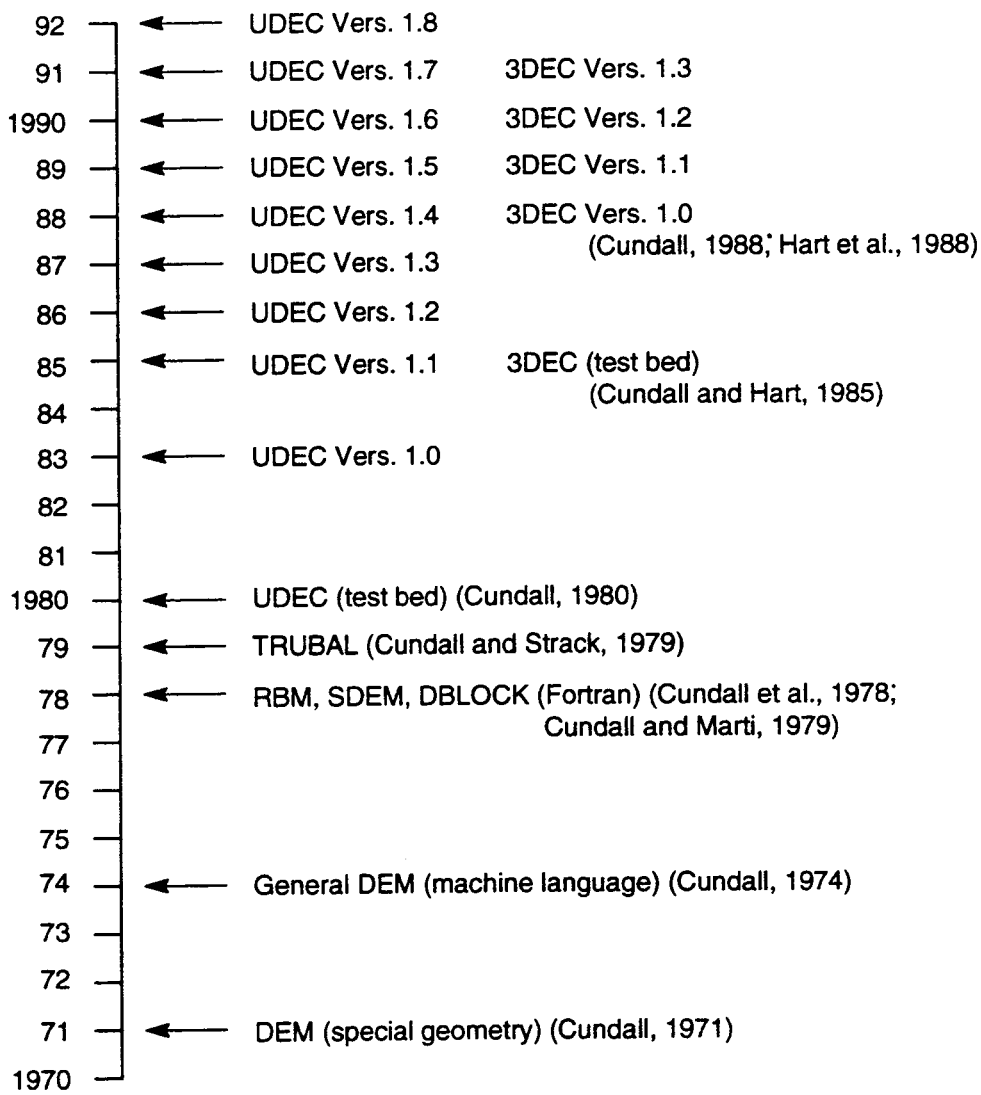


Figure 3-1. Chronology of the distinct element method

4 COMMENTS ON THE GIVEN SPECIFICATIONS FOR THE BMT3 PROBLEM

Overall, the specifications for the near-field repository model are relatively complete and well formulated. The following comments relate to specific aspects of the BMT model:

- Thermal Boundary Conditions. The dimensions of this near-field model are 50 × 50 m, with a tunnel centered within the model. With the heater positioned vertically below the tunnel floor, the horizontal distance to either the left or the right boundary of the model from the heater is 25 m. However, the distance from the bottom of the canister to the lower model boundary is only 17.5 m. As given in the specifications, the vertical and lower model boundaries are adiabatic (i.e., no heat flow across the boundaries), while a constant temperature is specified for the top boundary. The problem specifications request results after 100 yr of thermal loading. It is expected that, after years of heating, the temperatures along these boundaries will rise from the initial temperature. If the two vertical boundaries were designed to represent lines of symmetry, in which there would be another tunnel and a waste canister at an equal distance beyond these two vertical boundaries, then no-flux boundary conditions are valid regardless of the thermal time. The upper and lower boundaries are likely far-field conditions and not lines of symmetry. Due to their relatively close proximity to the heat source, the specified boundary conditions are appropriate only if very short thermal times are studied.

- Fracture Apertures. For this BMT problem, the fluid flow is largely governed by fracture apertures on the order of a few micrometers (see discussion in Section 5). Although the fracture pattern does have some apertures ranging up to 60 micrometers, these fractures do not form a complete flow path that transgresses through the model. Thus, they are interconnected with fractures having smaller apertures that, in turn, govern the flow. Because of large differences in fracture apertures as the problem progresses, a large number of explicit timesteps are required to reach fluid equilibrium upon excavating the tunnel and applying the thermal load. In addition, fluid flowrates into the tunnel appear to be extremely small. The apertures discussed in the problem specifications were not clearly defined. It would be interesting to know if these apertures are mechanical apertures or so-called conducting apertures.

- Material Properties. The bulk modulus for water was not specified. Although not critical for the analyses presented here, a more complete problem specification should include the bulk modulus of water. In specifying the water bulk modulus, it is important to note that as little as 1 percent of air dissolved in water can reduce the bulk modulus by one order of magnitude.

5 NEAR-FIELD REPOSITORY MODEL, BMT3

5.1 BRIEF DESCRIPTION OF THE PROBLEM

The near-field repository model has been designed to test various numerical modeling capabilities of different codes (e.g., discontinuum, continuum) in simulating THM-coupled processes in a near-field repository environment containing a tunnel and heater. The model has dimensions of 50 × 50 m and is centered about an origin located at a depth of 500 m below the surface. Figure 5-1 shows the locations and dimensions of the tunnel and heater for this near-field problem. The rock mass is assumed to be highly fractured, and a plane strain condition is assumed. The mechanical boundary conditions are such that all outward boundary surfaces of the model are fixed in the normal direction, except the top surface, at which the overburden weight is applied. The mechanical initial conditions are defined by an initial isotropic state of stress given as

$$\sigma_x^o = \sigma_z^o = -\rho g(500-z) \tag{5-1}$$

where

$\overset{\circ}{\sigma}_x$, $\overset{\circ}{\sigma}_z$ = initial horizontal and vertical stresses (MPa)
ρ = rock density (kg/m^3)
g = acceleration due to gravity (m/s^2)
z = vertical coordinate (m)

The hydraulic boundary conditions consist of no flux along the two vertical surfaces and bottom surface, as well as a constant water pressure along the top boundary, which corresponds to a depth of 475 m. The fluid pressure along the tunnel boundary is fixed at zero once the tunnel is excavated. All fractures are assumed to be fully saturated, at least initially. Initial thermal conditions consist of a constant temperature of 27 °C throughout the model. This initial temperature is held fixed along the top surface of the model, while both vertical surfaces and the lower surface are assumed adiabatic. The tunnel surface is assumed to behave as a convective boundary upon excavation in which the flux condition is given as

$$q_t = h(T_{\text{wall}} - T_g) \tag{5-2}$$

where

q_t = thermal flux across the tunnel surface (W/m^2)
h = heat transfer coefficient (W/m^2 °C)
T_{wall} = wall temperature (°C)
T_g = constant tunnel temperature (°C)

The heat source simulating the waste canister is assumed to decay exponentially with time according to the following relation

$$Q(t) = Q_o \exp(-\beta t) \tag{5-3}$$

where

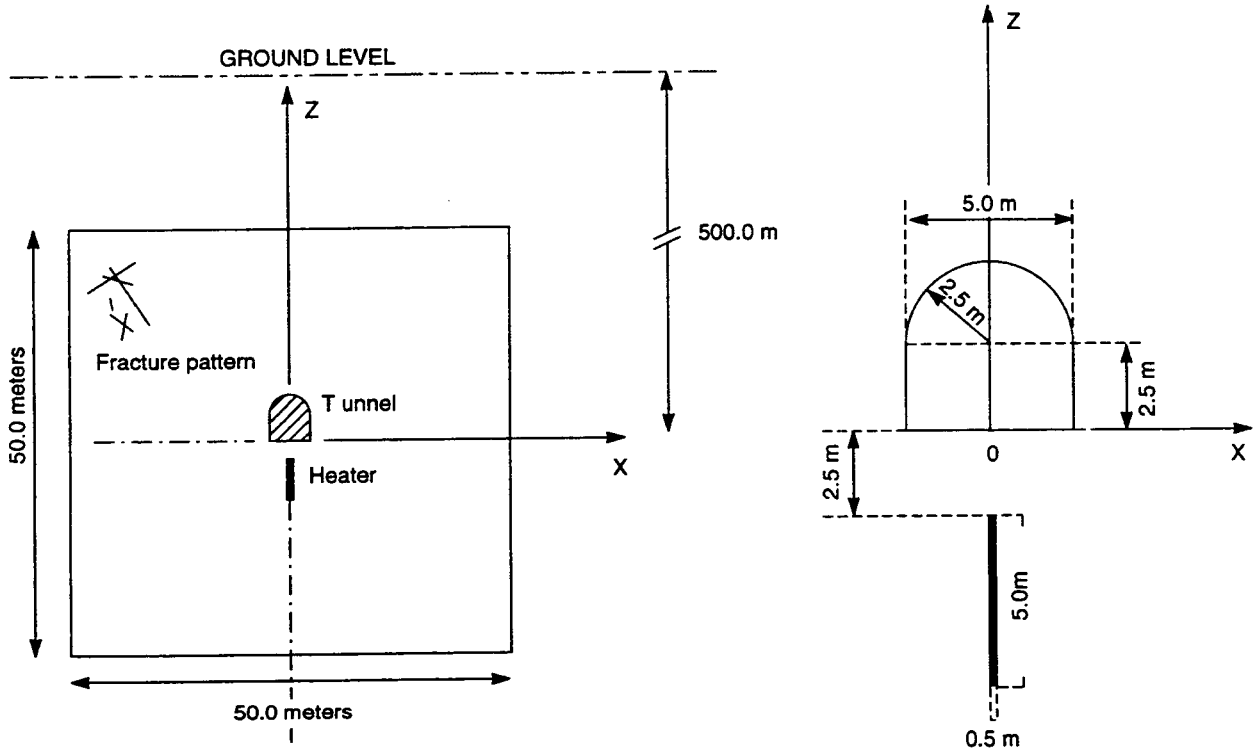


Figure 5-1. Near-field repository model, BMT3

$Q(t)$ = heat flux at time t (W/m^3)
Q_o = initial heat flux at time zero (W/m^3)
β = heat decay coefficient (1/s)
t = time (s)

For this problem, both Q_o and β are constant. The total power output of the heat source as a function of time is thus obtained by multiplying $Q(t)$ by the volume of the source, which in this problem is 2.5 m^3 assuming a unit depth. Material properties and other data for the thermal, hydrological, and mechanical behavior are given in the report on the problem specifications for BMT3 (DECOVALEX, 1992b).

The problem specifications for BMT3 give each individual fracture location, aperture, and joint set number for use in a discontinuum analysis of the problem. Conversely, equivalent permeabilities based on different square cell sizes are supplied for use in continuum formulations to the problem. The following discussion focuses on a discontinuum modeling approach used in this study. Figure 5-2 shows the 2D reference fracture pattern provided for the problem. A total of 6,580 fractures exist in this reference geometry. It can be seen that, in many locations throughout the model, these fractures form narrow blocks with very acute angles as well as blocks with very complex shapes. A few of these areas are encircled as shown in Figure 5-2. These encircled areas can potentially create some problems for the UDEC code, namely excessive contact overlap due to blocks with sharp corners as well as difficulties in zoning of blocks into deformable finite difference elements. Thus, some simplifications in the modeling approach and overall number of fractures are necessary in order to make the problem feasibly approachable, both in terms of those problems identified above as well as computer run time.

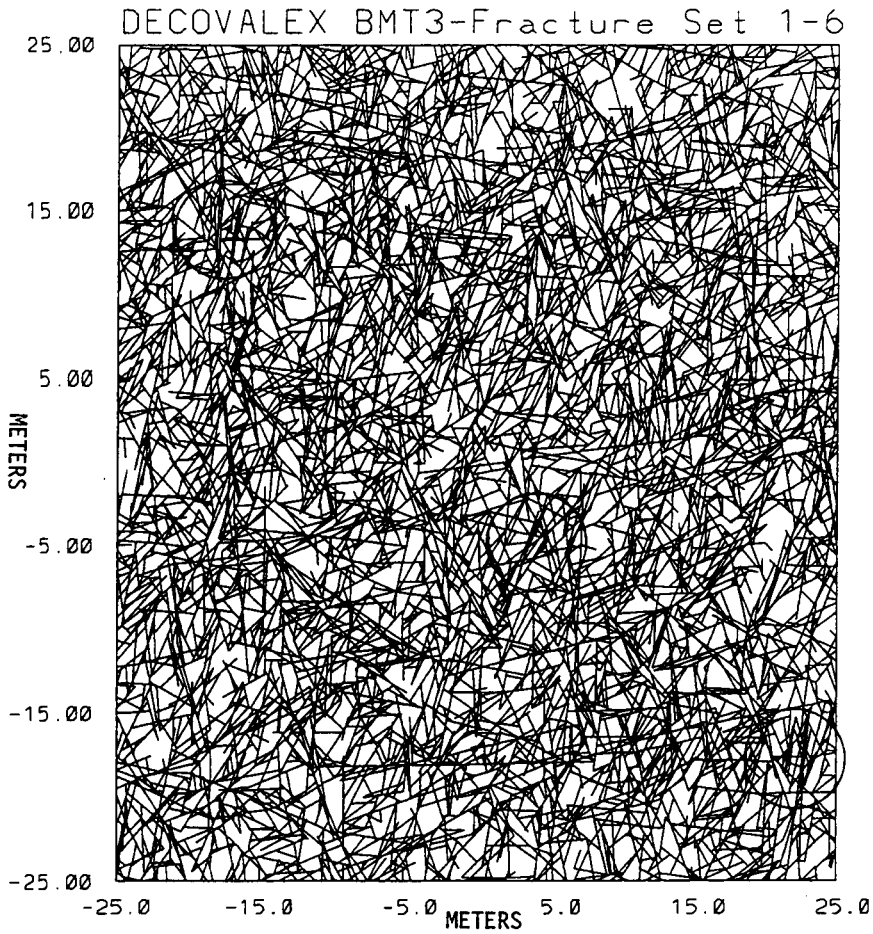


Figure 5-2. Reference 2D fracture pattern for BMT3 (three circled regions denote potential problem areas for discontinuum modeling approach)

Including only the dominant joint sets from the reference fracture pattern in the modeling effort would be one approach toward simplifying the problem. The fracture data provided in the problem specifications for BMT3 included a fracture set number associated with each individual fracture. For this 2D reference fracture pattern, six fracture sets were identified. Figures 5-3 through 5-8 show each of these sets plotted separately, in order to determine if a few dominant sets could be used for the discontinuum modeling effort. However, in viewing each of these figures, it can be seen that there is still significant variation in orientation of the fractures within each set, especially for fracture set 1. Fracture sets 2 through 6 show a little better correlation with some particular orientation; however, some sets appear to overlap, making it difficult to determine if one set would dominate over another. It was not clear from the problem specifications what was the discriminating factor for the fracture classification into these six sets. They do not appear to represent unique joint sets. The individual fracture sets presented in Figures 5-3 through 5-8 show large numbers of isolated fractures with very small lengths compared to the model geometry (i.e., less than 2 m). Thus, it appears that in order to get enough connectivity between fractures to form sufficient fluid flow paths, a number of fractures from all the different sets would be needed in the discontinuum model. Figure 5-9 shows the distribution in orientation of all joints from the reference fracture pattern, at 10-degree intervals. This histogram shows again the random nature

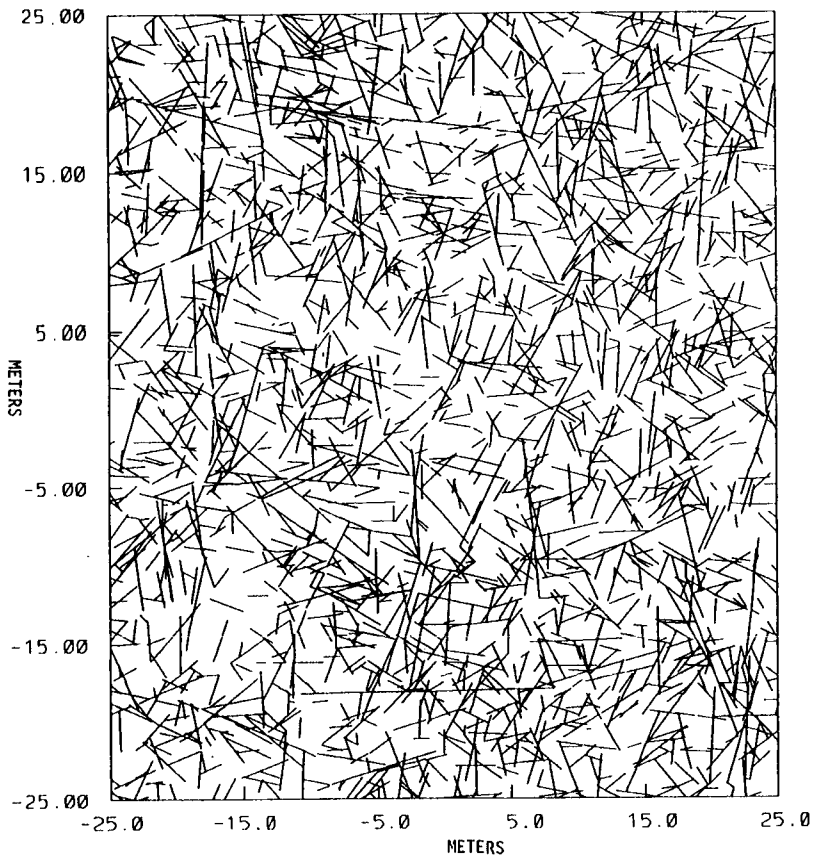


Figure 5-3. Fracture set 1 from the reference pattern

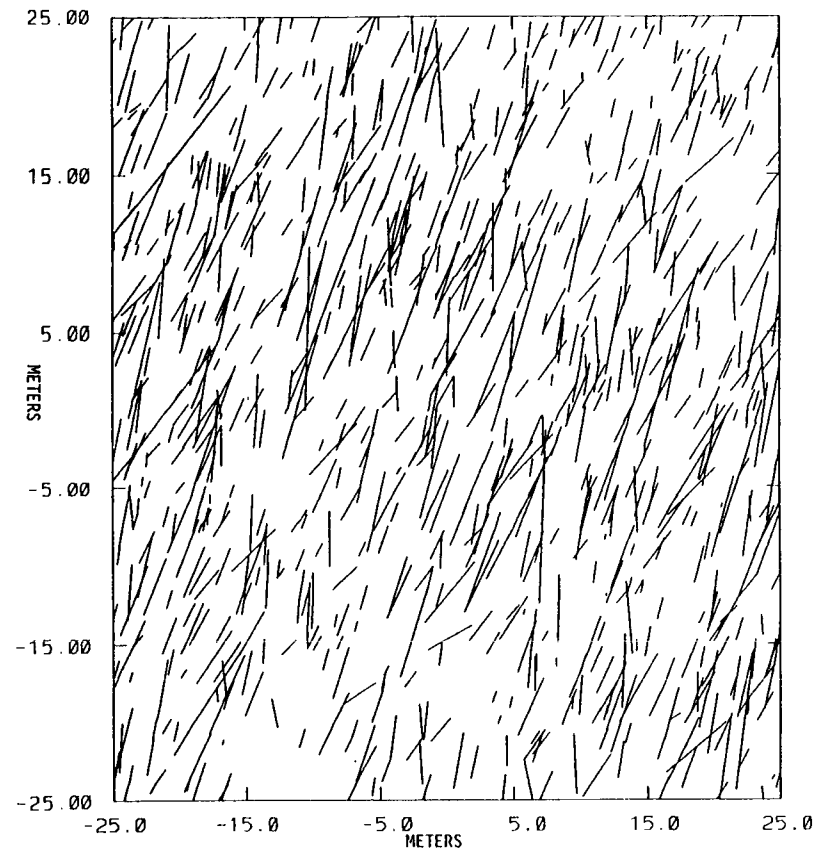


Figure 5-4. Fracture set 2 from the reference pattern

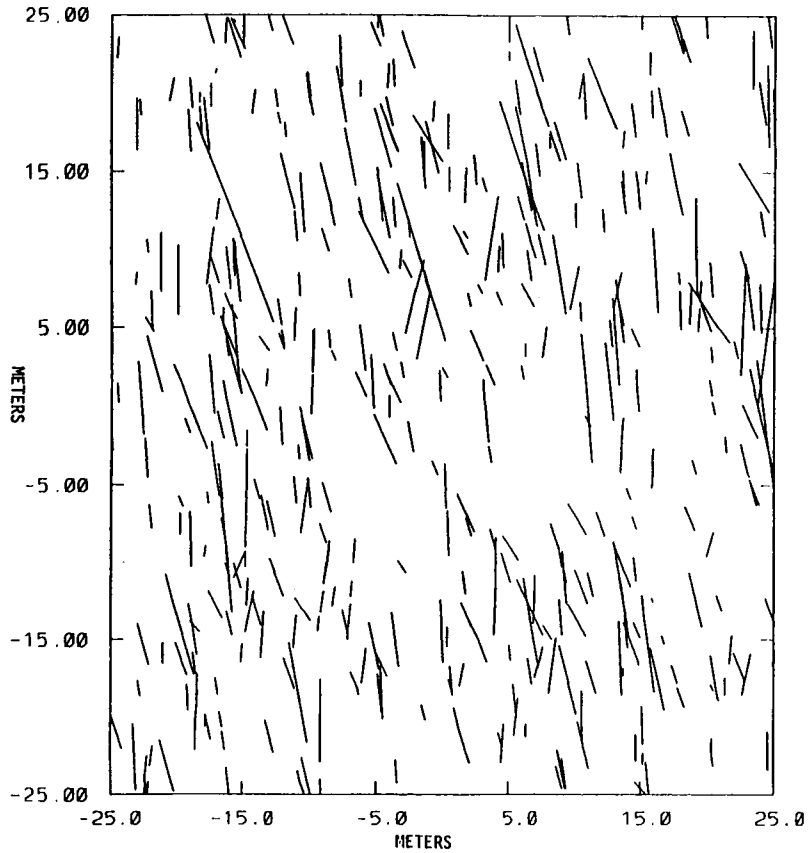


Figure 5-5. Fracture set 3 from the reference pattern

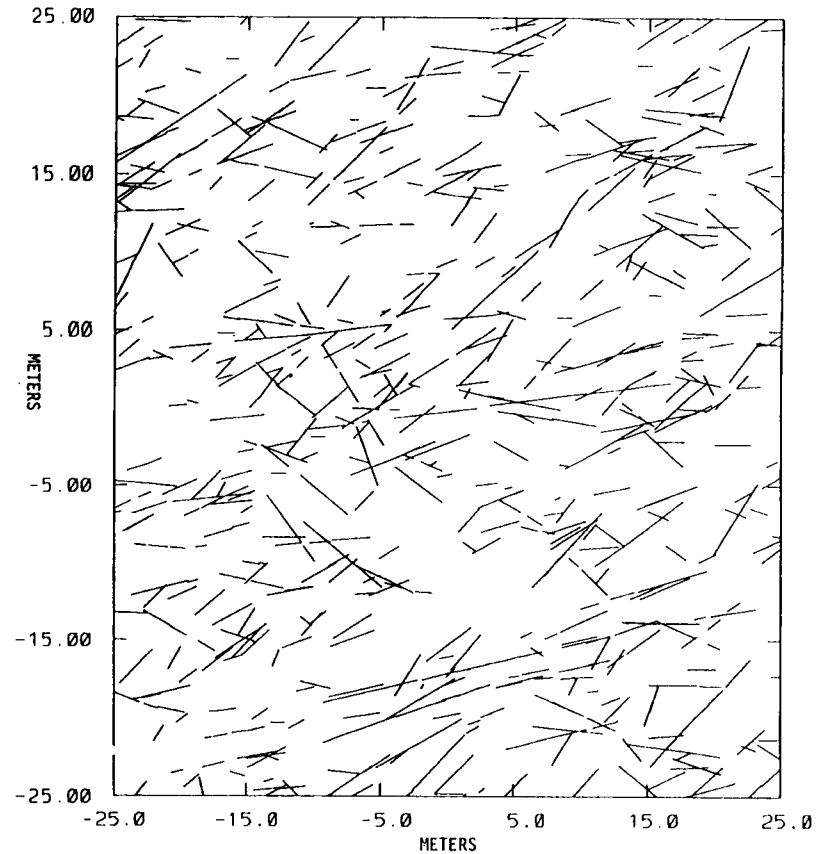


Figure 5-6. Fracture set 4 from the reference pattern

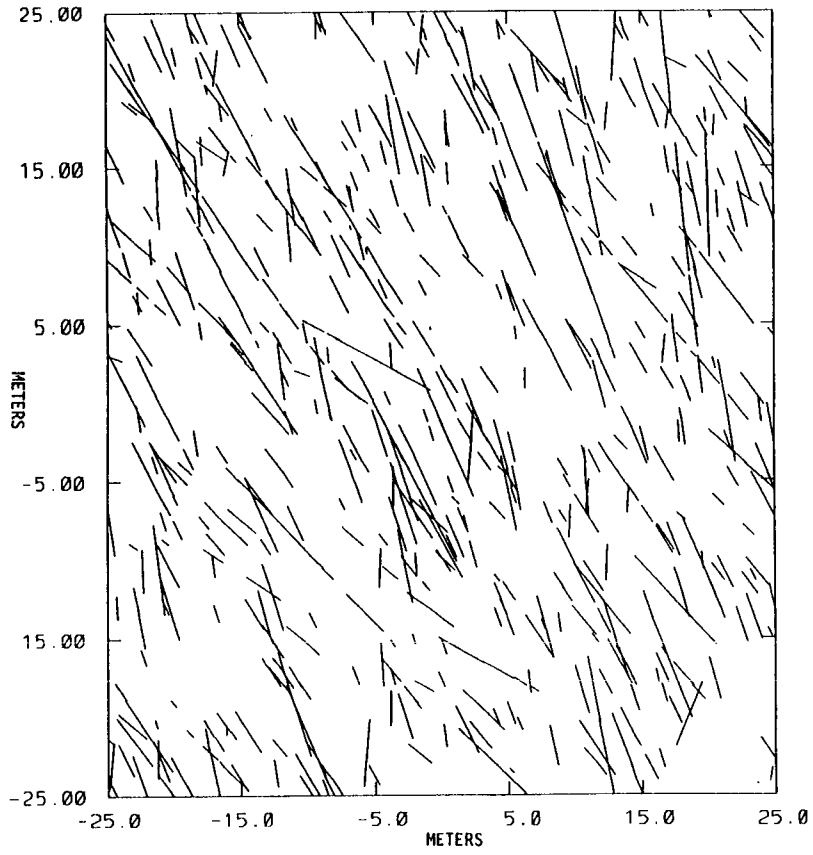


Figure 5-7. Fracture set 5 from the reference pattern

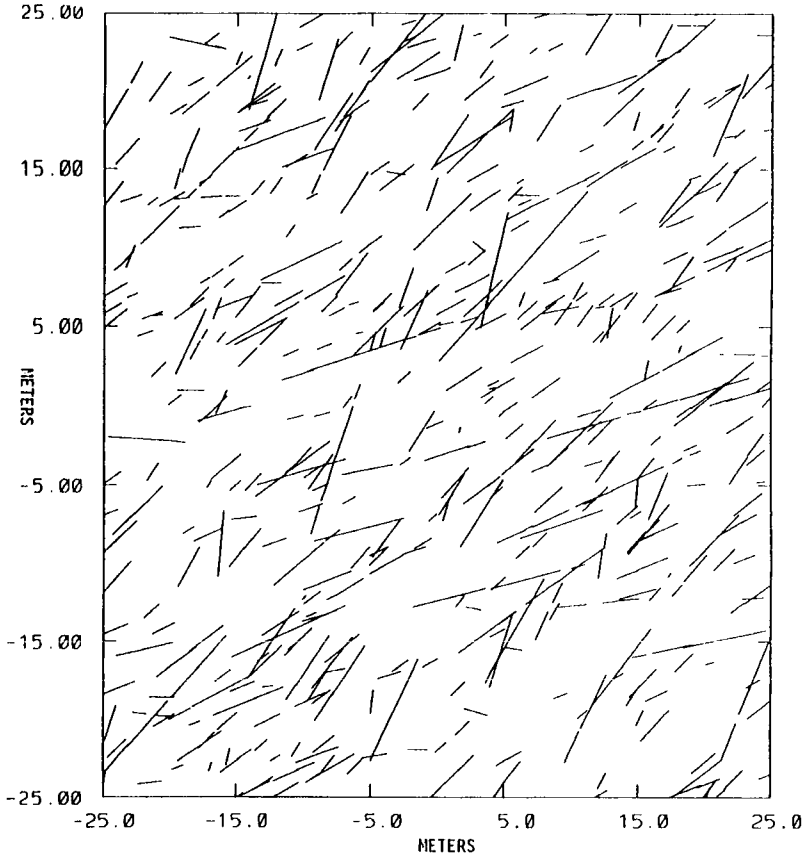


Figure 5-8. Fracture set 6 from the reference pattern

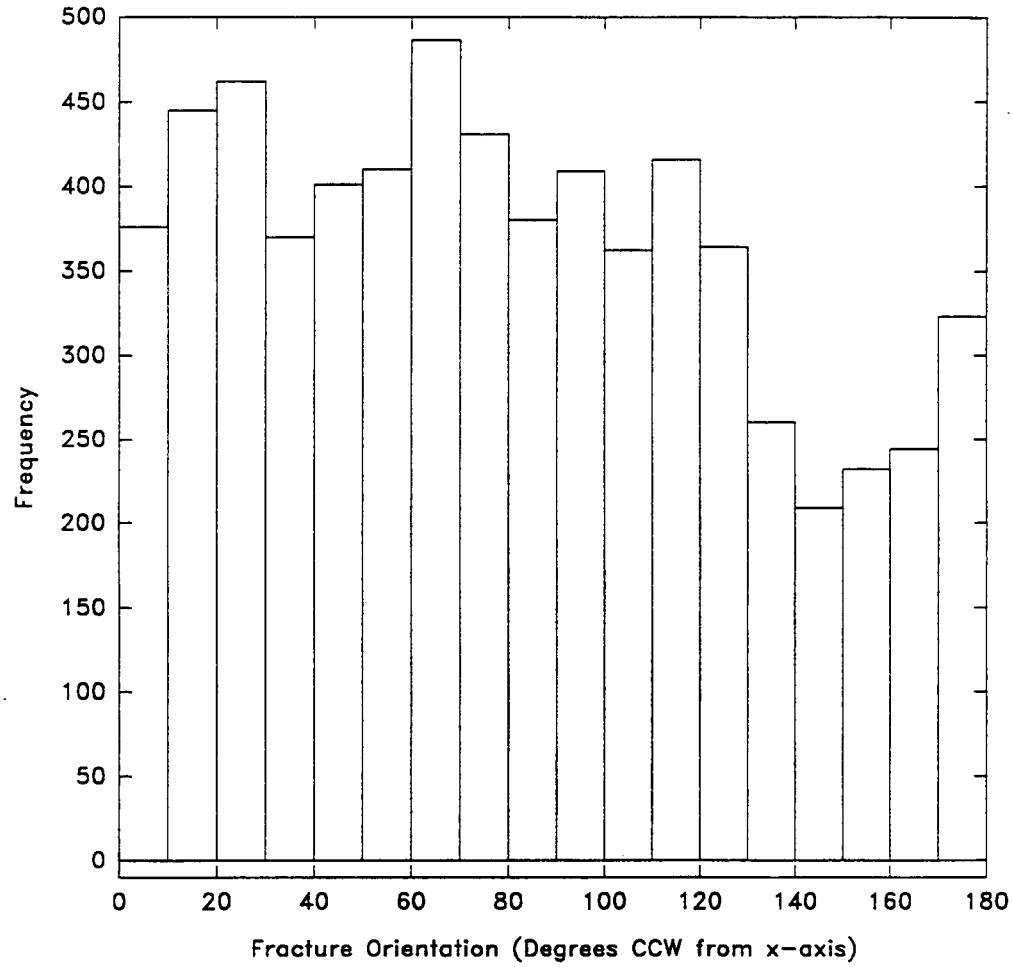


Figure 5-9. Fracture orientation distribution for the reference 2D fracture pattern

of the reference fracture pattern. There is approximately an equal number of fractures lying at any particular orientation.

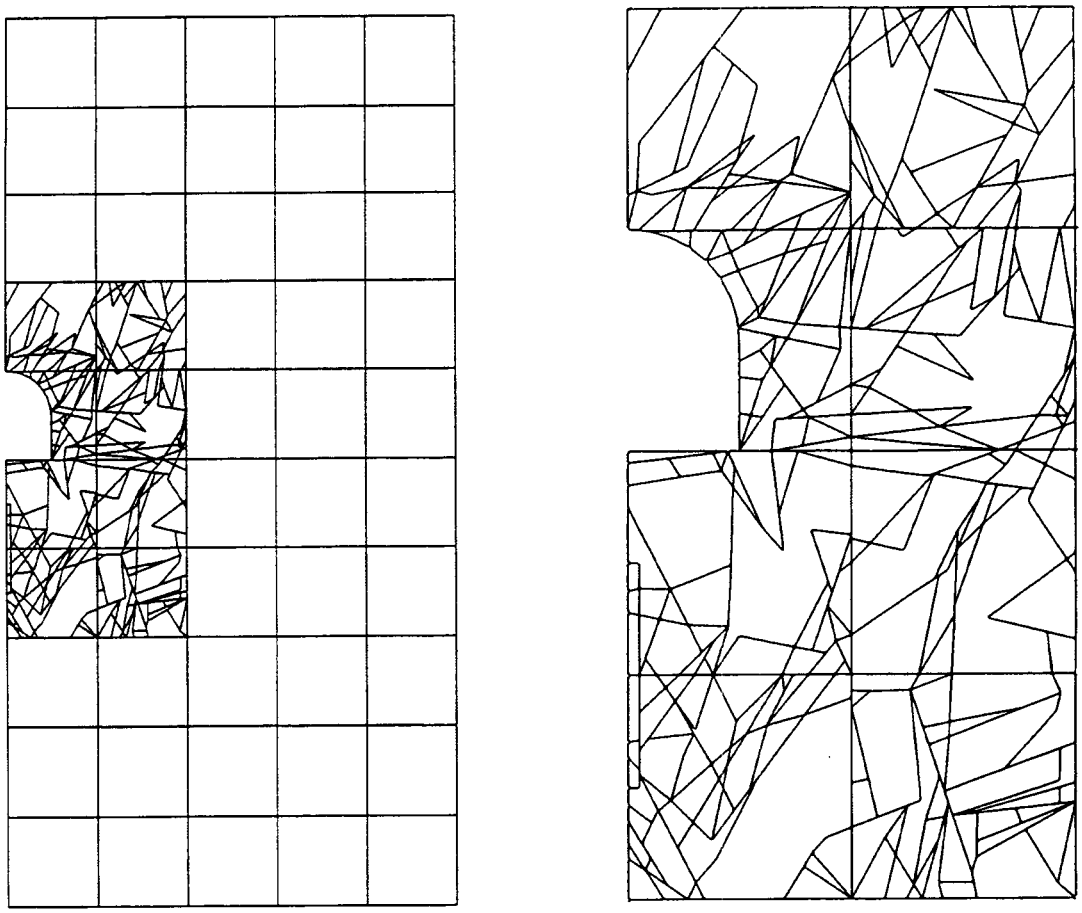
5.2 UDEC MODELING APPROACH

5.2.1 Coarse Model (Case A)

Since it was not possible to identify any preferential fracture orientation in the reference fracture pattern (Figures 5-2 and 5-9) and, based on the previous discussion regarding Figures 5-3 through 5-8, it was decided to simplify the UDEC model by including fractures from all six sets, but eliminating those fractures less than 2 m in length. This 2-m cutoff length was more or less arbitrarily chosen to reduce the number of fractures to make the problem computationally feasible with UDEC. This simplification could be viewed as a relaxation of one of the six geometric rules (DECOVALEX, 1992b) used in developing the reference fracture pattern. Namely, in creating the reference fracture pattern, all joints less than 0.5 m were eliminated. Application of this criterion (i.e., eliminating fractures shorter than 2 m) to the reference fracture set for the problem reduced the total number of fractures from 6,580 to 2,191. However, after this set of fractures was input into UDEC, problems occurred in certain areas of the

model in discretizing the blocks into finite difference triangular elements necessary to simulate elastic deformability. Again, this difficulty was probably due to those blocks having very acute angles or complex shapes causing problems with the corner-rounding algorithm in UDEC. Even though very small blocks were deleted prior to zoning, difficulties still arose in eliminating this problem. As a result, a model of the entire region could not be developed.

It was decided to simplify the modeling approach further by assuming symmetry about the vertical z axis and modeling only the right half. In addition, only those fractures from the previous model of the entire region described above and located within a region extending 10 m from the origin in the x direction as well as 10 m above and below the origin in the z direction were included in the revised UDEC model. This model is shown in Figures 5-10a and 5-10b. Again, this near-field tunnel region contains only those fractures from the reference fracture pattern whose lengths are larger than 2 m. This near-field 10 × 20 m symmetric region thus contains 211 of the 2,191 fractures from the previously discussed 50 × 50 m model. Also, after all the fracture data are input into UDEC, the code truncates any portions of the fractures that do not completely bisect an existing discrete element block. The remaining outer region shown in Figure 5-10a contains a uniform set of horizontal and vertical joints with



(a) (b)

Figure 5-10. UDEC model (Case A) showing discrete element blocks composing both the (a) inner and outer region and (b) detailed view of inner block region surrounding tunnel

an assumed spacing of 5 m. This outer region extends to the original model boundaries. The horizontal and vertical joints in this outer region allow the fluid to connect to the inner fractured region from the constant head boundary along the upper surface of the model. Since all the output monitoring points specified for the problem are located inside this inner fractured region (Figure 5-10b), the model was thought to be an acceptable compromise. The assumption of vertical symmetry was based on the observation that, on a large scale, the equivalent hydraulic data provided for the problem did not vary much in the x and z directions. For example, based on a length of 50 m, which is the actual dimension of the square model, the equivalent hydraulic conductivities are given as 0.1297×10^{-9} and 0.1347×10^{-9} m/s in the x and z directions (DECOVALEX, 1992b), respectively (differences between arithmetic mean values and geometric mean values were insignificant). All other boundary and loading conditions for the problem are also symmetric.

Finite difference discretization of the blocks within the model is shown in Figures 5-11a and 5-11b. The maximum edge length for the zones within the inner region was set at 1.5 m, while edge lengths in the outer region ranged from approximately 1.75 m near the transition area to 2.5 m towards the model boundaries. Zoning within the inner region was aided by allowing the uniformly spaced horizontal and vertical joints to extend through this region. These horizontal and vertical joints were input first into the model before the remaining fracture data were read in. This procedure allowed UDEC to form slightly more uniform blocks, which eliminated some of the block discretization problems encountered earlier. Future analyses should consider ordering the joints for input into UDEC, say starting at one side and proceeding toward the other side. This method would reduce the time it would take UDEC to form discrete blocks as the fracture data were input. Artificial joint properties were specified to those portions of the uniformly spaced horizontal and vertical joints within this inner fractured region. The artificial properties consisted of high strength and stiffnesses as well as zero permeability. These conditions mean that the artificial joints are mechanically and hydraulically inactive. This revised model contains 337 discrete blocks and 1,540 zones.

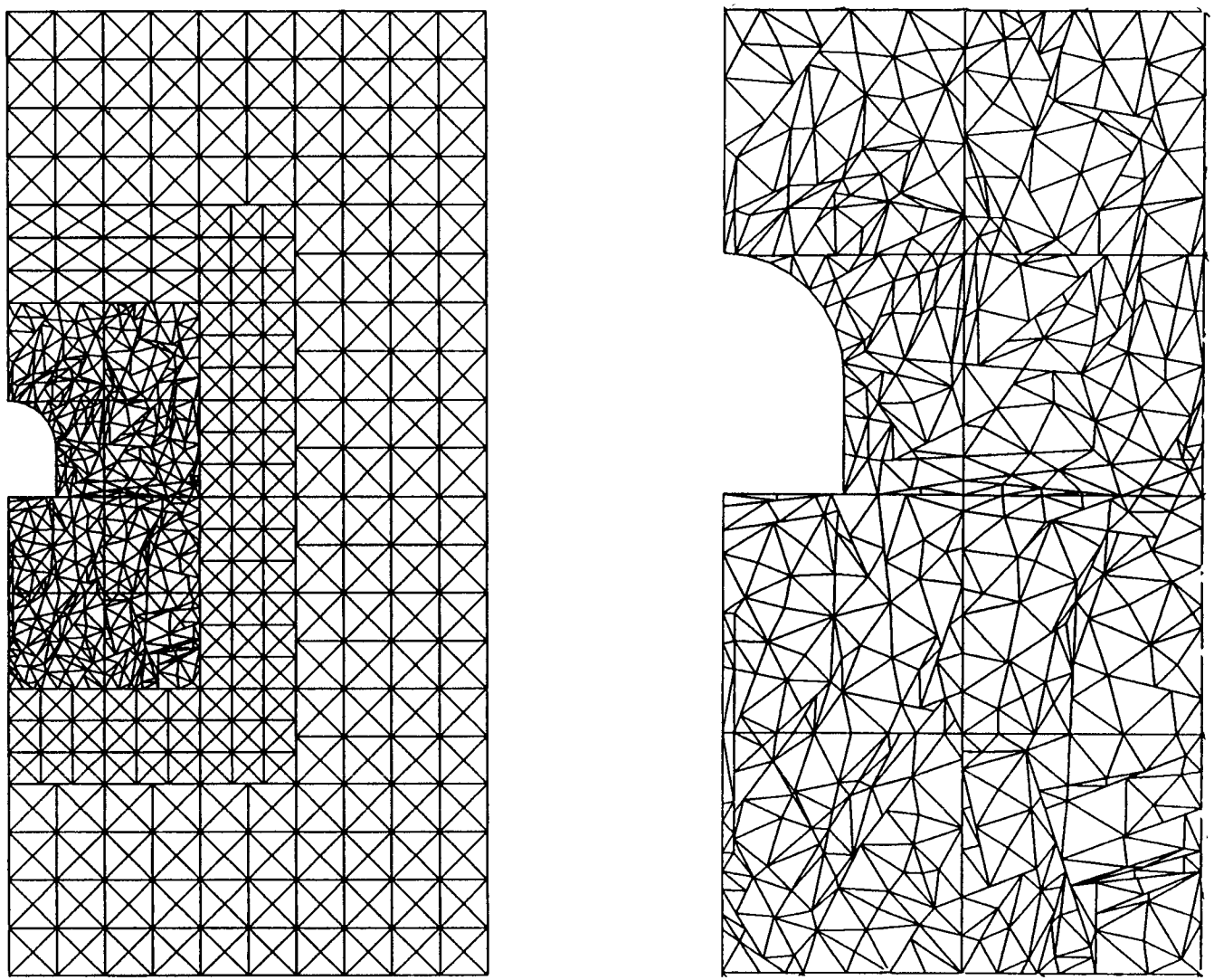
For the outer region, the joint stiffnesses for the horizontal and vertical joints were set the same as the fractures within the inner region; however, the intact elastic rock properties of the square blocks were reduced from the values specified in the problem to make the overall mechanical stiffness of this outer region equivalent to the original problem. A value for the reduced "intact" rock modulus was determined from the relation (Itasca, 1992)

$$\frac{1}{E_e} = \frac{1}{E_i} + \frac{1}{Sk_n} \tag{5-4}$$

where

E_e = equivalent elastic modulus of the fractured rock mass (MPa)
E_i = elastic modulus of the intact rock (MPa)
S = joint spacing (m)
k_n = joint normal stiffness (MPa/m)

The joint normal stiffness (k_n) was given as 1.0×10^5 MPa/m in the fracture property specifications for the problem. As discussed above, the joint spacing (S) in the outer region was assumed to be 5 m. Based on conducting a simple biaxial compression test using only a small sample from the reference fracture geometry, an equivalent elastic modulus (E_e) for the original problem was approximated as 1.2×10^4 MPa. Substituting these values into Eq. (5-4) and solving for the reduced intact rock modulus



(a) (b)

Figure 5-11. UDEC model showing (a) finite difference zoning of blocks in the inner and outer regions, and (b) detailed view of zoning within inner region around tunnel

for the outer blocks results in the value of E_i to be 1.23×10^4 MPa. A similar approach could have been taken in which the intact rock modulus (E_i) specified for the problem was used, and the joint normal stiffness (k_n) reduced according to Eq. (5-4) to establish an equivalent system for the outer domain. However, it was thought that the first approach would better preserve the equivalent hydraulic conductivity as discussed below. In addition to reducing the intact elastic modulus within this outer region, the joint hydraulic apertures were also modified so as to realistically represent the equivalent permeability. For a system of joints with spacing S, the average permeability for an equivalent continuum would be (Itasca, 1992)

$$k = \frac{\rho_w g}{12\mu} \frac{a^3}{S} \tag{5-5}$$

where

k = permeability of equivalent continuum (m/s)
ρ_w = density of water (kg/m^3)
μ = dynamic viscosity (N-s/m^2)
a = aperture (m)

The average equivalent permeability (k) was given in the data provided for the BMT3 problem as approximately 0.13×10^{-9} m/s, based on an element size of 50 m. Using values for the density and dynamic viscosity of water as given in the problem specifications and solving Eq. (5-5) for the aperture (a) gives a value of 9.26×10^{-6} m.

For the inner fractured region, the actual joint stiffnesses and strength properties given in the problem specifications were used, along with the intact rock properties for the blocks in this region. These stiffness and strength properties were specified in the problem as being the same for all joints. However, each fracture had associated with it its own distinct aperture. In the UDEC program, apertures as well as other fracture properties are normally assigned to fracture or joint sets and not to individual fractures themselves. Properties can be assigned to individual joints; however, the code currently allows only ten joint material property sets. As a result, representative fracture apertures for this inner model region had to be defined.

Figure 5-12 shows a plot of the distribution of apertures for all the 6,580 fractures provided, assuming an interval on the horizontal axis of 5.0×10^{-6} m (5 micrometers). This number shows that the majority of the fractures have very small apertures. From the number of fractures with apertures within each interval shown in Figure 5-12 and a total of 6,580 fractures in the model, the distribution results in 70 percent of the apertures being less than 5.0×10^{-6} m (5 micrometers) and 98 percent of the apertures being less than 15×10^{-6} m. Figure 5-13 shows a similar distribution in which a further breakdown of fractures with apertures less than 15×10^{-6} m was plotted. As seen in Figure 5-13, the majority of the fracture apertures are around 2 to 3 micrometers. To make maximum use of the ten allowable joint material property sets within UDEC, it was decided to assign an average aperture with different ranges of orientations of the fractures in the model. Table 5-1 shows the statistical relation for fracture apertures within various orientation intervals ranging from 0 to 180 degrees. For the UDEC model, the median aperture for fractures within each interval was used, even though Table 5-1 shows no statistically significant difference in this median value. This median value, which is approximately 3 micrometers for all the intervals, is consistent with the results in Figure 5-13 and allows at least some variation in the model.

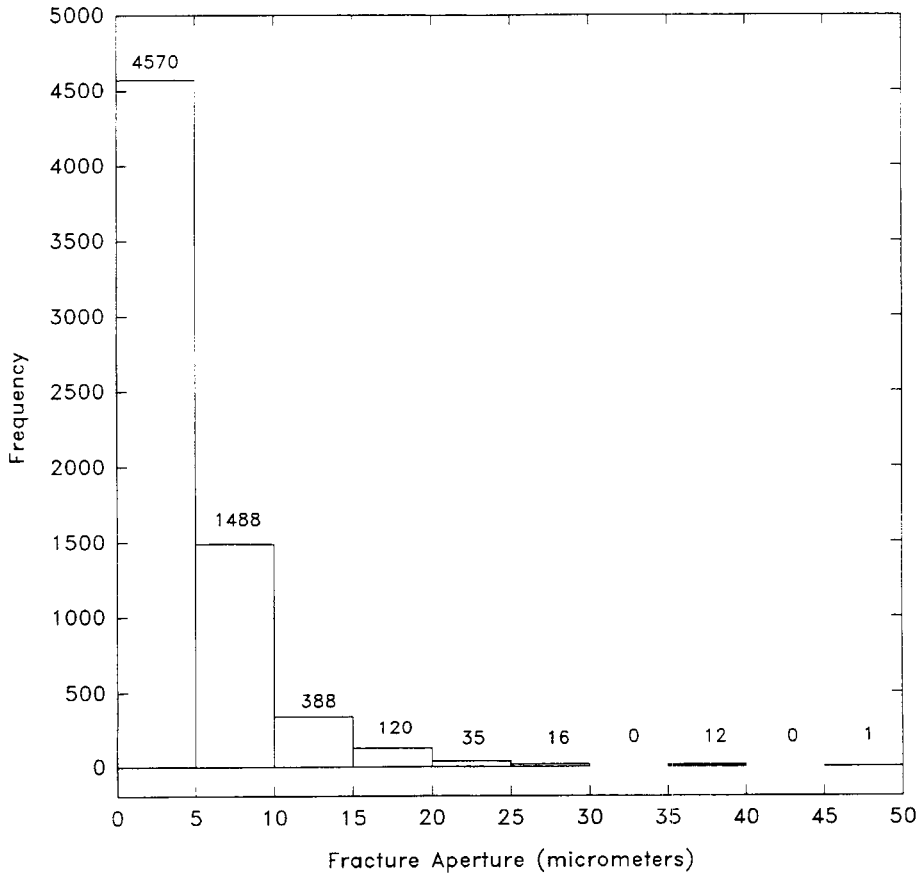


Figure 5-12. Aperture distribution for reference 2D fracture pattern

A determination was also made to test the assumption that using the median fracture values would accurately represent the fracture flow in the original model. For example, the fracture flow along any pathway in the original model is governed by the fracture segment with the minimum aperture. Since a small percentage of the fractures had an aperture significantly above the median values that were chosen, it was necessary to determine that these few large aperture fractures did not all connect together to form a single dominant flow path. If such was the case, our assumption might significantly underestimate the flow through the model. Figure 5-14 shows a plot of all the fractures with apertures greater than 10 micrometers. The figure shows that these fractures are fairly isolated and do not themselves connect to form a dominant flow channel towards the tunnel, which is in the center of the model. To create a dominant flow path, these fractures would have to be connected by fractures having smaller apertures. Since the flowrate within the channels will be governed by the smaller apertures, the apertures chosen for the UDEC model within this inner region, as discussed above, are thought to be representative of the fracture flow within the original network. It should be noted that, as shown in Table 5-1, the standard deviation in aperture is about 4 micrometers for all the intervals from the values used in UDEC. Thus, even though it has been shown that there are no dominant flow paths with large apertures through the model, there is some variation in aperture about the median values that could not be accounted for. For the UDEC model, steady-state fluid flow logic was used for all phases of the analysis. In steady-state analysis, fluid deformation is not taken into account (see Ahola et al., 1992, Section 2.4).

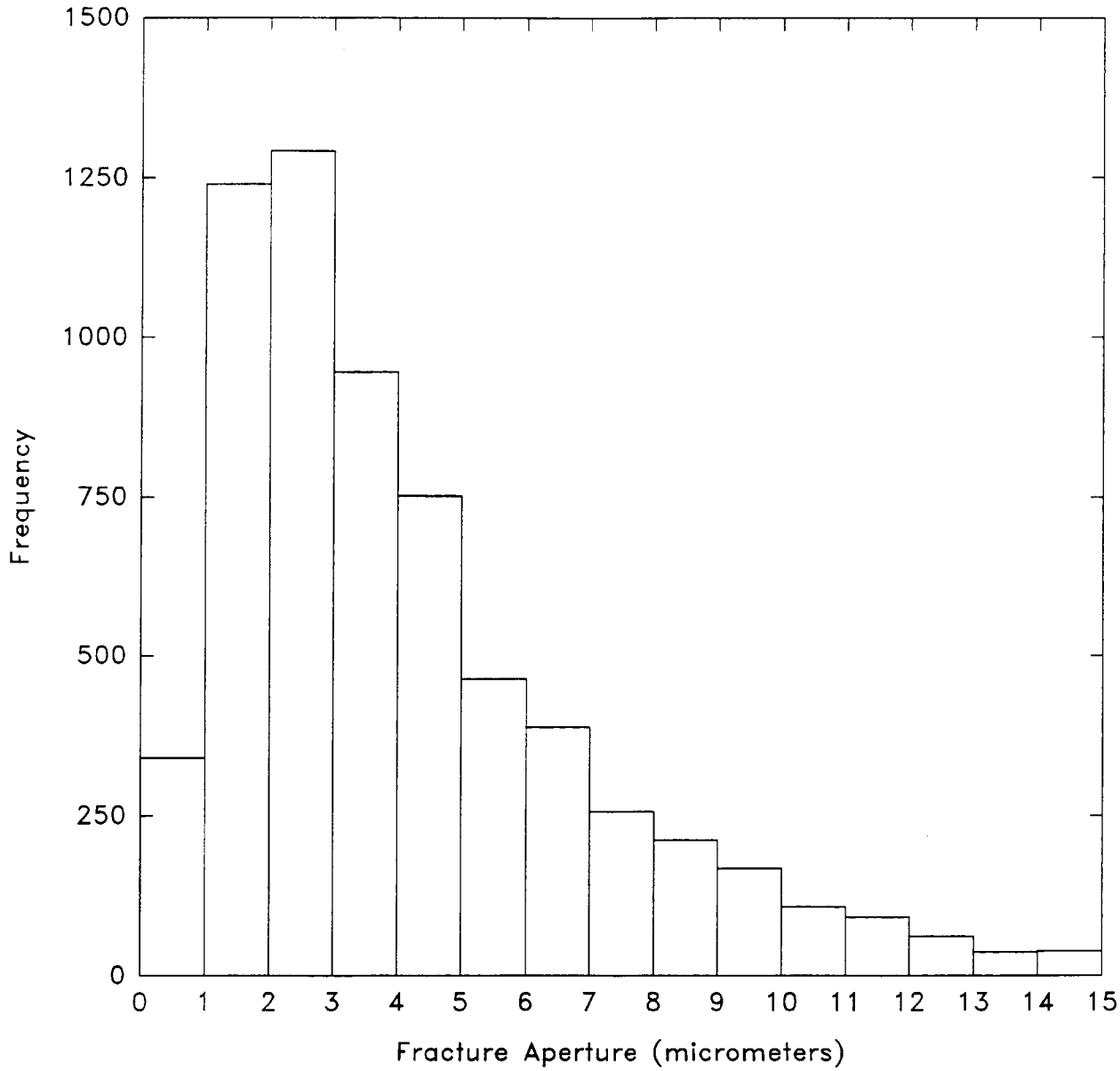


Figure 5-13. Aperture distribution for those fractures with apertures less than 15 micrometers from reference fracture pattern

5.2.2 Detailed Model (Case B)

A second UDEC model was also constructed, incorporating many more additional fractures from the reference fracture geometry. Again the vertical symmetry condition was used; however, the detailed fracturing was extended from the boundary of the excavation all the way to the outer model boundaries (Figures 5-15a and 5-15b). This symmetric model included all fractures greater than 1.5 m from the reference fracture geometry and, thus, contained slightly more detail around the excavation than the first model (Case A), which included only fracture lengths greater than 2.0 m.

Table 5-1. Statistical data on fracture aperture based on orientation

Fracture Orientation	0-20°	20-40°	40-60°	60-80°	80-100°	100-120°	120-140°	140-160°	160-180°
Minimum Aperture (micrometers)	0.43	0.32	0.64	0.26	0.39	0.56	0.52	0.55	0.47
Maximum Aperture (micrometers)	39.78	38.82	27.81	30.16	25.49	25.12	29.08	30.41	45.48
Mean Aperture (micrometers)	4.37	4.86	4.59	4.65	4.42	4.50	4.48	4.43	4.79
Median Aperture (micrometers)	3.26	3.53	3.38	3.20	3.45	3.20	3.65	3.08	3.78
Standard Deviation (micrometers)	3.94	4.48	3.75	4.33	3.53	3.64	3.72	4.03	3.86
Number of Fractures within Interval	821	832	811	917	789	778	624	441	567

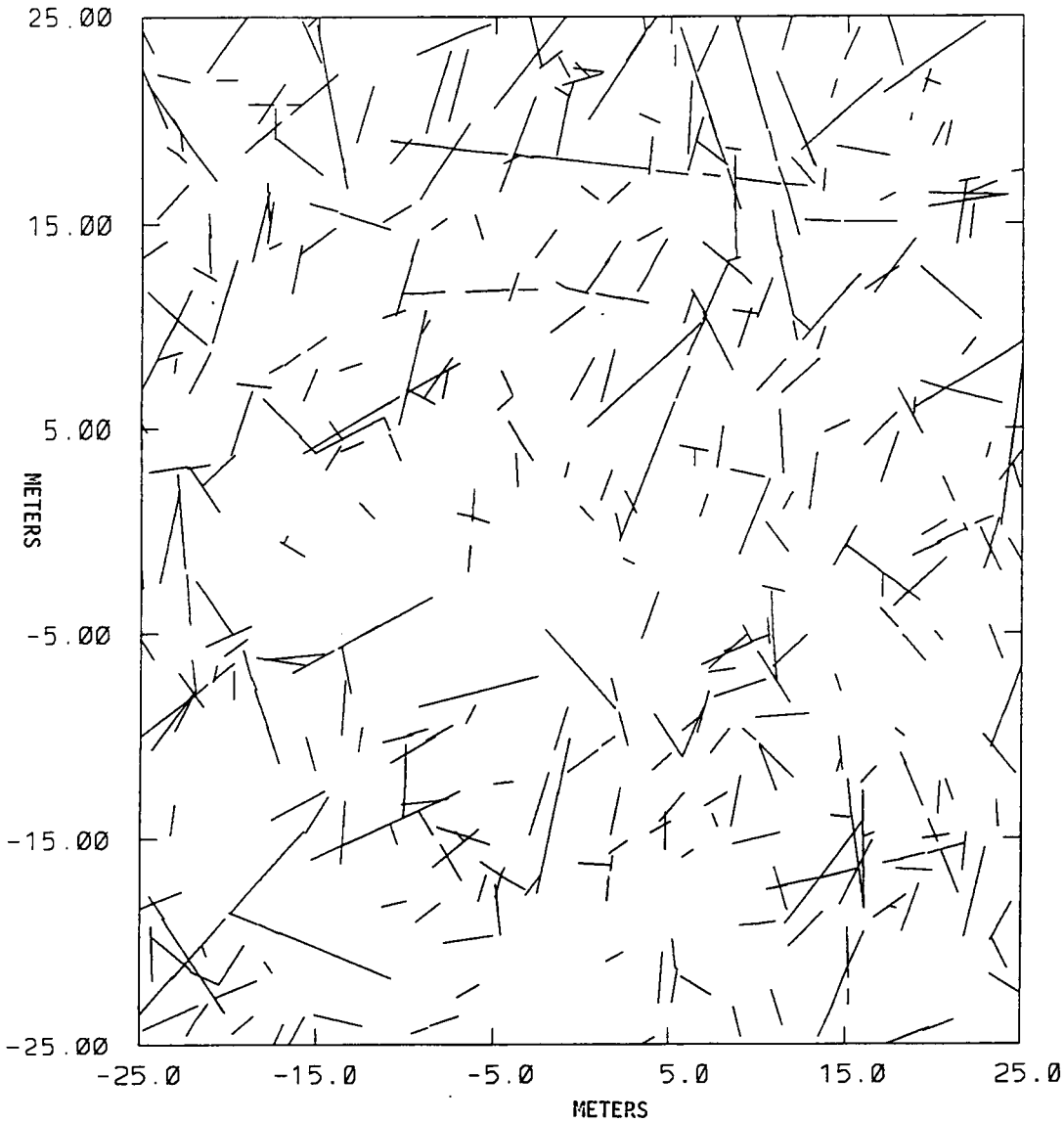
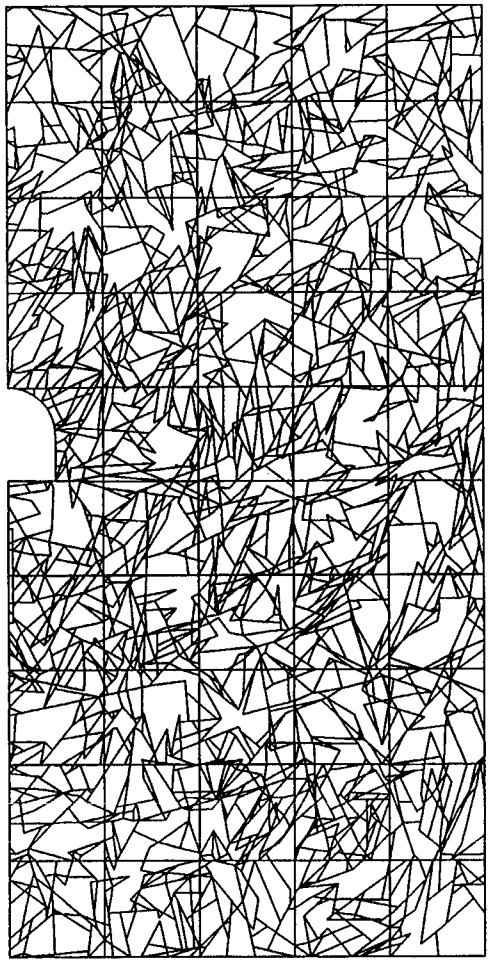
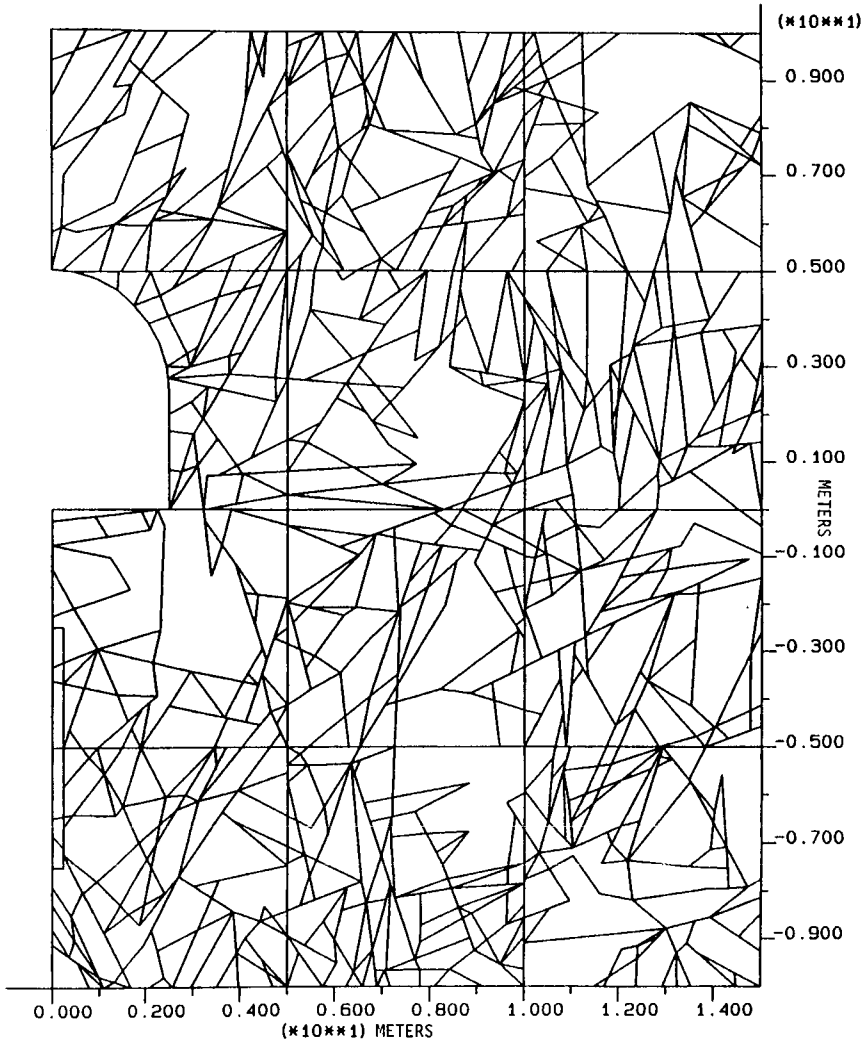


Figure 5-14. Location of fractures with apertures greater than 10 micrometers from reference fracture pattern



(a)



(b)

Figure 5-15. UDEC model (Case B) showing discrete element blocks for (a) the entire region and (b) the near-field region around the excavation

Based on the screening approach above, a total of 1,799 of the 6,580 fractures given in the 50 × 50 m reference geometry were utilized in this 25 × 50 m symmetric model. Again a uniform set of artificial joints spaced 5 m apart were input first into the model before the remaining 1,799 fractures were read in so as to reduce the complexity of the blocks for corner rounding and zoning. As previously discussed, these artificial horizontal and vertical joints were given higher stiffness and strength properties as well as zero permeability to make them mechanically and hydraulically inactive. The combination of the artificial fractures with the 1,799 fractures from the reference geometry formed 2,497 blocks. Using a minimum edge length of 1.5 m, these blocks were discretized into 6,001 finite difference zones, creating a total of 10,853 grid points. It should be noted that insertion of the artificial joints increases the computer run time due to the additional blocks, contacts, etc. created. The amount of additional time is not known.

For this more detailed model, no equivalent properties were required to be developed. The elastic moduli given in the problem specifications for the intact rock were assigned throughout the model. The fracture apertures were assigned based on orientation as listed in Table 5-1 and discussed in Section 5.2.1.

5.3 COMPUTER HARDWARE AND TIME REQUIREMENTS

The Near-Field Repository Model (BMT3) was run using UDEC installed on a Sun Sparc 10 workstation. For Case A, the computer time required to simulate mechanical and hydrologic equilibrium upon excavation was approximately 17 hr. The additional computer time required to simulate the 100 yr of thermal loading was approximately 83.5 hr. It should be noted that in THM analyses such as this, mechanical equilibrium is reached quite quickly, while hydrologic and thermal equilibria take much longer to be attained. As a result, much of the run time associated with this UDEC analysis was taken up in the hydrologic and thermal cycling. For this analysis, output files were created after each output time period. A listing of the UDEC input file for the Case A analysis is given in Appendix A. For Case B, the computer time required to simulate mechanical and hydrologic equilibrium upon excavation was approximately 400 hr. This large amount of time was due to the fact that the number of discrete element blocks and zones increased significantly, and the explicit time step dropped to about one-half that utilized for Case A. The additional computer time required to simulate 1 yr of thermal loading for Case B was approximately 500 hr. Since the largest thermal gradients occur during the initial heating period, smaller thermal time increments were specified and sufficient mechanical-hydrological cycling conducted after each increment to assure equilibrium. This process leads to the longer run times during the initial thermal loading period. The computer run time for the later stages of thermal loading would be substantially less, as thermal increments can be on the order of years. Also, since the thermal increments and number of mechanical-hydrological cycles are user defined, the run times could be further optimized. A listing of the UDEC input file for the Case B analysis is given in Appendix B.

6 RESULTS

Figure 6-1 shows the monitoring points, line segments, and regions at which output is required for BMT3. Results for stresses, displacements, and temperatures are given at the monitoring points, while results for the fluid flux across segments between the monitoring points are given. These results are tabulated in Appendix B for each of the three loading sequences as discussed below. Also, plots of stresses, displacements, fracture flowrates, as well as the normal stresses and temperatures along lines I and II shown in Figure 6-1 are presented in Appendix C. Histograms of the porosity and conductivity for each of the monitoring regions shown in Figure 6-1 could not be provided with the UDEC analysis.

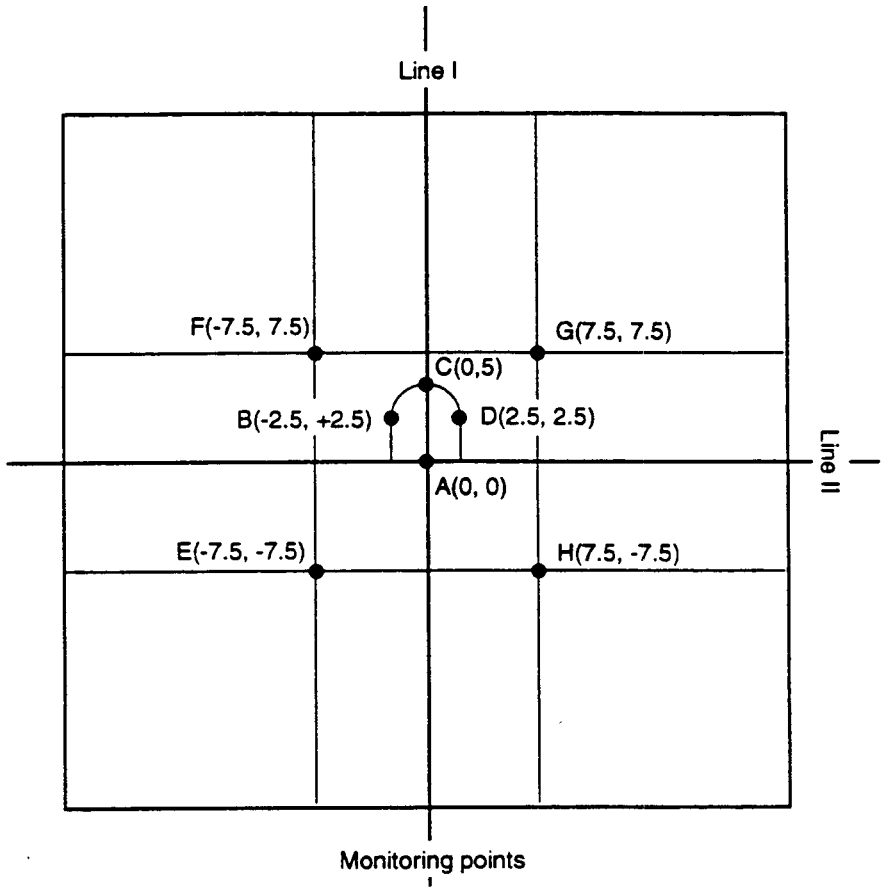
6.1 INITIAL HYDROMECHANICAL EQUILIBRIUM BEFORE TUNNEL EXCAVATION

The first loading sequence consists of establishing initial hydromechanical equilibrium in the model without the tunnel. The time at which hydromechanical equilibrium is reached is denoted as time $t = 0$. At this equilibrium time, the initial *in situ* stress varies linearly from 12.44 MPa at the top of the model to 13.75 MPa at the bottom of the model. Similarly, the fluid pressure within the fractures varies linearly from 4.66 MPa at the top to 5.15 MPa at the bottom of the model. The effective stress across the joints is the total mechanical stress less the fluid pressure. The *in situ* stress within UDEC was applied so that joint normal displacements (i.e., joint initial closure) were inhibited. Thus, at this initial hydromechanical equilibrium, the fracture apertures remained at the same values input for both UDEC runs. Joint shear displacements as well as gridpoint displacements were set to zero at this initial state prior to tunnel excavation. Initial stresses at the monitoring points are given in Table B-1 of Appendix B, and are approximately equal for both Cases A and B.

6.2 HYDROMECHANICAL EQUILIBRIUM AFTER TUNNEL EXCAVATION

The second loading sequence corresponds to excavating the tunnel at time $t = 0$, allowing the model to reach a new mechanical and hydrologic equilibrium as a result of the excavation-induced changes. Output during this loading sequence is required at times $t = 1/12$ and t^* years, where t^* denotes the time at which hydromechanical equilibrium is reached after tunnel excavation. In the distinct element modeling, UDEC uses an explicit time-marching scheme for the mechanical and hydrologic calculations. The explicit time step satisfying numerical stability criteria for this scheme was approximately 5.6×10^{-5} s for Case A and 2.1×10^{-5} s for Case B, due to the relatively small zone and block sizes in the models. As a result of these small time steps and the very slow convergence of the fluid flow, the steady-state flow option within UDEC was used to provide faster convergence than the standard transient flow calculations. As a result of using this scheme, it was not possible to obtain output at time 1/12 yr after excavation of the tunnel. Also, the time t^* could not be determined precisely, since this steady-state flow algorithm was used. Mechanical changes occur rather instantaneously, and thus at 1/12 yr the model would most likely be in mechanical equilibrium but not necessarily hydrologic equilibrium. It could be assumed that the hydrologic response is changing slowly at this time.

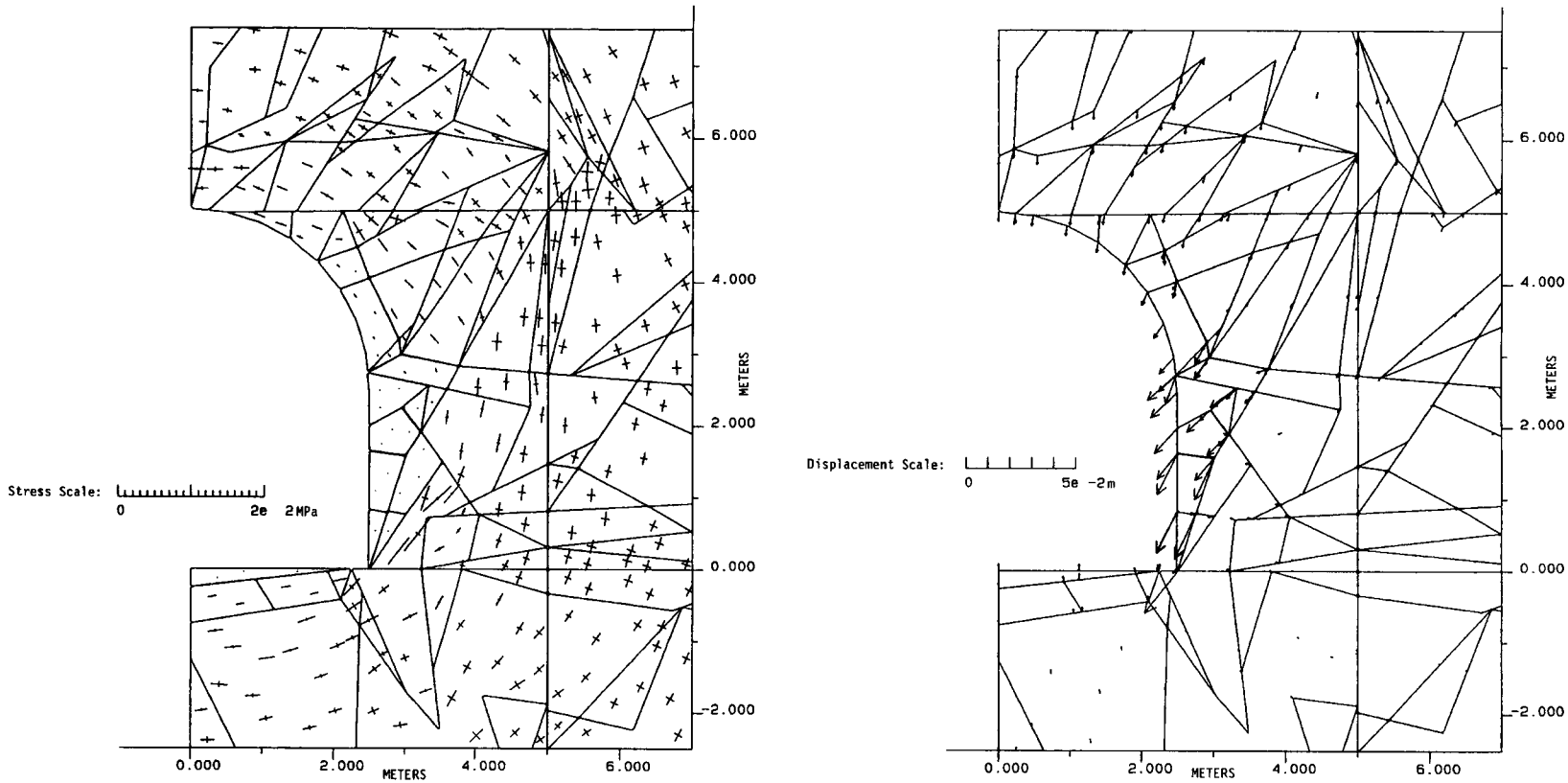
Figures 6-2a and 6-2b show the distribution of stresses and displacements directly around the tunnel (Case A) after the model has reached hydromechanical equilibrium upon excavation, which was taken as the state represented by the time $t = t^*$. In simulating this excavation, the fluid pressure was first set equal to zero in the region of the tunnel, and some explicit fluid flow timestepping was conducted prior to removing the tunnel blocks. This approach better simulates the drainage from the free face (i.e.,



1	2	3
4	5	6
7	8	9

Monitoring regions

Figure 6-1. Output monitoring points and regions for near-field repository problem



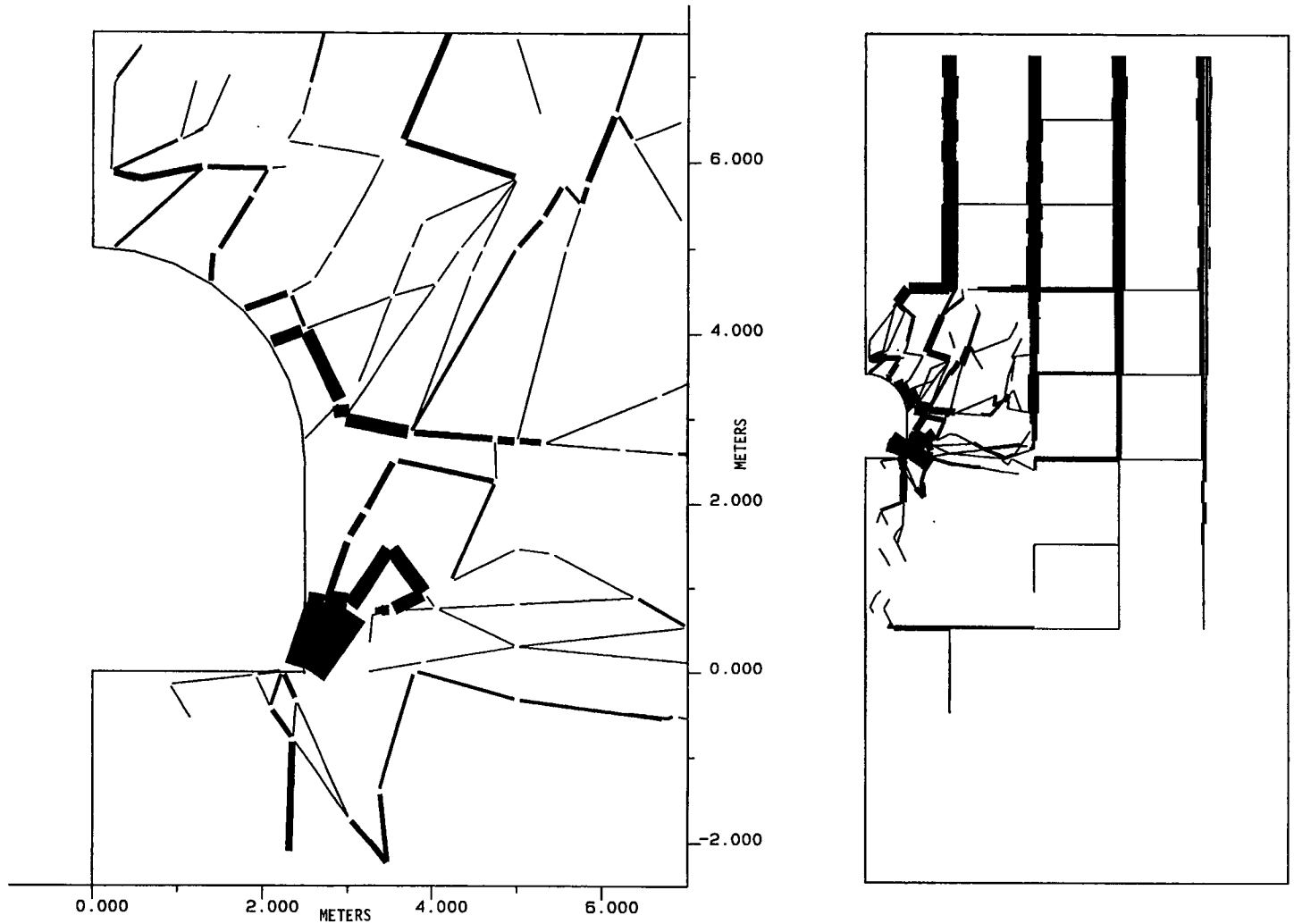
(a) (b)

Figure 6-2. UDEC results for Case A after excavation of tunnel ($t = t^*$) (a) principal stress vectors [maximum principal stress (compression) = 58.88 MPa, minimum principal stress (tension) = 6.81 MPa] and (b) displacement vectors (maximum displacement = 2.415×10^{-2} m)

in the out-of-plane or third direction) as actually occurs in tunneling. [It was found that setting the fluid pressure to zero at the same time as excavating the blocks resulted in much more mechanical instability physically due to *in situ* fluid pressure (approximately 5.0 MPa) existing just outside the excavation periphery.] In addition, the mechanical normal and shear stresses along the boundary of the tunnel were gradually reduced from their *in situ* values to zero over an additional period of time after the tunnel blocks were removed. Mechanical equilibrium was reached shortly after these tunnel boundary pressures reached zero; however, flow equilibrium was not reached until later.

As shown in Figures 6-2a and 6-2b, the right side and floor of the tunnel became destressed due to the orientation of the fractures in this area, and larger inward displacements also occurred in this region. The maximum inward displacement along the right portion of the tunnel is calculated to be approximately 24.2 mm. However, it should be noted that these few blocks along the right wall of the tunnel were physically unstable and gradually moved inward even though the rest of the model equilibrated upon excavation of the tunnel. A maximum compressive stress of 58.9 MPa occurred in the lower right side of the tunnel, as would be expected due to the sharp corner. Some tensile stresses on the order of a few megapascals also existed in this region. Figure 6-3a shows that the largest flowrate into the tunnel occurred along the fractures intersecting the tunnel in the lower right corner. This flow appeared reasonable due to larger inward displacements and orientation of the fractures in this area. The total flowrate into the right half of the tunnel at this equilibrium stage was 2.124×10^{-8} m^3/s. Water pressures in the majority of the fractures within the small (1 or 2 m) region around the tunnel shown in Figure 6-3a were approximately zero. The connection between flow in the inner fractured region and the outer region, which was assumed to be an equivalent medium, is depicted for Case A in Figure 6-3b. The figure shows that most of the flow occurred in the upper portion of the model; however, some flow extended below the tunnel in the outer region, eventually working its way up through the tunnel floor.

Figures corresponding to 6-2 and 6-3 for the stresses, displacements,and fracture flowrates for the Case B, UDEC model at this equilibrium time are given in Appendix C (i.e., Figures C-13 and C-14). In general, the results compared favorably between the runs representing Cases A and B. The principal stress vectors for Case B (Figure C-13a) were quite similar to those shown for Case A (Figure 6-2a); however, the predicted maximum compressive principal stress was somewhat higher at 71.8 MPa. Also, except for the right portion of the tunnel wall, the displacement vectors calculated for Case B (Figure C-13b) and Case A (6-2b) were very similar. Specific values for the stresses and displacements at the specified output monitoring points are tabulated in Appendix B at this equilibrium time period. Fluid flowrates in the vicinity of the tunnel for Case B are shown in Figure C-14. The results for Case B gave a somewhat higher flowrate (q) into the right half of the tunnel boundary (3.293×10^{-8} m^3/s) than that calculated for Case A (2.124×10^{-8} m^3/s). This discrepancy may be due to the fact that the model representing Case B had a slightly higher fracture density around the tunnel than that for Case A. To expand on this point, one can calculate a fracture density (f) for each of the two cases analyzed. Based on the 211 reference fractures utilized for Case A and 1,799 reference fractures utilized for Case B, these fracture densities are computed to be 1.055 and 1.439 fractures/m^2, respectively, for the two cases. Calculating the ratio q/f gives values of 2.013×10^{-8} and 2.288×10^{-8} for cases A and B, respectively. Thus, this ratio between the two cases shows a better correlation. If this ratio were truly constant, one could use the results from the simplified analysis (i.e., Case A) and, knowing the fracture density of the given reference fracture pattern, to calculate a better estimate of the flowrate (q) into the tunnel.



(a) (b)

Figure 6-3. UDEC results for Case A after excavation of tunnel ($t = t^*$) (a) fracture flowrates in vicinity of tunnel (tunnel inflow = 2.124×10^{-8} m^3/s) (b) fracture flowrates for entire model (Note: the thickness of the lines is proportional to the amount of flow, the minimum line thickness represents flow = 5.0×10^{-10} m^3/s)

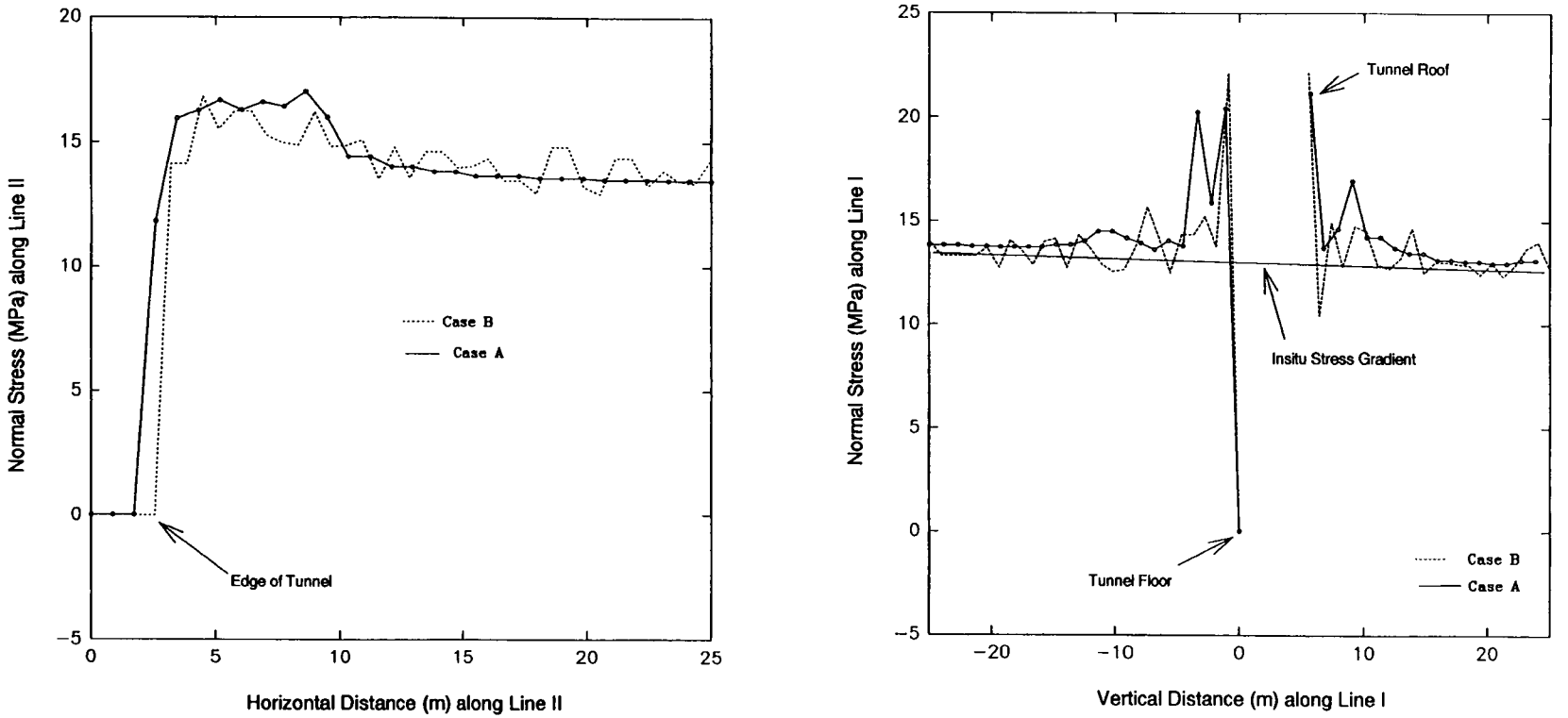
The normal stresses σ_{xx} and σ_{zz} at this equilibrium time (t^*) along lines I and II, respectively, are plotted in Figures 6-4a and 6-4b. The two figures show that, although there are some localized discrepancies between the stresses calculated between Cases A and B, the general stress trends are quite similar. The normal stress (σ_{xx}) (Figure 6-4b) along line I, extending vertically through the center of the tunnel, shows that the peak horizontal stress of approximately 20 MPa occurred a few meters below the tunnel invert, as expected due to the low angle jointing in this area and the square floor. A similar horizontal stress is indicated immediately into the roof of the tunnel.

6.3 HYDROMECHANICAL STATES DURING THERMAL LOADING

At time t^*, the thermal source was applied as a flux boundary condition along the segment of the boundary extending from $z = -2.5$ m to $z = -7.5$ m. Due to the use of vertical symmetry, only one-half of the total flux was applied, this value being 117.5 W/m^2. The results of this discrete element analysis assumed that, at each output thermal loading time, the model was in hydromechanical equilibrium. This assumption is usually reasonable since the mechanical and hydrologic time scales are smaller than the thermal time scale. In the UDEC code, the thermal and mechanical schemes operate on different time steps, with the thermal time being the "real" problem time. The normal approach in conducting such a THM analysis with UDEC is to run the thermal problem for some increment in time while the hydromechanical state is fixed. This time increment is usually chosen such that the maximum temperature rise between increments is maintained below some value (e.g., 20 °C) (Itasca, 1992). At this point, the thermal time is held fixed, and hydromechanical timestepping is initiated until equilibrium is reached with that temperature increment. This modeling approach keeps the out-of-balance forces generated after each thermal increment small and leads to more accurate results, especially if nonlinear behavior is present.

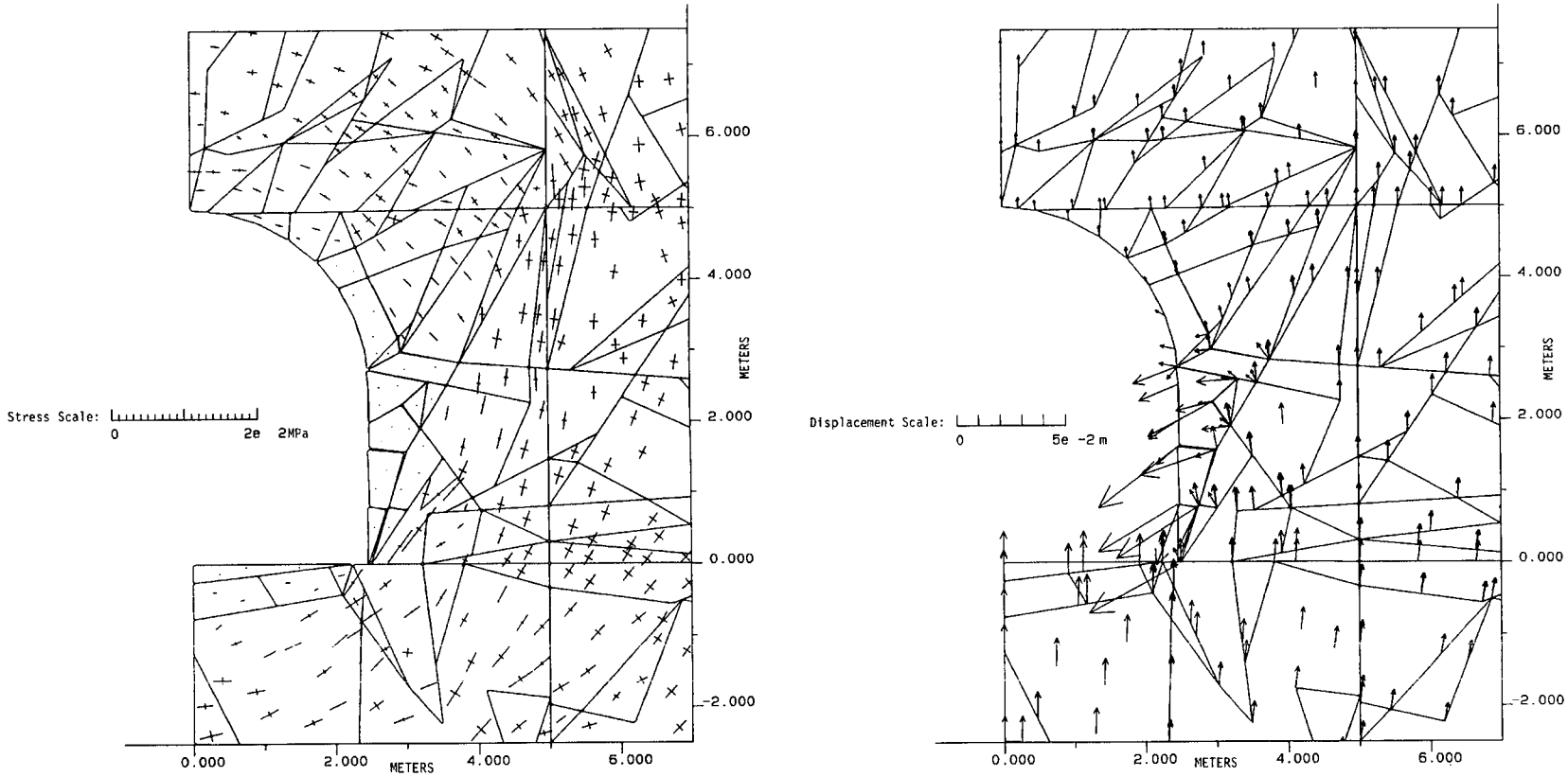
For Case A, explicit thermal timestepping was used for the first year of heating, with an explicit time step calculated in the program to be approximately 100 s. For the remaining heating period of up to 100 yr, the implicit thermal timestepping scheme was utilized with a larger time step of 10,000 s. For the specified thermal properties of the source and rock matrix, the peak temperature was reached after 4 yr of heating (approximately 172 °C at the canister midpoint). Figures 6-5a and 6-5b show the results from Case A for the principal stresses and gridpoint displacements after this peak temperature was reached (i.e., at time t_{max}). Upward displacement of the tunnel floor on the order of 15 mm is shown to occur as a result of the thermal expansion. Also, the maximum inward displacement along the tunnel wall increased to a value of 47.3 mm, causing some slight separation of the blocks in this area. Figure 6-5a shows the maximum compressive principal stress for this thermal loading increased 23 percent to 76.4 MPa, while the minimum principal stress increased only slightly to 7.7 MPa. Normal stresses along lines I and II are presented in Figures 6-6a and 6-6b. The horizontal stress within the immediate floor was seen to increase to approximately 40 MPa, compared with only 20 MPa after excavation (Figure 6-4b).

Temperatures along these same two lines are given in Figures 6-7a and 6-7b at this time period. The heat source caused only a slight increase in temperature in the roof of the tunnel at this time. Temperature contours within the modeled region as well as fracture flowrates into the tunnel are depicted in Figures 6-8a and 6-8b, respectively. The temperature contours showed the effect of the convective boundary condition around the perimeter of the tunnel. Comparison of the fracture flowrates plotted in Figures 6-3a and 6-8b shows a decrease in the flowrate through the upper portion of the tunnel wall after 4 yr of heating (i.e., $t = t_{max}$). This decrease in flow was a result of thermal expansion of the rock mass,



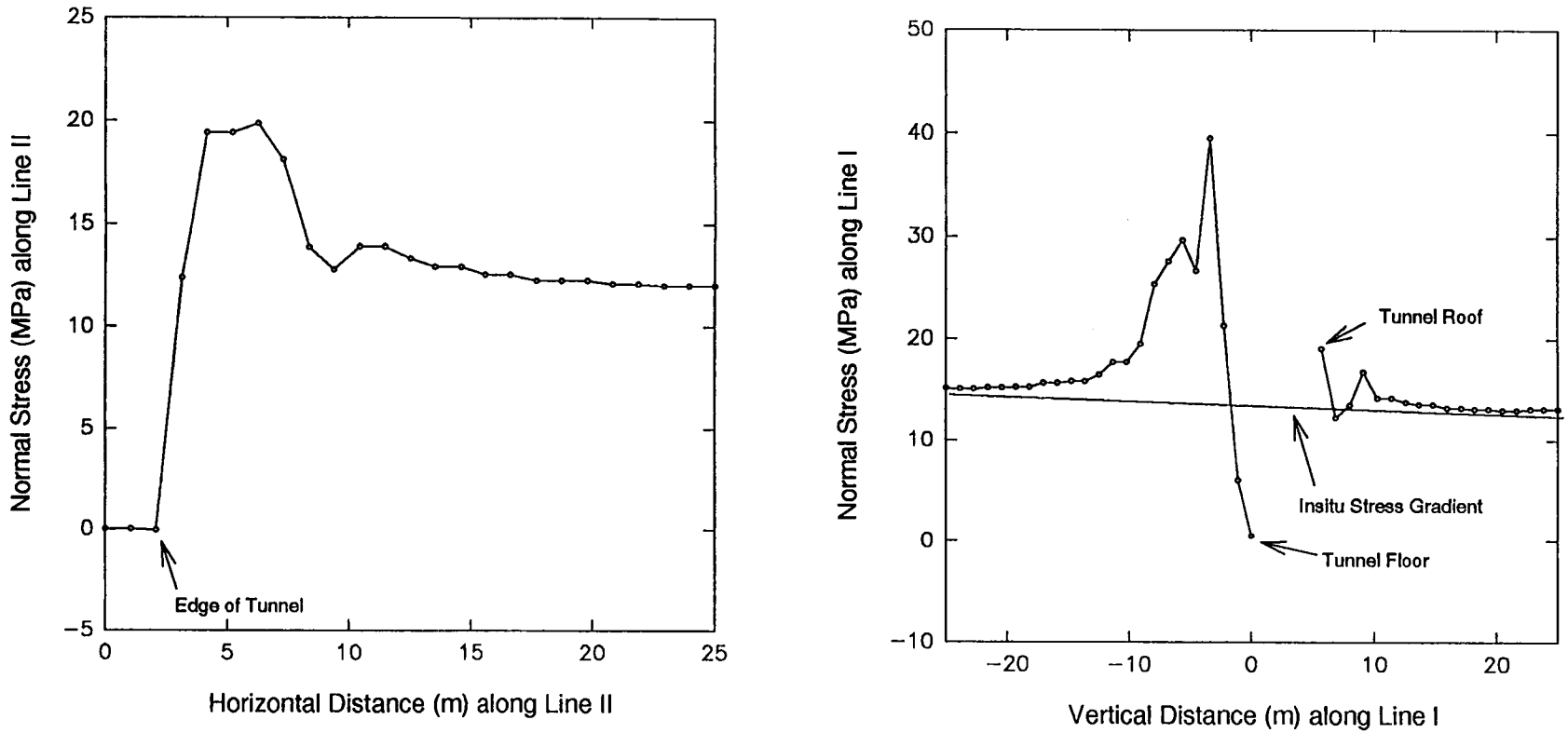
(a) (b)

Figure 6-4. UDEC results for Cases A and B after excavation of tunnel ($t = t^*$) (a) normal stress (σ_{yy}) along line II (b) normal stress (σ_{xx}) along line I



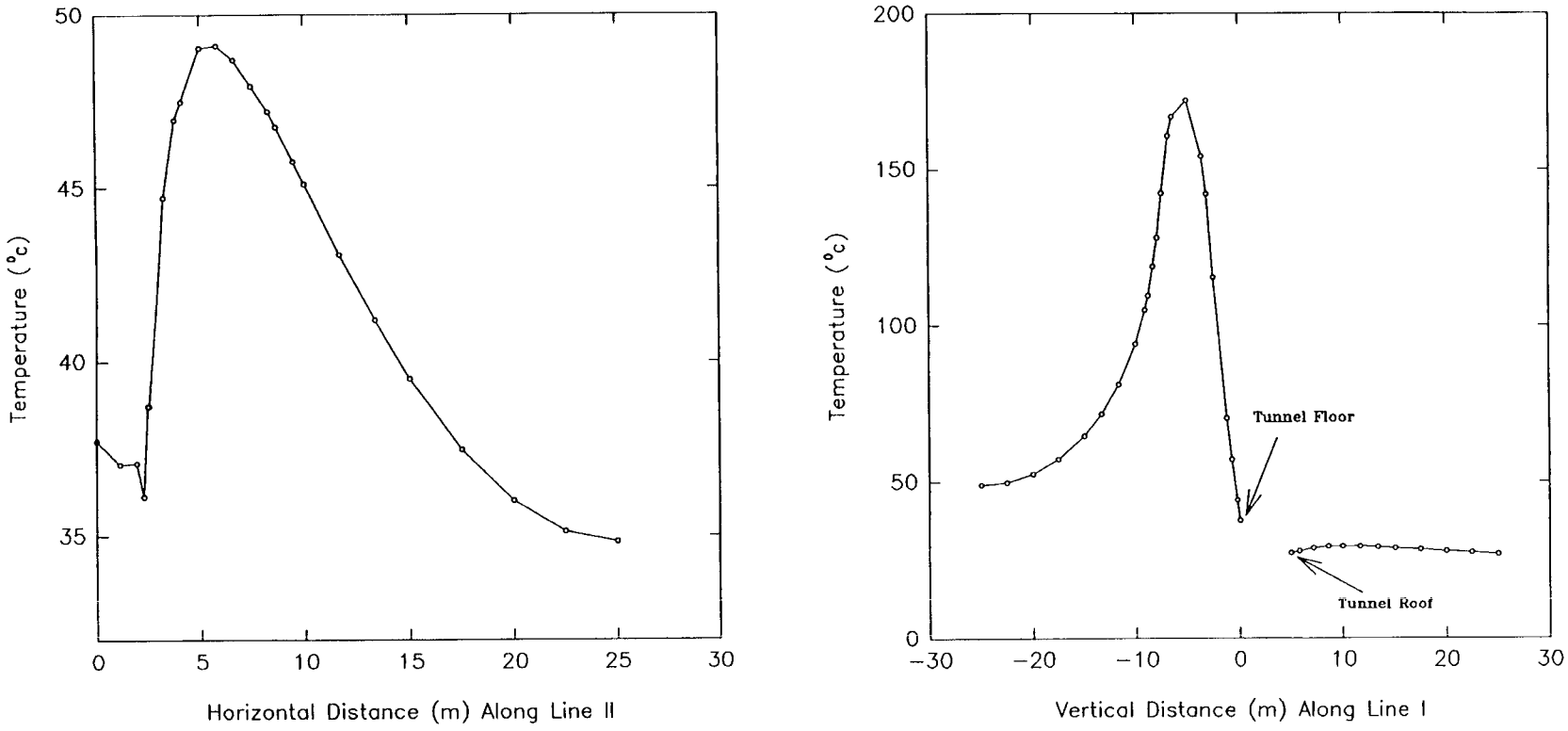
(a) (b)

Figure 6-5. UDEC results for Case A after 4 yr of heating ($t = t_{max}$) (a) principal stress vectors [maximum principal stress (compression) = 76.4 MPa, minimum principal stress (tension) = 7.71 MPa] (b) displacement vectors (maximum displacement = 4.732×10^{-2} m)



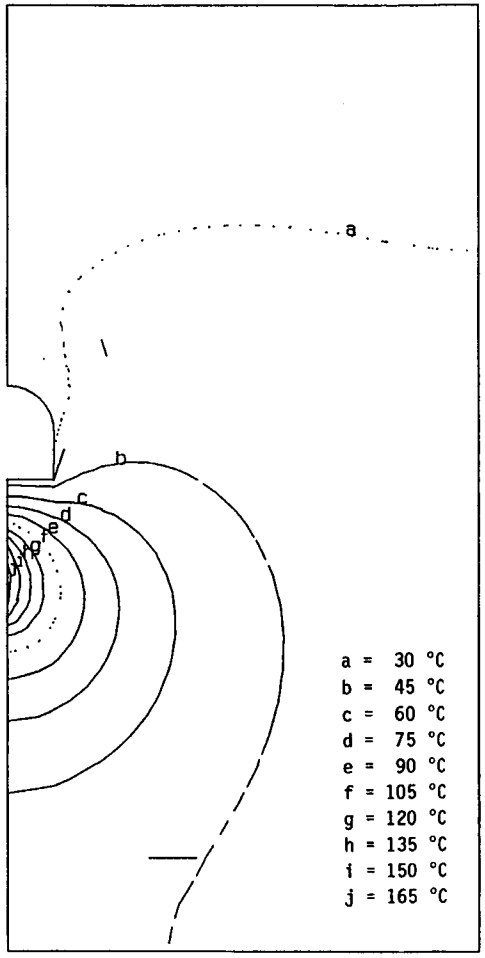
(a) (b)

Figure 6-6. UDEC results for Case A after 4 yr of heating ($t = t_{max}$) (a) normal stress (σ_{yy}) along line II, and (b) normal stress (σ_{xx}) along line I

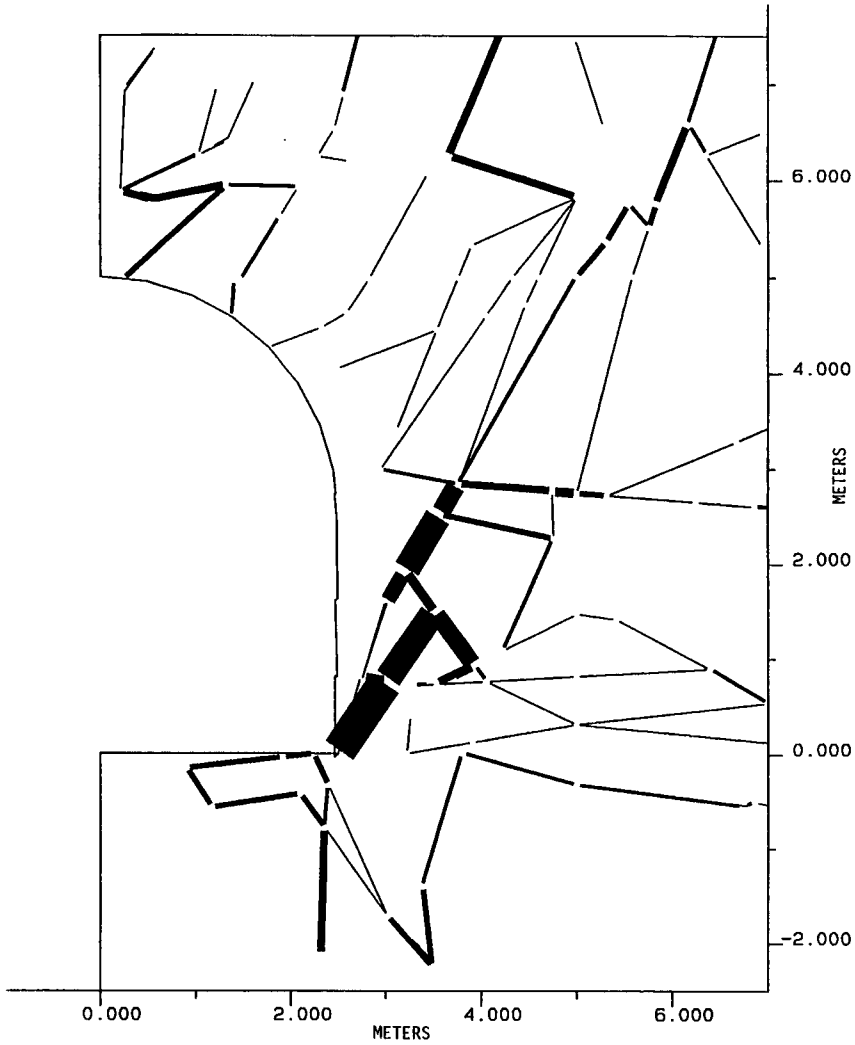


(a) (b)

Figure 6-7. UDEC results for Case A after 4 yr of heating ($t = t_{max}$) (a) temperature (°C) along line II, and (b) temperature (°C) along line I



(a)



(b)

Figure 6-8. UDEC results for Case A after 4 yr of heating ($t = t_{max}$) (a) temperature contours (°C), (b) fracture flowrates (tunnel inflow = 8.425×10^{-9} m^3/s) (Note: the thickness of the lines is proportional to the amount of flow, the minimum line thickness represents flow = 5.0×10^{-10} m^3/s)

pinching off the fractures in this region. The flowrate into the right half of the tunnel at this time period was 8.425×10^{-9} m^3/s, a significant reduction of 60 percent. Results for the temperatures, stresses, displacements, and fluid fluxes at the various monitoring points and segments at thermal output times t^*, $t^* + 1$ yr, t_{max}, $t^* + 30$ yr, and $t^* + 100$ yr are given in Appendix B. Graphical plots at these other time periods are given in Appendix C.

7 DISCUSSION OF THE RESULTS

The results presented in Section 6 are based on a number of simplifications of the original problem, namely the use of vertical symmetry, reduction in number of discrete fractures, as well as simplifications in the distribution of fracture apertures. However, the assumptions appear to be adequately justified (Section 5), so as to capture the overall characteristics of the thermal, mechanical, and hydrological behavior of the problem. The assumptions are further verified by the relatively good agreement between results from the two cases run using UDEC, each encompassing a vastly different extent of fracturing away from the tunnel boundary. Specifically, if one is interested in only the very near-field region around the tunnel, assuming equivalent properties for the outer domain (Case A) appears to be justified. The fairly small refinement in the results in incorporating a larger fractured zone (Case B) may not justify the computer expense.

In future comparison of the results with those obtained from other codes in Phase II of DECOVALEX, the simplifications made for the UDEC model will likely lead to somewhat more error in the fluid flow results than in the mechanical or thermal results. This likelihood is because small errors in the representative apertures used for the UDEC model (as discussed in Section 5) could lead to larger errors in the calculated flowrates as a result of the cubic flow law used in the program. Also, any simplifications in the fracture network for the UDEC model would likely have a larger impact on representing the actual flow pattern than, say, the actual mechanical displacements and stresses. This larger impact would likely be due to the fact that, except in the near vicinity of the tunnel, the relative joint displacements become small and the rock mass begins to act more as a continuum. The temperatures calculated by UDEC assume a continuum, so the simplifications made in the problem have no effect on the resulting temperatures calculated. Also, even though UDEC does not account for convective heat transfer in the fluid, the apertures and flowrates in this problem are so small that it is expected this effect can be neglected, as compared to the convective heat flux from the tunnel boundary. When significant fluid flow rates occur, convective heat flow through the fluid phase can transfer heat faster and more extensively than conductive heat flow through the solid phase. Also, because convective heat transfer can be an important aspect of thermal-hydrological coupling (if fluid flow rates are significant), the fact that it is not considered in UDEC may affect its suitability as a THM analysis tool. One final limitation with UDEC for this BMT problem was that the temperature dependency of the fluid density and dynamic viscosity specified for the problem could not be simulated. It is not known how much of an effect this assumption could have on the results.

8 RECOMMENDATIONS

The following are the recommendations for DECOVALEX regarding the BMT3 problem.

- The far-field boundaries are located too close to the given thermal source to model the 100-yr thermal loading requested by the specifications. The boundaries should be moved farther away or the time period to thermal loading should be reduced to make interpretation of the results more meaningful for typical repository settings.

  The method suggested by St. John (1985) can be applied to determine the radius of influence of a single waste container on rock temperatures as a function of time in order to determine the size of the area required in a model. The equation for temperature change at a distance, R, from a decaying point source of initial strength, Q_o is given by Christianson (1979)

$$\Delta T = \frac{Q_0}{\pi^{3/2}} \exp(-At) \frac{\sqrt{\pi}}{4\kappa} \exp(-R^2/4\kappa t) \text{ Re} \left[w \left(\sqrt{At} + \frac{iR}{\sqrt{4\kappa t}} \right) \right] \tag{8-1}$$

  where

  i = imaginary number $\sqrt{-1}$
  A = thermal constant
  κ = thermal diffusivity
  t = time (s)
  $w(z)$ = complex error function
  Re = real part of argument

  It is seen that the temperature change decays from the point source approximately proportional to

$$\exp\ (-R^2/4\kappa t) \tag{8-2}$$

  St. John (1985) suggested that $R^2/4\kappa t = 4$ is sufficient to ensure a small temperature change. This expression requires that

$$R \geq 4\sqrt{\kappa t} \tag{8-3}$$

  where t is time in years.

  Applying the above equation to the present problem for a time period of 100 yr and a thermal diffusivity of 39.4 m^2/yr, the radius of thermal influence, R, is determined to be approximately 251 m. In the present model, however, the distance from the heat source to the nearest boundary is only around 20 m. It should be noted that Eq. (8-1) is based on conductive heat transfer only. If convective heat transfer occurs as well, the value of R computed using Eq. (8-3) should be considered as a lower bound.

- Detailed evaluations should be made of the types of coupling required to achieve meaningful results from analyses similar to that performed for this BMT. If the couplings are shown to be relevant, they should be incorporated into UDEC. In particular, the ability to model matrix flow is an important feature to include in further studies of the proposed HLW repository at Yucca Mountain. The ability to simulate matrix flow could also eliminate the need to "connect" the larger aperture fractures through the smaller ones. The matrix could serve as the link between the fractures. This method could reduce even more the number of fractures required to model the problem. Additionally, the problem specifications described changes in fluid viscosity and density with changes in temperature. These couplings have recently been incorporated in UDEC and should be tested in further analysis of this and similar problems.

- A complete description of the problem should include specification of the water bulk modulus and air content.

- The analysis presented here assumes that fluid deformation can be ignored (i.e., only steady-state conditions are modeled). Rigorous transient analysis requires that the fluid deformability be taken into account properly. An implicit formulation that permits transient analysis has recently been incorporated into UDEC. This transient analysis algorithm should be tested and used in future analysis of this or similar problems. Results from transient and steady-state analyses should be compared to assess differences in the results, if any.

- It would be worthwhile to expend additional effort for a study on possible methods of identifying key flow paths. The current analysis appears to show that one need not model all of the fractures. It would be of interest to determine if the number of fractures could be reduced even more than was done in this analysis. On the other hand, it is possible that the method of selection employed in this work caused the removal of some short fractures that might have been crucial for the connectivity of larger ones.

9 SUMMARY AND CONCLUSIONS

A distinct element analysis of the near-field repository model (BMT3) using the computer code UDEC is presented as part of the Phase II study of DECOVALEX. No closed-form solution to this coupled THM problem exists, so final determination of accuracy of the results can only be made through benchmark comparisons with other codes used to analyze this problem in DECOVALEX. However, the present results obtained from UDEC appear reasonable from an engineering point of view and show that, given the extremely complicated fracture pattern within this near-field repository model, simplifications can be made to obtain an approximation of the coupled THM behavior of the original system. Specifically, if one is interested in only the THM response in the immediate vicinity of the tunnel, assuming "equivalent" mechanical and hydrological properties for the outer regions of the model appears justified. This assumption was verified through the two cases analyzed with UDEC.

With regard to the distinct element analysis, determinations can be made as to the specific locations around the tunnel where mechanical instabilities are likely to occur and fluid inflow into the tunnel is the highest. The UDEC code appears to adequately simulate the two-way hydromechanical coupling present in this problem, as well as the thermal impact on the hydromechanical response of the system. Calculations were carried out for only 100 yr after the thermal source was initiated. Results show the total flowrate into the tunnel decreasing after initiation of the heat source up to the time at which the peak temperature is reached. Upon subsequent decay of the heat, the flowrate is again seen to increase towards its initial value. A final report documenting the comparison of the results for BMT3 obtained from the different research teams involved in DECOVALEX will be issued by the Project Secretariat upon completion of the Phase II modeling activities.

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APPENDIX A

UDEC INPUT FILE FOR THE BMT3 PROBLEM

A-1. INPUT FILE FOR NEAR-FIELD REPOSITORY MODEL, BMT3 (CASE A)

```
set log on
set plot hp7475
start
* Bench Mark Test #3 - ANDRA/CEC
head
BMT #3 - Near Field THM Model (25x50 m symmetry model)- DECOVALEX Phase 3
thermal
* input block and joint geometry
round 0.04
set edge 0.2
bl 0,-25.0 0,25.0 25.0,25.0 25.0,-25.0
*
* input tunnel geometry
* (if tunnel geometry is given first it will be preserved)
*
crack -2.5,0.0  2.5,0.0
crack -2.5,0.0 -2.5,2.5
crack  2.5,0.0  2.5,2.5
arc 0.0,2.5 2.5,2.5 180.0 16
*
* divide block into a uniform grid
*
* vertical grid lines
*
jset 90 0 100 0 0 0 5 0
*
* horizontal grid lines
*
jset  0 0 100 0 0 0 5 0
crack 0 5.1 5 5
*
* input canister geometry
*
crack -0.25,-2.5  0.25,-2.5
crack  0.25,-2.5  0.25,-7.5
crack  0.25,-7.5 -0.25,-7.5
jdel
*
*   **** insert joint geometry *******
*
*   This is a 10m x 20m submodel of the original problem which contains only
*   those fractures whose length is greater than 2.0 meters.  The total
*   number of fractures in this model is 211. Symetry is assumed along the
*   vertical axis about the origin.
*
*       xbeg        ybeg        xend        yend
```

crack	6.59117222	-9.80582619	7.17430210	-7.86403847
crack	2.69646955	4.78434277	5.03880024	5.83283806
crack	6.35416794	6.26286173	8.48783302	7.09479284
crack	4.84300661	2.85582852	5.30710554	5.35770893
crack	2.94281960	2.98616838	4.85295010	5.74965143
crack	5.75955105	-8.63393974	6.72897720	-10.00000000
crack	8.16140366	-7.40391111	9.58018303	-5.82723951
crack	0.37941647	-7.21988010	1.69865036	-9.81375599
crack	8.45043659	-0.33581471	9.75589275	1.66353559
crack	6.43912125	-6.20957422	8.83298588	-5.75890875
crack	7.29822540	5.10207415	8.90244102	7.78932714
crack	1.10374451	3.03253222	4.75708723	2.25902557
crack	4.74125528	2.75306273	5.04491282	5.89620256
crack	6.17370796	4.79891872	8.77472973	6.55124569
crack	7.76080513	5.86816549	10.00000000	6.19294310
crack	8.82332897	8.91206455	9.26244164	10.00000000
crack	5.74375248	10.00000000	6.09442139	7.57500458
crack	4.12209225	-4.46626091	4.98523235	-1.88120675
crack	6.09299660	-0.79832613	10.00000000	0.62065226
crack	8.41843891	2.99248362	8.81285572	5.83529329
crack	1.32871914	-10.00000000	0.00000000	-9.09532261
crack	2.92644119	2.94608545	3.89760542	5.32202291
crack	0.76180607	-7.97176266	2.65855694	-6.30091286
crack	0.75155294	10.00000000	0.00000000	8.58545876
crack	8.98552895	8.06544495	10.00000000	9.28096485
crack	0.00000000	1.25817657	0.59492052	2.15336561
crack	7.31393051	-3.48312283	8.25614643	-0.76929426
crack	6.99329948	0.52873677	9.11027336	1.77682567
crack	1.06423903	3.73978853	4.46644878	4.71027327
crack	4.09581947	-1.76580763	6.18701744	-2.24054337
crack	3.11143446	-6.12348223	4.98892260	-2.51873922
crack	9.66149616	4.87212372	9.90764523	2.71739435
crack	1.02929616	6.25660133	1.73295450	8.86692429
crack	6.33557701	-5.34892654	7.69341373	-9.42074394
crack	0.00000000	0.55426216	2.10307932	4.03613710
crack	3.01786280	1.58513665	5.53954363	5.74074459
crack	8.71699715	0.07245338	10.00000000	-0.66414952
crack	0.25999272	6.95700502	2.60681176	10.00000000
crack	8.35612297	3.00431418	10.00000000	2.69262815
crack	7.06360579	-2.96896505	8.02165604	-0.73825824
crack	8.94960880	-1.13906240	10.00000000	1.08220029
crack	0.00000000	-0.76110911	2.09896684	-0.42819127
crack	0.00000000	5.77163315	2.00451422	6.71611214
crack	3.29582977	0.71081144	7.71767044	0.95578891
crack	1.10372877	3.03252912	7.44628000	2.54526734
crack	8.77940941	-0.83854097	9.86335945	-2.75234509
crack	0.54034740	5.78031158	2.45621252	6.52882290
crack	9.21316719	2.84180117	9.85375977	5.47435427

crack	0.94305909	1.48448360	3.41780949	3.67335367
crack	3.15743399	0.53202248	5.69294596	1.81631064
crack	4.76643562	-2.74496841	6.88762379	-0.58818519
crack	0.44092223	3.09528351	1.43354952	4.99353313
crack	1.67056465	9.38376617	3.19256973	8.01964951
crack	0.00000000	-7.88655567	0.51888049	-8.28833675
crack	7.68311501	3.11535835	7.97511101	5.09827995
crack	6.90937185	1.92517567	9.06467056	4.41447163
crack	7.80707026	-9.07452011	10.00000000	-7.84894180
crack	7.80950785	-8.72340965	10.00000000	-7.70054197
crack	6.66739845	-8.24903584	10.00000000	-7.68865013
crack	6.87042427	8.15547752	9.17457581	7.74027634
crack	0.28082407	-5.81728792	2.24864626	-3.92351294
crack	5.31476402	2.70900512	7.97513390	5.09829235
crack	4.18443298	0.56449586	2.96506190	2.25307083
crack	2.00078011	-4.27198219	0.29847062	-6.66526508
crack	9.86648655	-6.54026937	7.08802700	-7.60538435
crack	6.56507921	-7.80585527	4.43090677	-8.62398434
crack	3.48817611	-2.25463462	3.15744376	0.53204399
crack	3.07050157	2.88142538	2.12314963	4.77467155
crack	8.78801632	6.62463379	8.18301868	3.28605103
crack	4.64440632	-4.25562572	3.02151728	-6.23303509
crack	5.07618427	-10.00000000	3.93149519	-9.28045368
crack	3.54736185	5.16522884	0.55815446	3.47412014
crack	0.09904623	3.21438503	0.00000000	3.15835071
crack	6.63401937	-7.82935095	6.33163214	-5.31608248
crack	9.67775249	-5.43228674	6.74188566	-6.56740141
crack	10.00000000	-7.42838621	7.55452061	-8.09986687
crack	2.06046104	-1.19423521	0.04232872	-0.91352856
crack	0.07120478	7.68442488	0.00000000	7.62997818
crack	1.32012153	5.93619108	0.36344814	2.84493876
crack	0.93718290	-3.09434271	0.00000000	-1.25144291
crack	2.43137836	-6.03256607	0.00000000	-1.25144303
crack	9.14166927	-9.63814259	6.95171404	-9.64456654
crack	10.00000000	-4.23017740	8.03917408	-3.75838733
crack	1.03104258	-2.87613773	0.00000000	-5.19295263
crack	2.87104607	7.13127708	0.06806767	2.76620197
crack	0.08060360	2.78572416	0.00000000	2.66020036
crack	4.53628063	-4.55224657	2.49976015	-4.12939310
crack	2.11725998	-4.04997253	0.00000000	-3.61035419
crack	0.11090517	-0.70553100	0.00000000	-1.04196632
crack	5.58712626	-8.18076515	4.95358419	-5.54295921
crack	4.95358992	-5.54298306	4.45529985	-3.46830726
crack	2.84055495	-5.99188089	1.18475175	-8.80335617
crack	10.00000000	-7.26672649	6.14954996	-8.40168095
crack	7.16134644	-2.68175340	4.71749687	-4.30878353
crack	4.93216133	-4.36828279	3.90015340	-1.15690863
crack	9.66592407	-6.52968454	9.62903786	-8.70198441

crack	4.91583252	-4.61072159	1.67895532	-8.94599342
crack	8.55226040	7.85240269	7.27604437	10.00000000
crack	10.00000000	-1.00007832	7.83120155	-0.71306771
crack	8.02167130	-0.73827380	3.80715156	-0.18054020
crack	3.48300791	7.60280180	3.47943044	10.00000000
crack	0.26946443	7.17697144	0.09903289	3.21435714
crack	0.16562401	4.76263237	0.05510876	2.19310021
crack	9.76216316	6.88159418	6.87042046	8.15548420
crack	8.65240860	7.37047005	6.68277836	8.23814487
crack	1.86859202	-8.69202614	0.37284160	-7.21339083
crack	0.37285906	-7.21340799	0.00000000	-6.84481573
crack	0.15298218	-3.87726212	0.00000000	-4.16524315
crack	1.05769718	-10.00000000	0.00000000	-8.26536942
crack	6.29728127	-7.80412292	5.75448418	-10.00000000
crack	10.00000000	-9.91980648	8.80550289	-9.00777054
crack	5.41891289	-5.37677765	2.32556057	-6.48159504
crack	5.27506065	5.83823776	2.36505342	6.19493008
crack	10.00000000	8.25090504	6.24274254	2.63770008
crack	6.49523687	3.01491690	5.01677084	0.80614364
crack	1.50346315	-6.22117519	0.29976535	-4.51933670
crack	6.26842260	4.86271048	4.94758558	7.53501749
crack	7.81414127	-8.05620003	7.80067587	-10.00000000
crack	9.13211632	2.59082651	8.64318085	4.61238909
crack	7.87359619	8.99444199	7.60110569	10.00000000
crack	3.07719994	1.71311951	0.59327281	1.44702125
crack	3.01987123	-1.72380328	1.56746066	1.50070572
crack	3.20646477	-6.70320702	1.97529984	-9.10658836
crack	9.69122028	0.83126456	3.20816588	0.10431087
crack	2.24510741	-0.00367822	0.00000000	-0.25542516
crack	6.92403173	-8.69742966	6.24207878	-10.00000000
crack	0.58293021	8.53192043	0.00000000	7.56651115
crack	2.31412005	-2.55159879	0.00000000	-3.13695407
crack	9.61396980	-6.10408926	9.31543541	-3.65846586
crack	7.40467358	-1.28601623	7.31290245	-3.50815749
crack	7.31290340	-3.50813222	7.19377422	-6.39269924
crack	7.20155478	-6.20429897	7.04479742	-10.00000000
crack	10.00000000	-2.30187321	8.18683720	-3.79393291
crack	4.92404985	-10.00000000	4.11463356	-8.97795486
crack	4.26410818	8.90324020	3.53552604	6.32486343
crack	8.21401882	-0.09900278	5.15835285	1.54555321
crack	9.80130577	0.65202415	8.72367668	2.40606451
crack	7.46215057	4.45943260	6.16444969	6.57168102
crack	0.79670644	-10.00000000	0.00000000	-8.77337360
crack	6.17373371	4.79890585	4.57590771	7.17177629
crack	4.34004593	-2.98839998	3.32745385	-5.28793669
crack	2.38106394	-8.00565338	1.12275028	-5.50638628
crack	4.52092218	8.82963085	4.45914698	10.00000000
crack	3.92430401	-4.20416927	2.72984648	-7.53849697

crack	8.29977226	1.29897261	6.10399818	2.28791046
crack	7.18328667	-5.07416105	4.98600864	-5.36519575
crack	10.00000000	2.07513404	7.54494667	-1.55435109
crack	7.89067507	-1.04323506	6.75792933	-2.71785617
crack	7.11844969	-0.42588508	6.00439215	-2.59631586
crack	10.00000000	-2.20168638	9.50456524	-0.93450153
crack	3.52585530	-2.49425554	1.91455054	-0.04072917
crack	4.26595592	-4.71675682	1.90824115	-6.15164661
crack	9.18967819	6.99991846	8.61490154	10.00000000
crack	5.81648397	5.70190382	3.66661882	6.24324465
crack	5.49244356	5.81065655	4.60160589	8.42154884
crack	7.86703205	3.80043793	5.35964680	2.70556498
crack	5.40420294	10.00000000	4.67884827	8.57344341
crack	4.67885780	8.57346058	3.40465665	6.06748676
crack	0.07254207	2.59829426	0.00000000	2.49582744
crack	7.75737858	1.54325247	6.37883949	3.15061617
crack	2.92790508	8.25687504	2.29386425	5.93410444
crack	3.96366429	-8.36987686	1.88158727	-9.41966057
crack	5.38246918	-7.32860136	2.56579494	-7.99640799
crack	6.67404366	10.00000000	5.94501829	8.60813904
crack	8.32397461	-2.02528667	6.17937183	-5.56759071
crack	6.53842878	-4.97452545	5.49871397	-6.69185257
crack	4.51560259	-8.31568718	3.49587584	-10.00000000
crack	9.24496078	4.58399820	7.47258568	2.91740274
crack	9.24496841	4.58400536	7.24231148	2.70087194
crack	7.28459454	10.00000000	5.83165073	5.74634409
crack	5.83166647	5.74639130	4.23741293	1.07903457
crack	4.06820154	0.58364969	3.38774467	-1.40846467
crack	0.52937746	-9.58842564	0.33347762	-6.61602926
crack	0.32079896	-6.42365646	0.13764885	-3.64471269
crack	3.66745520	1.68845057	2.06072140	-0.47978836
crack	7.10239029	7.99733305	6.07816029	10.00000000
crack	7.46982384	10.00000000	4.91494894	7.50310230
crack	3.44142222	6.06301355	0.06804395	2.76618528
crack	3.29584289	2.43112493	0.58041072	0.96934146
crack	3.76100016	7.12276888	1.89455557	5.61059713
crack	6.59394884	10.00000000	4.63774633	8.49262047
crack	2.94356155	7.18714237	0.25478256	5.11526585
crack	2.39606500	-0.33887029	2.21309638	-2.57717133
crack	2.26338696	-1.96195507	2.08413434	-4.15479755
crack	2.26652074	-1.92362106	2.00052810	-5.17757654
crack	10.00000000	-7.97623730	9.63121510	-9.63823795
crack	7.23186064	-6.06030941	6.40281248	-10.00000000
crack	5.18686676	6.26452446	2.06070662	-0.47983456
crack	9.96431065	2.73231888	9.51840115	0.44572997
crack	7.51130295	-3.05962491	6.58513737	-5.15339661
crack	2.14070082	-8.83710766	1.21098197	-10.00000000
crack	3.45819378	6.05114174	0.20805013	5.74947071

```
crack   2.29638863   5.94330597   0.00000000   5.73015976
crack   2.84469175   9.75615597   1.32740355   6.39705372
crack   8.49779987  -0.14572340   3.13301873   0.73762488
crack   3.13305378   0.73761910   0.84866560   1.11375952
crack   3.74235630   6.35712194   2.58934641   4.62323713
crack   0.71722990  10.00000000   0.00000000   8.18017960
crack   2.40528083  -6.06646442   1.91245043  -8.63327312
crack   7.06361246  -2.96894670   6.11753607  -5.74933147
crack   2.88564491  -3.31924891   1.24314356  -6.76770020
crack   1.50346327  -6.22115612   0.29744500  -8.75320625
crack   7.95547199  -1.63533080   6.09149265  -3.32028008
crack   1.17155409  -0.57530469   0.00000000   1.30710888
crack   5.31754303  -5.56747532   3.31286693  -5.91096687
crack   1.50336218  -6.22101641   0.00000000  -6.47861099
crack   4.64980221  -2.88581777   2.14044428  -7.44577694
crack   8.80582237  -0.88515371   7.31421232  -2.23245502
crack   7.36758089  -2.18424988   5.85086012  -3.55423260
crack   9.80722904 -10.00000000   8.67709446  -8.12487316
crack   6.24336720  -8.02225208   4.80148792  -9.84525776

*
save b3_d31.sav
res b3_d31.sav
*
* generate finite difference zones
*
gen 0 10 -10 10 edge 1.5 ; inner region
gen 0,15 10,15 quad 2.5 ; intermediate zone size between inner & outer region
gen 10,15 -10,10 quad 2.5
gen 0 15 -15,-10 quad 2.5
gen quad 4.5 ; outer region
pr max
*
* apply insitu stresses and pore pressures for initial mechanical state
*
grav 0.0 -9.81
fluid d=0.001
insitu stress -13.096 0.0 -13.096 ygrad 0.0262 0.0 0.0262 nodisp ywtable 500
*
* apply mechanical and hydrologic boundary conditions
*
bound -10.1,25.1 24.99,25.1  stress 0.0 0.0 -12.441  pp = 4.66 ;top
bound  24.99,25.1 -25.1,25.1 xvel=0.0  imperm ; right-hand-side
bound -10.1 25.1,-25.1 -24.99 yvel=0.0 imperm ; bottom
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
*
damp auto
set delc off
```

```
*
* define mechanical and thermal properties for matrix and joints
* Note: vertical and horizontal joints were artificially inserted, and
* thus their strength was set high and permeability either set to zero
* or set to equivalent permeability
*
* define material properties
prop mat=1 k=3.704e+04 g=2.439e+04 d=0.00267
prop mat=1 cond=3.0 thexp=9.0e-06 spec=9.0e+08
prop jmat=1 jkn=1.0e+06 jks=1.0e+06 jc=10000.0 jfric=80.0 jdil=0.0 &
  jtens=10000.0 jperm=0.0 ares=3.0e-6 azero=3.0e-6

* outer region
prop mat=2 k=0.76e+04 g=0.5e+04 d=0.00267
prop mat=2 cond=3.0 thexp=9.0e-06 spec=9.0e+08
*
* ******************************************************************
*                                                                  *
*                          KEY                                     *
*                                                                  *
*  JMAT    Description                                             *
*  ----    ------------------------------------------------        *
*    1     Near-field artificial joints (no permeability)          *
*    5     Far-field  artificial joints (with permeability)        *
*  2,3,4   "Real" angled joints                                     *
* 6,7,8,9,10  "     "      "                                        *
*                                                                  *
* ******************************************************************
*
change mat 2
ch 0 10 -10 10 mat 1
change jmat 5
change -.1 10.0 -10.0 10.0 jmat 1
change angle    1     20.0   jmat=2
change angle  20.0    40.0   jmat=3
change angle  40.0    60.0   jmat=4
change angle  60.0    89.999 jmat=7
change angle  90.001  100.0  jmat=6
change angle 100.0    120.0  jmat=7
change angle 120.0    140.0  jmat=8
change angle 140.0    160.0  jmat=9
change angle 160.0    179.999 jmat=10
change -0.1 10.1 9.99 10.01 ang -1 1 jmat 5
change -0.1 10.1 -10.01 -9.99 ang -1 1 jmat 5
change 9.99 10.01 -11 11 ang 89 91 jmat 5
*
* Explicit real joints
prop jmat=2 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
```

```
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.2602e-6
prop jmat=3 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.5267e-6
prop jmat=4 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.3788e-6
prop jmat=6 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.4455e-6
prop jmat=7 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.200e-6
prop jmat=8 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.6512e-6
prop jmat=9 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.0844e-6
prop jmat=10 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.7785e-6
*
* farfield vertical and horizontal joints
prop jmat=5 jkn=1e5 jks=1e4 jc=1000 jfric=80.0 jdil=0.0 &
 jtens=100000.0 jperm=8.333e7 ares=9.26e-6 azero=9.26e-6
set jmatdf 2
* !!!! NOTE !!!! elastic rock properties for MAT=2 have been adjusted according to
* 1/E equivalent = (1/E intact) + (1/ S*Kn)


*
* cycle mechanically to consolidate before applying fluid pressure
*
his unbal damp
his sxx 0.0,5.1 syy 0.0,5.1 xdis 0.0,5.1 ydis 0.0,5.1 pp 0.0,2.5
cycle 500
pr max
save b3_d3c.sav

rest b3_d3c.sav
*
* reset gridpoint and joint shear displacements to zero before
* setting pore pressures to zero and excavating tunnel to define
* initial state
*
reset hist,disp jdis
*
*  define monitoring locations
*
hist unbal
hist ncyc=10  xdis 0.0,0.0 ydis 0.0,0.0 xdis 0.0,5.0 ydis 0.0,5.0  &
 xdis 2.5,2.5 ydis 2.5,2.5
hist  xdis 7.5,7.5 ydis 7.5,7.5 xdis 7.5,-7.5 ydis 7.5,-7.5
hist sxx 0.0,0.0 syy 0.0,0.0 sxx 0.0,5.0 syy 0.0,5.0 sxx 2.5,2.5 syy 2.5,2.5
```

```
hist  sxx 7.5,7.5 syy 7.5,7.5 sxx 7.5,-7.5 syy 7.5,-7.5
hist pp 3.0,2.5 pp 7.5,2.5 pp 7.5,7.5 pp 2.5,-7.5 pp 20.0,-10.0
*
* set pore pressure in tunnel to zero to simulate 3-dimensional exc. effect
*
pfix  -2.5,2.5 0.0,2.5 press 0
pfix ann 0 2.5 0 2.5 press 0

*
* define fluid properties
*
fluid dens=0.001 bulk=2000.0
set ptol 0.005
set sflow on
set capratio=20
*
* cycle until steady state flow is reached before excavating tunnel
*
cycle 1500
pr max
save b3_d32a.sav
cycle 1500
pr max
save b3_d32b.sav
cycle 2000
pr max
save b3_d32c.sav
*

rest b3_d32c.sav
*
* excavate tunnel
*
del 0.0,2.5 0.0,2.5 area=10
del ann 0 2.5 0 2.5
*
reset damp
*
* fix boundary pressure within tunnel to zero
*
bound cor 101 504 pp 0 ;check if corner addresses are correct
* gradually reduce mechanical stress
bound cor 101 504 stress -13.096 0.0 -13.096 ygrad 0.0262 0.0 0.0262
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
pfix -1 26 22 25 p = 4.67 ;top -- this is necessary because BOUND PP is lost
* bound -1 26 24 26 pp 4.66
cy 1
bound cor 101 504 stress 13.096 0.0 13.096 ygrad -0.0262 0.0 -0.0262 hist lin
```

```
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
cy 15000
pr max
bound cor 101 504 xfree yfree
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
pfree dom 33582
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
save b3_d33.sav
*
rest b3_d33.sav
set ovtol 0.075
*
* reset time for thermal calculations (i.e. starting at t*)
*
reset time
*
* define thermal boundary conditions and initial temperature conditions
* Note: boundaries not specified are assumed adiabatic within the code
*
this ntcyc=50 tem 0.0,0.0  tem 0.0,5.0 tem 2.5,2.5 tem 7.5,7.5 tem 7.5,-7.5
this tem 0.0,-5.0
*
initem 27.0 -1 25.1 -25.1 25.1
tfix 27.0 -1 25.1 24.9 25.1
thapp -2.6,2.6  -0.1,5.1 conv 7.0 27.0
thapp -.01 0.01 -7.51 -2.49 flux 1.175e2  -6.342e-10
* !!!!! Note !!!! print thermal to be sure correct thermal boundaries are used

*
* run thermal time to 1 month
*
run age=1e5 temp=10000 step=10000000 tol 0.1
reset damp
cycle 500
pr max
run age=2e5 temp=10000 step=10000000
reset damp
```

```
cycle 500
pr max
run age=3e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=5e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=10e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=12.5e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=15e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=17.5e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=20e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=22.5e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=25e5 temp=10000 step=10000000
reset damp
cycle 500
pr max
run age=2.628e6
reset damp
cycle 5000
pr max
save bmt3_t1m.sav
*
* run thermal time to 2 month
*
run age=3.128e6 temp=10000 step=10000000
reset damp
```

```
cycle 1000
pr max
run age=3.628e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=4.128e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=4.628e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=5.256e6 temp=10000 step=10000000
reset damp
cycle 5000
pr max
save bmt3_t2m.sav
*
* run thermal time to 4 month
*
run age=6.256e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=7.256e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=8.256e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=9.256e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=10.512e6 temp=10000 step=10000000
reset damp
cycle 5000
pr max
save bmt3_t4m.sav
*
* run thermal time to 6 month
*
run age=11.512e6 temp=10000 step=10000000
reset damp
```

```
cycle 1000
pr max
run age=12.512e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=13.512e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=14.512e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=15.768e6 temp=10000 step=10000000
reset damp
cycle 5000
pr max
save bmt3_t6m.sav
*
* run thermal time to 1 year
*
run age=16.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=17.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=18.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=19.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=20.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=21.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=22.768e6 temp=10000 step=10000000
reset damp
```

```
cycle 1000
pr max
run age=23.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=24.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=25.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=26.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=27.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=28.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=29.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=30.768e6 temp=10000 step=10000000
reset damp
cycle 1000
pr max
run age=3.1536e7 temp=10000 step=10000000
reset damp
cycle 15000
pr max
save bmt3_t1y.sav
*
* run thermal time to 2 years
*
set delc on
run age=6.3072e7 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t2y.sav
```

```
*
* run thermal time to 3 years
*
run age=9.4608e7 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t3y.sav
*
* run thermal time to 4 years
*
run age=1.26144e8 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t5y.sav
*
* run thermal time to 10 years
*
run age=3.1536e8 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t20y.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 temp=10000 step=10000000 impl delt=10000
reset damp
cycle 7500
pr max
save bmt3_t30y.sav
```

```
*
* run thermal time to 50 years
*
run age=1.5768e9 temp=10000 step=10000000 impl delt=15000
reset damp
cycle 7500
pr max
save bmt3_t50y.sav
*
* run thermal time to 75 years
*
run age=2.3652e9 temp=10000 step=10000000 impl delt=15000
reset damp
cycle 7500
pr max
save bmt3_t75y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 temp=10000 step=10000000 impl delt=15000
reset damp
cycle 7500
pr max
save bmt3_t100y.sav
ret
```

A-2. INPUT FILE FOR NEAR FIELD REPOSITORY MODEL, BMT3 (CASE B)

```
set log on
set plot hp7475
start
* Bench Mark Test #3 - ANDRA/CEC
head
BMT #3 - Near Field THM Model (25x50 m symmetry model)- DECOVALEX Phase 3
thermal
* input block and joint geometry
round 0.04
set edge 0.2
bl 0,-25.0 0,25.0 25.0,25.0 25.0,-25.0
*
* input tunnel geometry
* (if tunnel geometry is given first it will be preserved)
*
crack -2.5,0.0  2.5,0.0
crack -2.5,0.0 -2.5,2.5
crack  2.5,0.0  2.5,2.5
arc 0.0,2.5 2.5,2.5 180.0 16
*
* divide block into a uniform grid
*
* vertical grid lines
*
jset 90 0 100 0 0 0 5 0
*
* horizontal grid lines
*
jset  0 0 100 0 0 0 5 0
crack 0 5.1 5 5
*
* input canister geometry
*
crack -0.25,-2.5  0.25,-2.5
crack  0.25,-2.5  0.25,-7.5
crack  0.25,-7.5 -0.25,-7.5
jdel
*
*   **** insert joint geometry *******
*
*   This is a 25m x 50m symetric model of original problem which containing
*   those fractures whose length is greater than 1.5 meters.  The total
*   number of fractures in this model is 1799. Symetry is assumed along the
*   vertical axis about the origin.
*
*       xbeg        ybeg        xend        yend
```

crack	23.33602333	20.32882309	23.39620018	24.08877182
crack	4.13260984	-25.00000000	4.31378841	-23.28691673
crack	21.74075699	-19.78973579	22.97421646	-15.48524284
crack	24.50070190	9.78133297	24.88295364	12.70333195
crack	0.00000000	-24.03818703	1.94622862	-22.36032677
crack	4.09698200	-13.40081501	5.05601025	-12.06076336
crack	8.74509430	-23.10149765	9.10017776	-24.63155365
crack	4.42045784	-20.81682968	4.44001865	-22.77442169
crack	6.59117222	-9.80582619	7.17430210	-7.86403847
crack	19.47251129	-9.10560894	21.12483597	-6.32455873
crack	18.78196716	-16.84454536	18.79039001	-19.38670921
crack	15.12233925	-6.63942385	15.92867851	-3.68551779
crack	18.93015099	23.44024277	24.54879570	24.33553314
crack	0.32831395	-11.10403061	1.84978092	-11.14503670
crack	23.88401222	7.82680416	24.02155876	4.73558140
crack	2.69646955	4.78434277	5.03880024	5.83283806
crack	1.31771600	8.80830097	2.81783867	11.25477505
crack	21.03395844	1.70521569	22.74908829	2.18687010
crack	7.82184935	-19.05258751	10.12699509	-19.63195610
crack	21.96252441	14.27537441	22.19463730	15.88897800
crack	15.15027714	-19.69667816	16.26069450	-17.82819366
crack	24.13150024	-16.66344643	24.63582611	-14.67451286
crack	8.15428162	6.53609085	9.92993355	7.33156681
crack	6.35416794	6.26286173	8.48783302	7.09479284
crack	21.70634651	21.71467209	23.12771797	20.42255783
crack	12.92757225	-5.18987751	14.01950645	-6.36001778
crack	11.41725159	-25.00000000	11.68892288	-22.11925125
crack	0.00000000	-13.78340530	1.88251460	-13.75352478
crack	12.66808033	5.53111649	12.90563297	3.82332921
crack	14.22749043	-9.28809261	15.53681087	-7.92324209
crack	4.84300661	2.85582852	5.30710554	5.35770893
crack	14.10418320	1.32608616	14.46382523	3.32411480
crack	10.40914822	3.56549978	10.53311443	1.92367649
crack	9.28702450	-16.71718407	10.87684727	-16.82119179
crack	7.26500463	21.81293488	8.14677525	20.38976288
crack	21.34667969	1.17495060	22.70825195	2.57889867
crack	13.46660709	8.08383942	15.97140026	6.67577982
crack	5.48852062	20.92749214	5.98299217	22.58478737
crack	17.65549278	18.96224976	18.75818443	20.18522644
crack	15.60083580	-2.11937404	17.85944939	-2.15719724
crack	2.51347423	-15.72948456	3.84089494	-14.94062233
crack	21.65235710	-16.58272171	21.86160851	-14.75062466
crack	13.01408195	-8.78830242	14.24884415	-11.62300587
crack	3.11822748	-19.56136322	5.48392725	-18.78120804
crack	14.58201981	21.93416595	14.80084991	20.41018295
crack	3.11725783	-13.60427475	3.78042293	-11.58602905
crack	16.12805367	-8.65456581	18.96288872	-10.05241394

crack	13.09817696	-19.80746269	14.45563889	-18.69943428
crack	15.68890667	-9.70480537	16.29728699	-8.24989510
crack	4.26867962	24.30119514	6.65634203	25.00000000
crack	22.93018723	11.43375874	24.46963120	11.60017681
crack	23.08048630	9.22052956	25.00000000	9.94467068
crack	10.89261818	19.47818756	11.59441376	17.77796555
crack	16.43954277	-8.80815792	17.89264870	-9.79711056
crack	20.83421326	-6.49287844	22.37382889	-7.04137754
crack	11.10759258	24.90816498	12.62437725	25.00000000
crack	20.12753677	13.40404606	20.94988251	14.92816257
crack	9.62214756	-6.17113161	10.96813297	-8.20474148
crack	8.96848583	-12.38696289	9.12110996	-14.69816971
crack	4.83486271	-18.99524689	5.52560520	-20.45862579
crack	10.06479073	-5.28264809	10.76986694	-3.56936741
crack	0.98547989	1.52199876	1.63732767	2.95697069
crack	18.86126137	-10.14210892	22.66012764	-6.78863764
crack	11.68686199	14.23234558	13.17820263	12.80018425
crack	2.94281960	2.98616838	4.85295010	5.74965143
crack	5.75955105	-8.63393974	6.92912197	-10.28203201
crack	0.00000000	15.64925671	2.16693044	18.46773720
crack	8.16140366	-7.40391111	9.58018303	-5.82723951
crack	15.87376785	-13.55260277	18.42908478	-14.76881599
crack	21.94045639	-15.78320503	22.80610275	-17.61113930
crack	0.00000000	18.53727150	0.39767218	18.70089531
crack	3.24844408	-0.23475695	4.37969303	-1.83025622
crack	22.89069176	10.63875294	24.65461922	10.95787716
crack	7.68183327	-6.35580540	8.31926155	-7.74887753
crack	24.36482048	-12.30830288	25.00000000	-13.80092525
crack	0.00000000	21.22981834	0.35834664	21.32938004
crack	7.46474552	11.07006741	9.47835064	11.45211315
crack	4.98844481	-0.33659849	6.50968122	-0.97248161
crack	22.45981216	15.08857632	24.18255234	15.60823345
crack	6.42302370	3.70433068	6.97928476	5.24539661
crack	0.37941647	-7.21988010	1.69865036	-9.81375599
crack	23.60102081	-6.85702038	25.00000000	-8.06042767
crack	3.94386148	-14.67062664	5.99474573	-11.93919277
crack	9.63987541	4.90989685	11.31360817	2.76104403
crack	6.69808197	-21.07380104	7.36826420	-19.30865288
crack	14.35425854	9.70806599	16.40373611	11.61930561
crack	22.18921661	-16.70098495	23.33203506	-14.50332451
crack	17.08326340	-9.51456356	17.56210709	-11.17196751
crack	21.38636589	-6.68959522	21.83109474	-4.77572155
crack	14.92946815	10.24448299	16.56033707	10.68647289
crack	22.27401733	-22.41225243	22.55601692	-25.00000000
crack	7.12265158	12.70363998	8.56477451	11.77343750
crack	13.45051861	-5.75030565	15.33320713	-1.92056167
crack	22.68775177	19.56634521	25.00000000	21.77651596
crack	8.45043659	-0.33581471	9.75589275	1.66353559

crack	15.54474449	8.71280479	17.23055458	12.34537315
crack	6.43912125	-6.20957422	8.83298588	-5.75890875
crack	14.55943298	20.19368172	15.70262909	21.21894264
crack	0.00000000	-14.57732964	0.44453353	-14.00316620
crack	15.71410275	5.13865662	17.48200607	5.43328190
crack	22.81870842	-19.39104843	23.22072411	-17.92021561
crack	0.00000000	15.03215504	1.36216784	15.97529793
crack	12.30187416	-8.19172096	12.44858932	-6.44366407
crack	7.70501947	4.85569715	8.51358891	6.37531805
crack	20.16601181	22.45648956	21.16417313	20.45857239
crack	15.36509037	-7.08234262	18.33750343	-4.95249033
crack	0.00000000	-20.96974373	1.55449522	-21.38439560
crack	23.75800514	-19.17401314	24.54505730	-16.23536491
crack	7.95774651	6.20686150	9.51508141	6.99044609
crack	14.79880714	-6.37304401	15.04513741	-4.55504036
crack	12.89953232	-22.98175240	15.83057499	-25.00000000
crack	11.85038280	-20.25206375	13.70038891	-18.52486038
crack	0.00000000	-23.69736290	0.19538730	-23.86976051
crack	10.06427860	11.41682053	10.11931133	12.96665001
crack	15.21838188	-21.42652512	17.43346596	-19.42034531
crack	6.48055077	9.91263008	6.74434090	8.05889511
crack	23.75418472	20.14069176	24.40475082	21.81969261
crack	17.80368996	24.26280594	20.13610649	24.24354935
crack	0.00000000	-19.83091354	0.99237019	-19.64970779
crack	7.37631941	-10.82333946	8.42910862	-9.64022446
crack	7.29822540	5.10207415	8.90244102	7.78932714
crack	24.86512947	20.33103943	25.00000000	16.84065628
crack	1.10374451	3.03253222	4.75708723	2.25902557
crack	4.74125528	2.75306273	5.04491282	5.89620256
crack	10.33257961	19.67900467	10.66335392	21.36953735
crack	10.38514519	-0.32156485	10.59136963	-1.81523895
crack	8.65345001	-21.68619919	10.20686913	-21.66198349
crack	16.98961639	1.14985681	17.13167191	2.80085731
crack	6.17370796	4.79891872	8.77472973	6.55124569
crack	22.58789825	2.95143795	25.00000000	5.95323515
crack	16.93865585	-7.75732136	17.93284607	-9.88307285
crack	19.93424988	9.64685822	20.26915359	11.70007706
crack	8.27127075	-7.45152378	8.95853806	-9.24430943
crack	10.20273590	8.06328678	12.22748947	8.13378811
crack	12.26814938	-18.35585594	13.45116329	-16.16300011
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crack	23.50373459	10.00225639	25.00000000	11.32582283
crack	0.00000000	-14.70355320	1.88668609	-13.83965588
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crack	6.92249537	-25.00000000	7.89918947	-23.14100266
crack	1.17698801	22.00587463	1.78359377	24.27204514
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crack	22.14286232	6.55204821	24.58079720	10.39351559
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crack	3.47726870	11.44722748	4.25093365	13.21129417
crack	22.73171043	9.13352871	25.00000000	9.69935322
crack	0.41893128	-8.49813557	1.09362900	-9.83994198
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crack	21.71002960	-14.77613640	22.16940689	-13.32550621
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crack	5.66856575	10.51994133	6.09442139	7.57500458
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crack	17.06722450	-18.78584862	18.04163933	-20.47405434
crack	18.80998993	18.18578148	20.57461548	17.62720299
crack	15.83158588	-7.21624374	17.29666710	-4.16262245
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crack	6.39312029	-22.63963127	7.10583639	-20.74081230
crack	9.70954323	-3.46886492	10.48159027	0.12771082
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crack	18.98417091	-17.64963913	20.19660378	-18.76373672
crack	16.03645515	4.20169783	17.78641319	5.69264078
crack	13.79821110	23.96229553	15.34472752	24.44374466
crack	15.97178936	-11.22537231	16.83602715	-9.40732384
crack	22.26379967	-20.14789391	23.51466942	-17.52462578
crack	1.39830744	10.50118828	3.59471273	11.13631630
crack	0.00000000	21.97295761	1.05291176	22.23675156
crack	0.00000000	-3.33022547	0.95827103	-2.94782209
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crack	12.21200752	11.85018253	13.76036644	11.91189098
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crack	12.70398712	17.11690521	15.61694145	17.45263672
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crack	2.45302391	19.80555344	2.36094904	22.85986328
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crack	6.28609419	-15.58376598	5.99586821	-17.79783821
crack	12.25573540	14.47628593	11.55809593	16.47777939
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crack	10.47300720	19.59084892	8.58759594	25.00000000
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crack	21.31153488	1.28776336	19.25066757	2.65368366
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crack	20.14860344	-0.81195396	17.64527321	-1.60390782

crack	14.70543098	-11.25340080	14.45215797	-9.63911057
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crack	21.11667252	-20.04751015	18.84592819	-19.79083061
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crack	0.10094112	-15.87729263	0.00000000	-15.85603714
crack	20.83917809	11.88682175	19.09181023	12.09513092
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crack	5.27781391	21.42793846	4.35853291	19.85344505
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crack	22.48223495	6.07868338	21.47759247	7.20752287
crack	21.47760391	7.20750952	20.15043640	8.69874477
crack	19.16843033	9.80214977	17.95996857	11.16000271
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crack	8.34291744	-25.00000000	7.72250080	-22.40081978
crack	16.38890648	1.58229256	15.55795670	0.20396930
crack	18.69090080	9.76851273	16.89460564	9.07454300

crack	9.98231792	-10.29049683	8.34669781	-9.73282623
crack	0.03063196	22.48553658	0.00000000	22.46932220
crack	11.05012894	16.94453621	8.62985611	17.17147255
crack	5.94330978	17.42337418	4.14626217	17.59187317
crack	3.71304059	17.63249588	0.00000000	17.98064613
crack	2.38106394	-8.00565338	1.12275028	-5.50638628
crack	21.86374664	9.78730679	20.48279953	11.03174877
crack	2.90785122	18.79924202	1.30403471	18.74040031
crack	22.40027809	9.96683407	19.79703331	9.09581661
crack	4.52092218	8.82963085	4.40405226	11.04380131
crack	9.86925602	16.49931526	8.66571903	19.11272621
crack	21.36430168	4.35670376	18.71539116	3.15028143
crack	19.37017250	3.44849539	17.80736351	2.73672867
crack	16.59032059	2.18243790	14.29015732	1.13484967
crack	14.46283627	1.21349478	12.84102154	0.47485417
crack	8.71132565	13.26661491	8.65098476	16.15925980
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crack	4.73832655	-4.64667988	3.74811888	-5.97351933
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crack	10.11264896	2.24165487	8.46397114	2.82876158
crack	24.44924355	-0.35662043	23.32584190	-3.07569265
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crack	24.88017845	23.48366928	23.30326271	23.34361267
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crack	4.94759655	7.53500938	3.74234366	6.35710621
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crack	12.30936146	-0.40150785	11.37805843	2.60990739
crack	11.93759346	20.35670471	11.33958435	18.01635742
crack	11.33959007	18.01637650	10.91592789	16.35834885
crack	10.91593075	16.35836220	10.39540386	14.32124329
crack	19.67491531	23.89729881	17.85494995	24.12696648
crack	17.66017914	24.15154457	16.02919006	24.35736656

crack	16.17328644	24.33918190	14.00800133	24.61242867
crack	14.17406750	24.59147072	11.22719479	24.96334648
crack	22.02808762	-21.09243965	20.37891388	-17.25792503
crack	20.14410210	-16.71195984	18.96134377	-13.96191025
crack	18.96135521	-13.96193886	17.95751762	-11.62790489
crack	13.69370747	10.39598656	13.52466297	8.67482758
crack	13.52950382	8.72411060	13.32441425	6.63593388
crack	12.49546242	-15.83868504	11.21004677	-18.19531059
crack	20.14937973	9.06537247	19.32001495	7.58931875
crack	24.27422333	-0.41747004	24.04322815	2.10086942
crack	8.01194191	-17.55368614	6.98671532	-14.74501705
crack	17.27013969	-9.59561539	14.96440029	-10.38686180
crack	15.03086281	-10.36405468	13.42414284	-10.91542339
crack	8.41695023	-16.24095917	7.88002205	-14.65376949
crack	7.95760202	-14.88310242	7.08308172	-12.29797363
crack	20.82331085	-18.72339249	20.24967194	-15.95881939
crack	5.31754303	-5.56747532	3.31286693	-5.91096687
crack	3.28143096	-5.91635323	1.48419166	-6.22430134
crack	1.50336218	-6.22101641	0.00000000	-6.47861099
crack	16.98289680	11.34106827	13.20986843	5.49631119
crack	5.00677919	2.78208184	4.34719706	1.40044379
crack	12.40937805	-9.15073586	12.00939560	-10.94833946
crack	10.72055149	-16.81097603	10.37178326	-15.06554031
crack	0.95414209	-3.12767386	0.00000000	-3.20665789
crack	0.76849943	-18.53943062	0.55165774	-16.69625664
crack	24.44120598	-1.67093492	23.31126213	-3.09404922
crack	23.27222824	-3.14320993	21.90034866	-4.87103224
crack	17.51913071	24.34445572	16.23417282	22.21899033
crack	20.24665070	4.80357933	19.57548904	6.43307686
crack	20.12531662	5.09816074	19.16889572	7.42023373
crack	11.50382233	3.13716888	11.01916504	1.10511875
crack	4.64980221	-2.88581777	2.14044428	-7.44577694
crack	7.74613953	11.22878551	7.00785828	12.97520351
crack	7.00787544	12.97516155	4.24496174	19.51088142
crack	21.87442017	-19.32330513	20.77777100	-17.66827202
crack	20.21215820	-16.81466293	19.14700699	-15.20716763
crack	20.14412308	-16.71198654	16.67138672	-11.47103405
crack	5.19541836	16.19501305	3.76291275	16.64268303
crack	3.15793943	16.83174324	1.37097359	17.39018822
crack	0.48376524	17.66744995	0.00000000	17.81863213
crack	6.80496979	18.79753494	5.12140751	15.98250961
crack	6.80496931	18.79753494	4.19207621	14.42860794
crack	24.08193398	1.67902255	23.15921974	-3.81619191
crack	22.91341400	-5.28008986	22.20278549	-9.51224327
crack	25.00000000	-16.56772232	24.61707306	-14.57705116
crack	5.39190578	11.21462440	4.41800022	13.76951408
crack	4.47132015	13.62963772	3.92412663	15.06511402
crack	8.80582237	-0.88515371	7.31421232	-2.23245502

```
crack   7.36758089  -2.18424988   5.85086012  -3.55423260
crack  16.08720016  15.25041294  15.61827660  13.33623028
crack  17.34222794   1.03544033  16.16809845  -0.05129990
crack   5.84289265 -17.72801018   1.70839524 -19.16531944
crack   1.27995324 -19.31426048   0.00000000 -19.75922012
crack  14.76442814 -12.21819305  13.38824177 -13.93369675
crack  13.67046356 -13.58188820  12.27613068 -15.32001114
crack  12.74845123 -14.73123550  10.32815933 -17.74827957
crack  11.26797962 -12.48095322   9.79878139 -13.90332603
crack  12.26833916   4.82618284  11.27820396   6.00429201
crack  14.65059376 -18.03613853  13.80185795 -16.62791252
crack  13.91529560 -16.81612587  13.12439823 -15.50386524
crack  12.66043091 -14.73404884  11.70936966 -13.15604210
crack  11.47875977 -12.77341366   9.94610405 -10.23042202
crack  10.07838345 -10.44990063   8.67709446  -8.12487316
crack   5.45471144 -25.00000000   5.27947140 -23.35884666
crack   5.27947378 -23.35886955   5.02541494 -20.97955894
crack  24.64583397 -11.98484707  23.58230782 -13.20906353
crack  14.48088074  -7.53507042  11.55371475  -7.42738533
crack   6.24336720  -8.02225208   4.80148792  -9.84525776
crack  20.38620758   6.98326492  20.13312149   9.20828056
crack   3.64423418  24.39149094   1.12252748  25.00000000
crack  12.50012112  14.66392708  11.08220005  17.71795464
crack  11.85360241  16.05644798  11.08644390  17.70881462

*
save blocks.sav
res blocks.sav
*
* delete very small blocks
*
del area=5.0e-4
jdel
*
round 0.01
gen 0 25 -25 -20 edge 1.5
gen 0 25 -15 0 edge 1.5
gen 0 25 5 15 edge 1.5
gen 0 25 15 20 edge 1.5
gen 0 25 20 25 edge 1.5
gen 0 20 0 5 edge 1.5
gen 0 20 -20 -15 edge 1.5
gen 20 25 -17 -15 edge 1.5
gen 22 25 -20 -15 edge 1.5
gen 20 25 -20 -18.5 edge 1.5
gen 20 21 -20 -15 edge 1.5
gen bl 407069 edge 1.0
gen bl 1043685 edge 1.0
```

```
del bl 1044884
del bl 194399
gen 20 25 0 5 edge 1.5
*
save zones.sav
*
res zones.sav
pr max
*
* apply insitu stresses and pore pressures for initial mechanical state
*
grav 0.0 -9.81
fluid d=0.001
insitu stress -13.096 0.0 -13.096 ygrad 0.0262 0.0 0.0262 nodisp ywtable 500
*
* apply mechanical and hydrologic boundary conditions
*
bound -10.1,25.1 24.99,25.1  stress 0.0 0.0 -12.441  pp = 4.66 ;top
bound  24.99,25.1 -25.1,25.1 xvel=0.0  imperm ; right-hand-side
bound -10.1 25.1,-25.1 -24.99 yvel=0.0 imperm ; bottom
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
*
damp auto
set delc off
*
* define mechanical and thermal properties for matrix and joints
* Note: vertical and horizontal joints were artificially inserted, and
* thus their strength was set high and permeability either set to zero
* or set to equivalent permeability
*
* define material properties
prop mat=1 k=3.704e+04 g=2.439e+04 d=0.00267
prop mat=1 cond=3.0 thexp=9.0e-06 spec=9.0e+08
prop jmat=1 jkn=1.0e+06 jks=1.0e+06 jc=10000.0 jfric=80.0 jdil=0.0 &
  jtens=10000.0 jperm=0.0 ares=3.0e-6 azero=3.0e-6
*
* ****************************************************************
*                                                  *
*                      KEY                           *
*                                                  *
*  JMAT    Description                                 *
*  ---    ------------------------------------------- *
*    1    Artificial joints (no permeability)          *
*  2,3,4,5  "Real" angled joints                        *
* 6,7,8,9,10  "    "     "                            *
*                                                  *
* ****************************************************************
*
```

```
change mat=1 jmat=1
change angle    1     20.0   jmat=2
change angle  20.0    40.0   jmat=3
change angle  40.0    60.0   jmat=4
change angle  60.0    80.0   jmat=5
change angle  80.0    89.999 jmat=6
change angle  90.001  100.0  jmat=6
change angle 100.0   120.0   jmat=7
change angle 120.0   140.0   jmat=8
change angle 140.0   160.0   jmat=9
change angle 160.0   179.999 jmat=10
*
* Explicit real joints
prop jmat=2 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.2602e-6
prop jmat=3 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.5267e-6
prop jmat=4 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.3788e-6
prop jmat=5 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.1973e-6
prop jmat=6 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.4455e-6
prop jmat=7 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.200e-6
prop jmat=8 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.6512e-6
prop jmat=9 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.0844e-6
prop jmat=10 jkn=1.0e+05 jks=1.0e+04 jc=0.1 jfric=30.0 jdil=0.0 &
 jtens=0.0 jperm=8.333e7 ares=3.0e-6 azero=3.7785e-6
*
set jmatdf 2
*
* cycle mechanically to consolidate before applying fluid pressure
*
his unbal damp
his sxx 0.0,5.1 syy 0.0,5.1 xdis 0.0,5.1 ydis 0.0,5.1 pp 0.0,2.5
cycle 500
pr max
save b3_d3c.sav

rest b3_d3c.sav
*
* reset gridpoint and joint shear displacements to zero before
* setting pore pressures to zero and excavating tunnel to define
* initial state
*
```

```
reset hist,disp jdis
*
*  define monitoring locations
*
hist unbal
hist ncyc=10  xdis 0.0,0.0 ydis 0.0,0.0 xdis 0.0,5.0 ydis 0.0,5.0  &
 xdis 2.5,2.5 ydis 2.5,2.5
hist  xdis 7.5,7.5 ydis 7.5,7.5 xdis 7.5,-7.5 ydis 7.5,-7.5
hist sxx 0.0,0.0 syy 0.0,0.0 sxx 0.0,5.0 syy 0.0,5.0 sxx 2.5,2.5 syy 2.5,2.5
hist  sxx 7.5,7.5 syy 7.5,7.5 sxx 7.5,-7.5 syy 7.5,-7.5
hist pp 3.0,2.5 pp 7.5,2.5 pp 7.5,7.5 pp 2.5,-7.5 pp 20.0,-10.0
*
* set pore pressure in tunnel to zero to simulate 3-dimensional exc. effect
*
pfix  -2.5,2.5 0.0,2.5 press 0
pfix ann 0 2.5 0 2.5 press 0

*
* define fluid properties
*
fluid dens=0.001 bulk=2000.0
set ptol 0.005
set sflow on
set capratio=20
*
* cycle until steady state flow is reached before excavating tunnel
*
cycle 1500
pr max
save b3_d32a.sav
cycle 1500
pr max
save b3_d32b.sav
cycle 2000
pr max
save b3_d32c.sav
*

rest b3_d32c.sav
*
* excavate tunnel
*
del 0.0,2.5 0.0,2.5 area=10
del ann 0 2.5 0 2.5
*
reset damp
*
* fix boundary pressure within tunnel to zero
```

```
*
bound cor 101 504 pp 0 ;check if corner addresses are correct
* gradually reduce mechanical stress
bound cor 101 504 stress -13.096 0.0 -13.096 ygrad 0.0262 0.0 0.0262
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
pfix -1 26 22 25 p = 4.67 ;top -- this is necessary because BOUND PP is lost
* bound -1 26 24 26 pp 4.66
cy 1
bound cor 101 504 stress 13.096 0.0 13.096 ygrad -0.0262 0.0 -0.0262 hist lin
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
cy 15000
pr max
bound cor 101 504 xfree yfree
bound -.01 .01 -100 100 xvel=0.0 imperm ; left-hand-side
save b3_d32d.sav
*
res b3_d32d.sav
pr max
pfree dom 130579
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
cycle 2000
pr max
save b3_d33.sav
*
rest b3_d33.sav
pr max
cycle time=0.2
pr max
cycle time=0.2
pr max
save b3_d33a.sav
*
rest b3_d33a.sav
*
set ovtol 0.075
*
* reset time for thermal calculations (i.e. starting at t*)
*
reset time
```

```
*
* define thermal boundary conditions and initial temperature conditions
* Note: boundaries not specified are assumed adiabatic within the code
*
this ntcyc=50 tem 0.0,0.0  tem 0.0,5.0 tem 2.5,2.5 tem 7.5,7.5 tem 7.5,-7.5
this tem 0.0,-5.0
*
initem 27.0 -1 25.1 -25.1 25.1
tfix 27.0 -1 25.1 24.9 25.1
thapp -2.6,2.6  -0.1,5.1 conv 7.0 27.0
thapp -.01 0.01 -7.51 -2.49 flux 1.175e2  -6.342e-10
*
* run thermal time to 1 month
*
run age=1e5 delt=100.0 temp=10000 step=10000000 impl tol 0.05
reset damp
cycle 1000
pr max
run age=2e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=3e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=5e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=10e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=12.5e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=15e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=17.5e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=20e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
```

```
cycle 1000
pr max
run age=22.5e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=25e5 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1000
pr max
run age=2.628e6 delt=100.0 temp=10000 step10000000 impl
reset damp
cycle 7500
pr max
save bmt3_t1m.sav
*
* run thermal time to 2 month
*
run age=3.128e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=3.628e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=4.128e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=4.628e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=5.256e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 7500
pr max
save bmt3_t2m.sav
*
* run thermal time to 4 month
*
run age=6.256e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=7.256e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
```

```
cycle 1500
pr max
run age=8.256e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=9.256e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=10.512e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 7500
pr max
save bmt3_t4m.sav
*
* run thermal time to 6 month
*
run age=11.512e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=12.512e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=13.512e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=14.512e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=15.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 7500
pr max
save bmt3_t6m.sav
*
* run thermal time to 1 year
*
run age=16.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=17.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
```

```
cycle 1500
pr max
run age=18.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=19.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=20.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=21.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=22.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=23.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=24.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=25.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=26.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=27.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=28.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=29.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
```

```
cycle 1500
pr max
run age=30.768e6 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 1500
pr max
run age=3.1536e7 delt=100.0 temp=10000 step=10000000 impl
reset damp
cycle 5000
pr max
save bmt3_t1y.sav
*
* run thermal time to 2 years
*
set delc on
run age=6.3072e7 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t3y.sav
*
* run thermal time to 4 years
*
run age=1.26144e8 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t5y.sav
*
* run thermal time to 10 years
*
run age=3.1536e8 temp=10000 step=10000000 impl delt=1000
```

```
reset damp
cycle 7500
pr max
save bmt3_t10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t20y.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t30y.sav
*
* run thermal time to 50 years
*
run age=1.5768e9 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t50y.sav
*
* run thermal time to 75 years
*
run age=2.3652e9 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t75y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 temp=10000 step=10000000 impl delt=1000
reset damp
cycle 7500
pr max
save bmt3_t100y.sav
ret
*
```

APPENDIX B

TABULAR OUTPUT FROM UDEC FOR THE BMT3 PROBLEM

Table B-1. Stress components at monitoring points (A-H)

Time (yr)	Stress Components	Stress at Monitoring Points (MPa)							
		A	B	C	D	E	F	G	H
$t = 0$ (Case A)	σ_{xx}	-13.10	N/A	-12.97	-13.03	N/A	N/A	-12.90	-13.29
	σ_{zz}	-13.10	N/A	-12.97	-13.03	N/A	N/A	-12.90	-13.29
$t = 0$ (Case B)	σ_{xx}	-13.04	N/A	-12.78	-12.99	N/A	N/A	-12.76	-13.13
	σ_{zz}	-12.88	N/A	-12.73	-12.79	N/A	N/A	-12.92	-13.14
$t = 1/12$ (Case A)	σ_{xx}	*	N/A	*	*	N/A	N/A	*	*
	σ_{zz}	*	N/A	*	*	N/A	N/A	*	*
$t = t^*$ (Case A)	σ_{xx}	-0.01	N/A	-16.50	0.00	N/A	N/A	-13.23	-13.46
	σ_{zz}	-0.01	N/A	-3.39	-0.34	N/A	N/A	-15.26	-13.16
$t = t^*$ (Case B)	σ_{xx}	0.02	N/A	-19.91	0.00	N/A	N/A	-11.47	-13.21
	σ_{zz}	-0.01	N/A	-4.79	-0.01	N/A	N/A	-13.78	-13.17
$t = t^* + 1$ (Case A)	σ_{xx}	-0.48	N/A	-11.54	0.08	N/A	N/A	-12.01	-17.63
	σ_{zz}	-0.01	N/A	-1.72	0.01	N/A	N/A	-16.01	-12.09
$t = t^* + 1$ (Case B)	σ_{xx}	-0.51	N/A	-15.66	0.07	N/A	N/A	-10.83	-16.42
	σ_{zz}	-0.01	N/A	-3.32	0.18	N/A	N/A	-15.47	-12.86
$t = t_{max}$ (Case A)	σ_{xx}	-0.54	N/A	-12.23	0.11	N/A	N/A	-12.99	-21.32
	σ_{zz}	-0.01	N/A	-1.69	0.35	N/A	N/A	-16.08	-12.28
$t = t^* + 30$ (Case A)	σ_{xx}	-0.41	N/A	-17.22	0.12	N/A	N/A	-16.01	-24.57
	σ_{zz}	-.01	N/A	-3.39	0.43	N/A	N/A	-15.16	-11.66
$t = t^* + 100$ (Case A)	σ_{xx}	-0.11	N/A	-15.62	0.03	N/A	N/A	-14.10	-16.34
	σ_{zz}	0.0	N/A	-3.05	0.12	N/A	N/A	-15.35	-12.65

*Results not obtainable due to use of steady-state flow logic
N/A = Not Applicable (Symmetry Assumed)
Note 1: Compressive stresses negative
Note 2: t_{max} calculated to be 4 yr.

Table B-2. Displacement components at monitoring points (A-H)

Time (yr)	Displacement Components	Displacement at Monitoring Points (mm)							
		A	B	C	D	E	F	G	H
$t = 0$	U_x	0.0	N/A	0.0	0.0	N/A	N/A	0.0	0.0
	U_z	0.0	N/A	0.0	0.0	N/A	N/A	0.0	0.0
$t = 1/12$	U_x	*	N/A	*	*	N/A	N/A	*	*
	U_z	*	N/A	*	*	N/A	N/A	*	*
$t = t^*$ (Case A)	U_x	0.0	N/A	0.0	-11.94	N/A	N/A	-0.59	-0.56
	U_z	3.06	N/A	-4.47	-11.68	N/A	N/A	-1.86	0.13
$t = t^*$ (Case B)	U_x	0.0	N/A	0.0	-7.24	N/A	N/A	-0.61	-.57
	U_z	2.91	N/A	-4.45	-6.95	N/A	N/A	-2.14	-0.09
$t = t^* + 1$ (Case A)	U_x	0.0	N/A	0.0	-11.35	N/A	N/A	-0.11	1.81
	U_z	9.03	N/A	-0.87	-7.95	N/A	N/A	2.16	1.66
$t = t^* + 1$ (Case B)	U_x	0.0	N/A	0.0	-6.05	N/A	N/A	-0.09	1.38
	U_z	9.37	N/A	-0.99	-1.62	N/A	N/A	1.52	1.21
$t = t_{max}$ (Case A)	U_x	0.0	N/A	0.0	-18.57	N/A	N/A	0.0	2.30
	U_z	14.52	N/A	5.13	-7.57	N/A	N/A	8.25	5.82
$t = t^* + 30$ (Case A)	U_x	0.0	N/A	0.0	-31.96	N/A	N/A	0.0	1.23
	U_z	22.16	N/A	14.40	-10.18	N/A	N/A	17.28	13.03
$t = t^* + 100$ (Case A)	U_x	0.0	N/A	0.0	-32.92	N/A	N/A	-0.60	-0.36
	U_z	18.70	N/A	0.97	-22.77	N/A	N/A	3.75	3.92

*Results not obtainable due to use of steady-state flow logic
N/A = Not Applicable (Symmetry Assumed)
Note: t_{max} calculated to be 4 yr.

Table B-3. Water flux (m^3/s) across the monitoring segments (ABCD-HE)

Time (yr)	Monitoring Segments				
	CDA	EF	FG	GH	HE
$t = 0$	0.0	N/A	0.0	0.0	0.0
$t = 1/12$	*	N/A	*	*	*
$t = t^*$ (Case A)	2.124×10^{-8}	N/A	--+	--	--
$t = t^*$ (Case B)	3.293×10^{-8}	N/A	--	--	--
$t = t^* + 1$ (Case A)	1.946×10^{-8}	N/A	--	--	--
$t = t^* + 1$ (Case B)	2.527×10^{-8}	N/A	--	--	--
$t = t_{max}$ (Case A)	8.425×10^{-9}	N/A	--	--	--
$t = t^* + 30$ (Case A)	1.764×10^{-8}	N/A	--	--	--
$t = t^* + 100$ (Case A)	1.808×10^{-8}	N/A	--	--	--

*Results not obtainable at this time due to use of steady-state flow option

--+ Indicates results were not obtainable with UDEC

N/A = Not Applicable (Symmetry Assumed)

Note 1: In the above columns, only the flux across the segments on right half of the model has been provided for this symmetric analyses.

Note 2: t_{max} calculated to be 4 yr.

Table B-4. Temperatures (°C) at monitoring points (A-H)

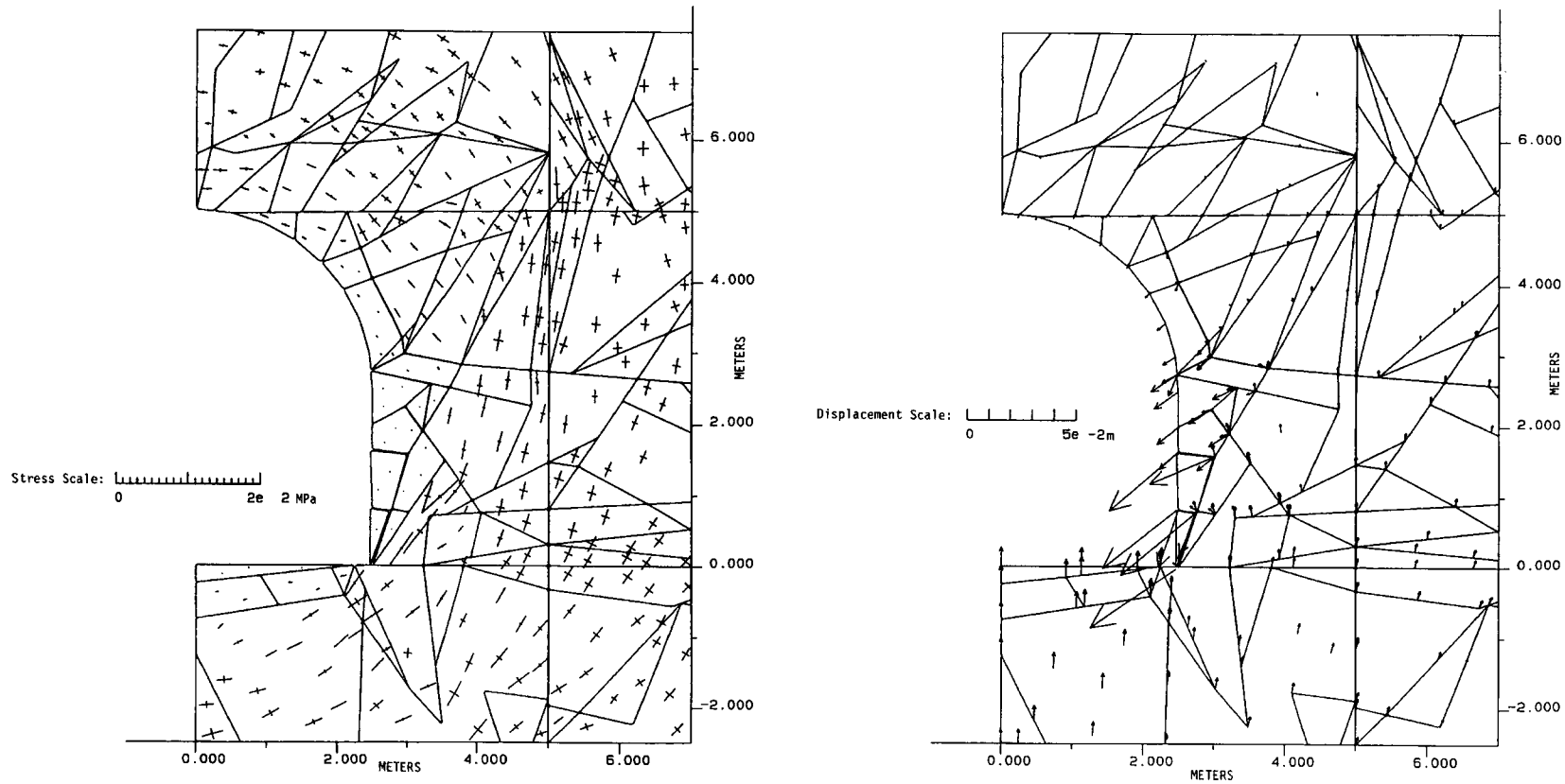
Time (yr)	Monitoring Points							
	A	B	C	D	E	F	G	H
$t = t^*$	0	N/A	0	0	N/A	N/A	0	0
$t = t^* + 1$	36.48	N/A	27.05	28.23	N/A	N/A	28.27	48.78
$t = t_{max}$	37.70	N/A	27.26	29.11	N/A	N/A	32.80	68.02
$t = t^* + 30$	35.20	N/A	27.56	29.51	N/A	N/A	39.35	78.29
$t = t^* + 100$	29.13	N/A	27.16	27.69	N/A	N/A	30.59	41.24

N/A Not Applicable (Symmetry Assumed)

Note: t_{max} calculated to be 4 yr.

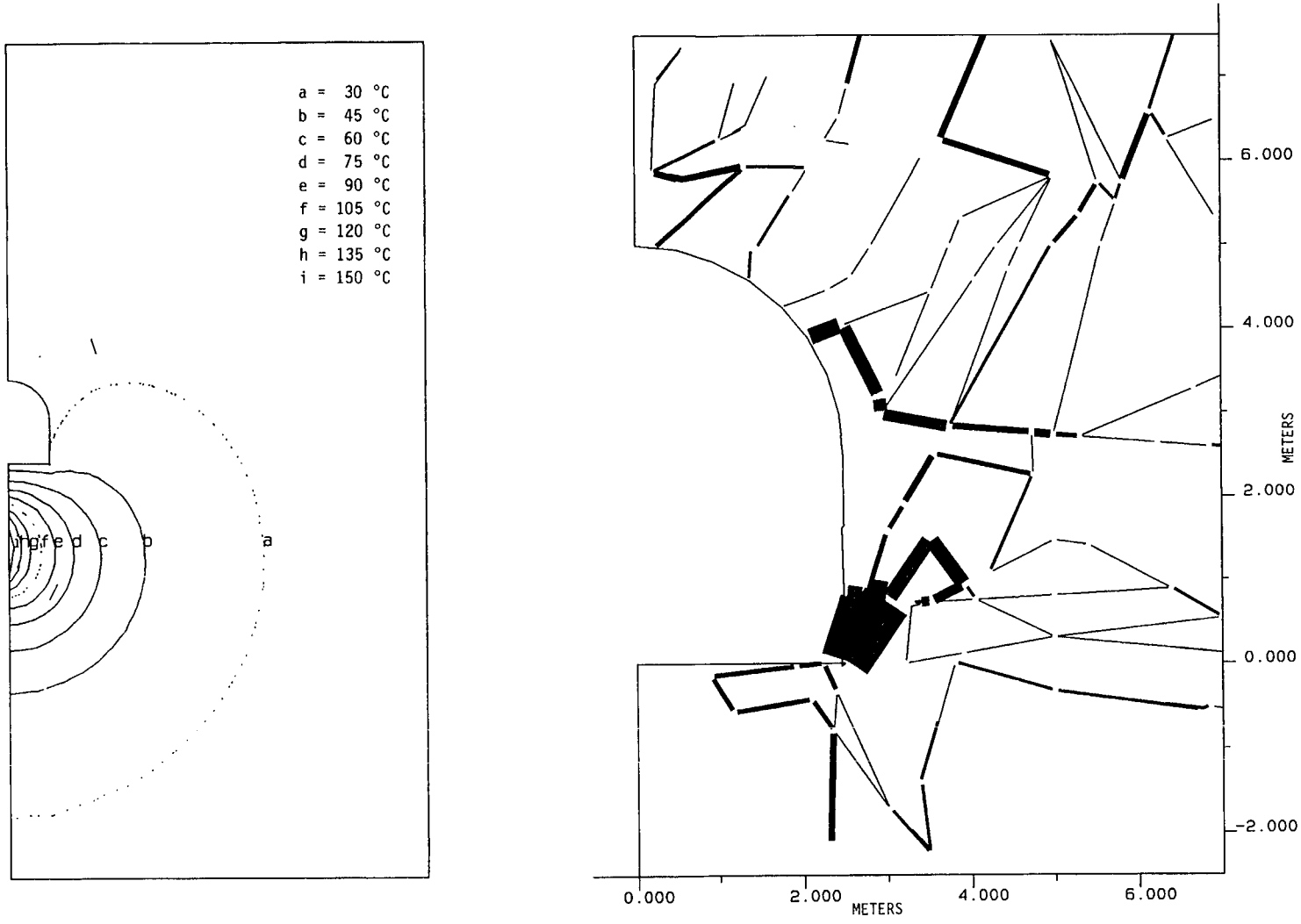
APPENDIX C

GRAPHICAL OUTPUT FROM UDEC FOR THE BMT3 PROBLEM



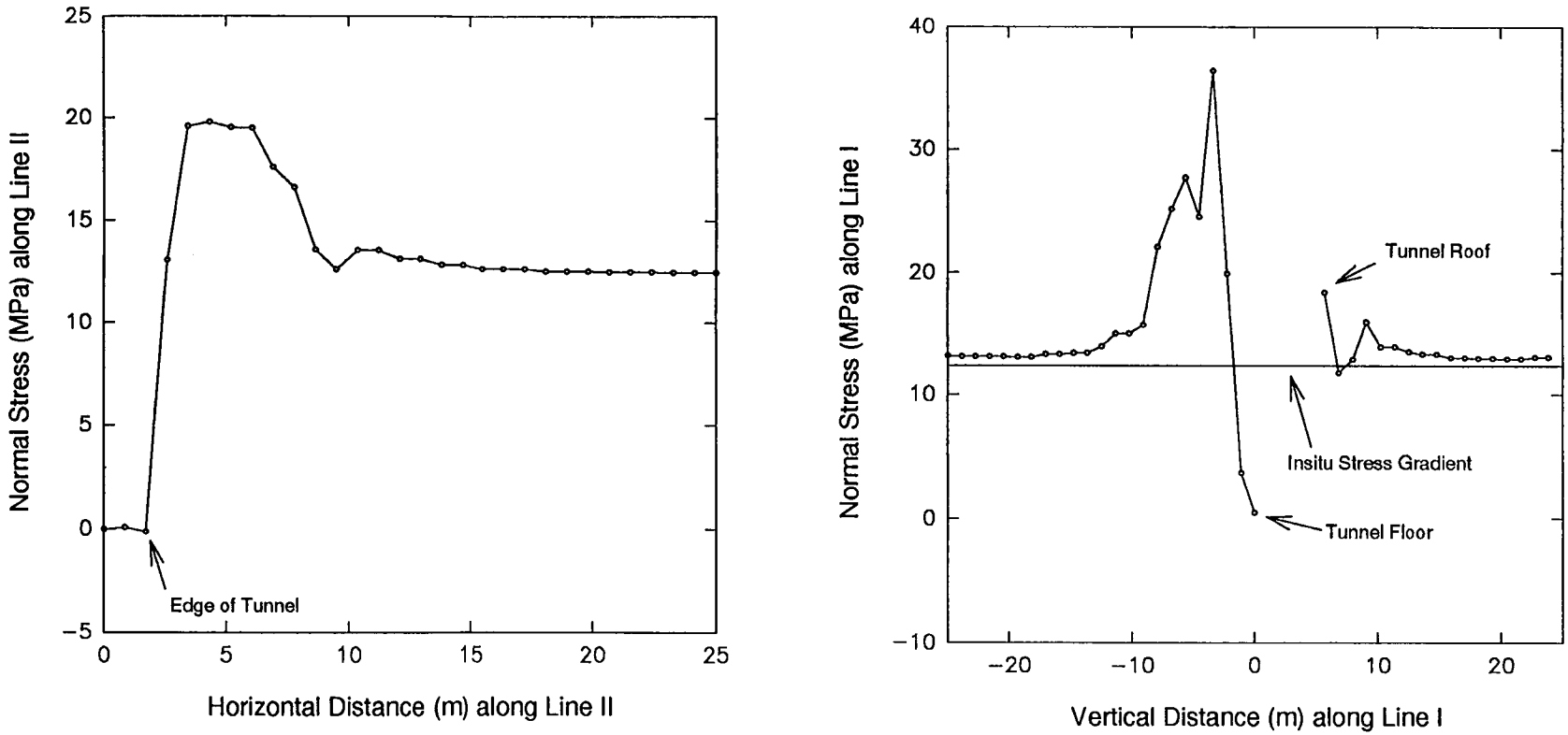
(a) (b)

Figure C-1. UDEC results for Case A after 1 yr of heating ($t = t^* + 1$ yr) (a) principal stress vectors [maximum principal stress (compression) = 77.57 MPa; minimum principal stress (tension) = 7.83 MPa], and (b) displacement vectors (maximum displacement = 4.905×10^{-2} m)



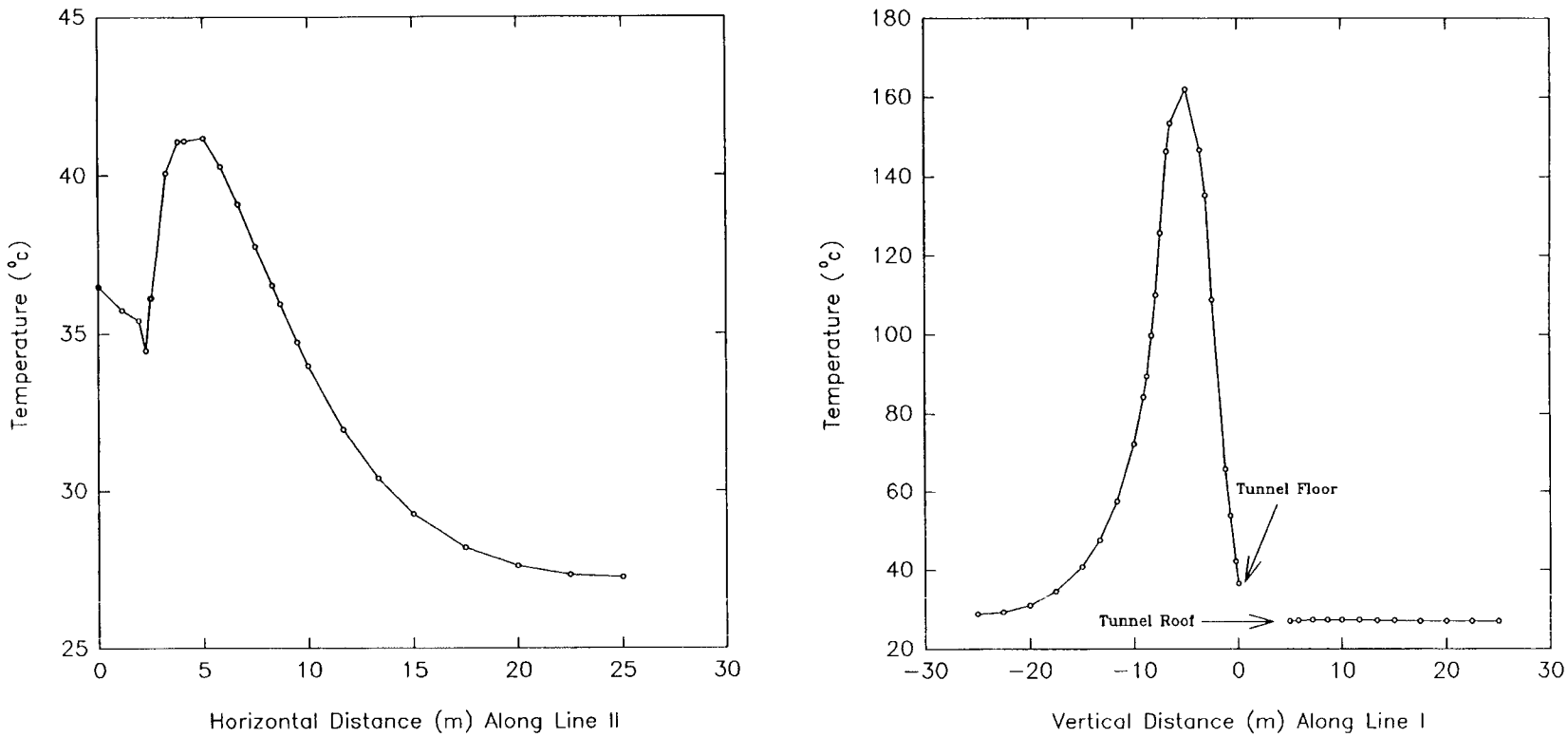
(a) (b)

Figure C-2. UDEC results for Case A after 1 yr of heating ($t = t^* + 1$ yr) (a) temperature contours (°C), and (b) fracture flowrates (tunnel inflow = 1.946×10^{-8} m^3/s)



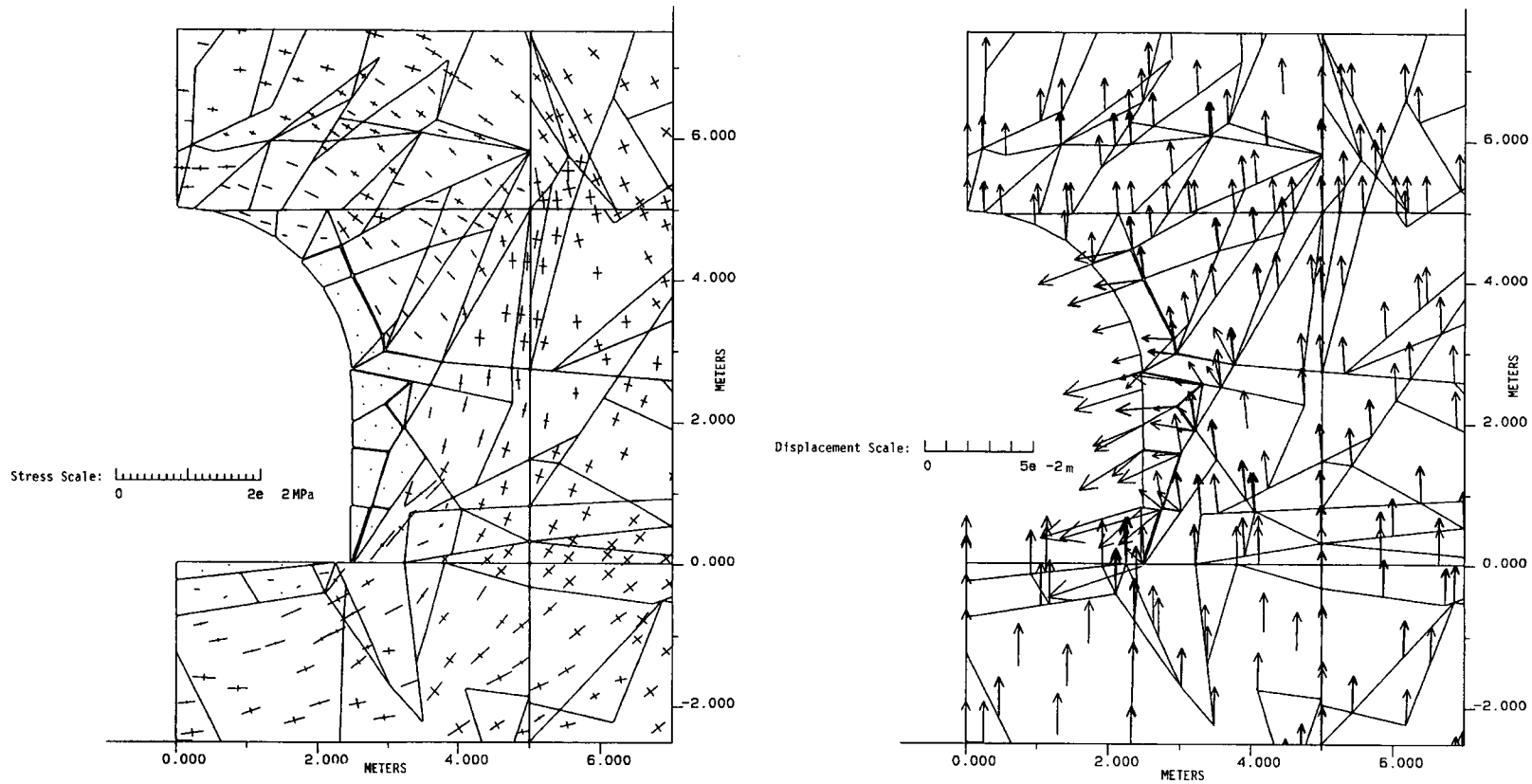
(a) (b)

Figure C-3. UDEC results for Case A after 1 yr of heating ($t = t^* + 1$ yr) (a) normal stress (σ_{yy}) along line II, and (b) normal stress (σ_{xx}) along line I



(a) (b)

Figure C-4. UDEC results for Case A after 1 yr of heating ($t = t^* + 1$ yr) (a) temperature (°C) along line II, and (b) temperature (°C) along line I



(a) (b)

Figure C-5. UDEC results for Case A after 30 yr of heating ($t = t^* + 30$ yr) (a) principal stress vectors [maximum principal stress (compression) = 64.58 MPa, minimum principal stress (tension) = 6.82 MPa], and (b) displacement vectors (maximum displacement = 4.926×10^{-2} m)

a = 30 °C
b = 40 °C
c = 50 °C
d = 60 °C
e = 70 °C
f = 80 °C
g = 90 °C
h = 100 °C
i = 110 °C
j = 120 °C
k = 130 °C

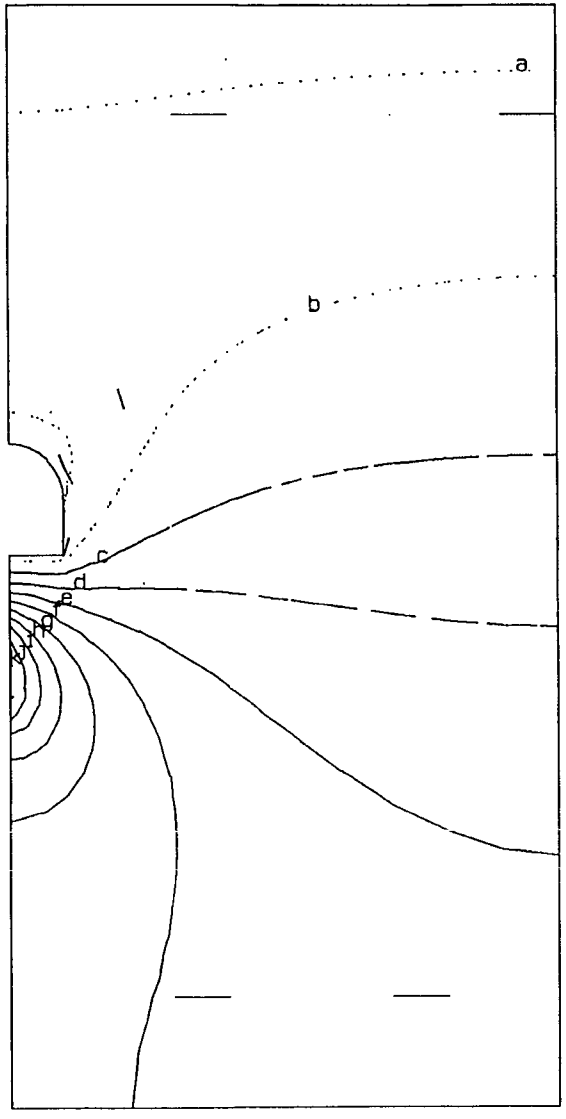
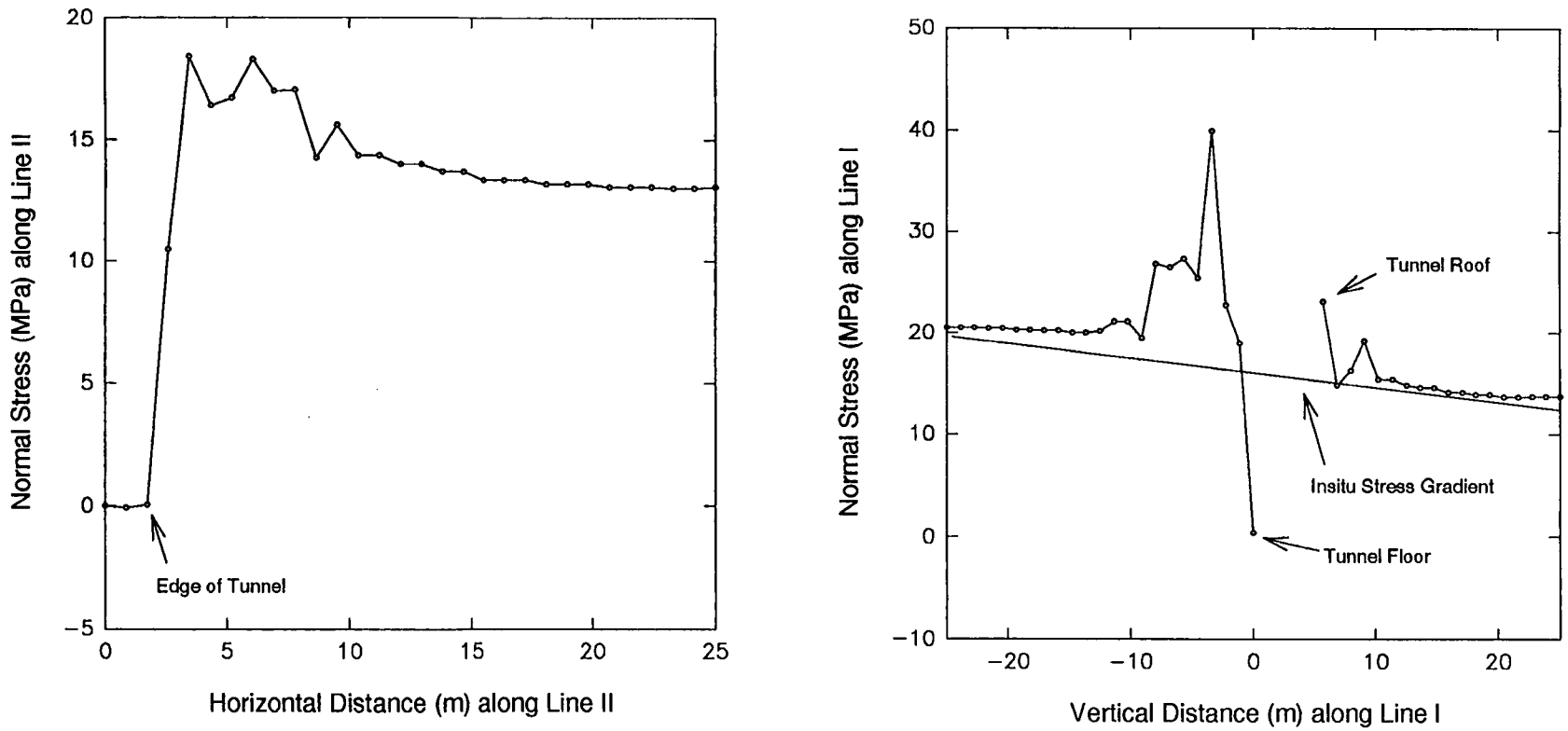
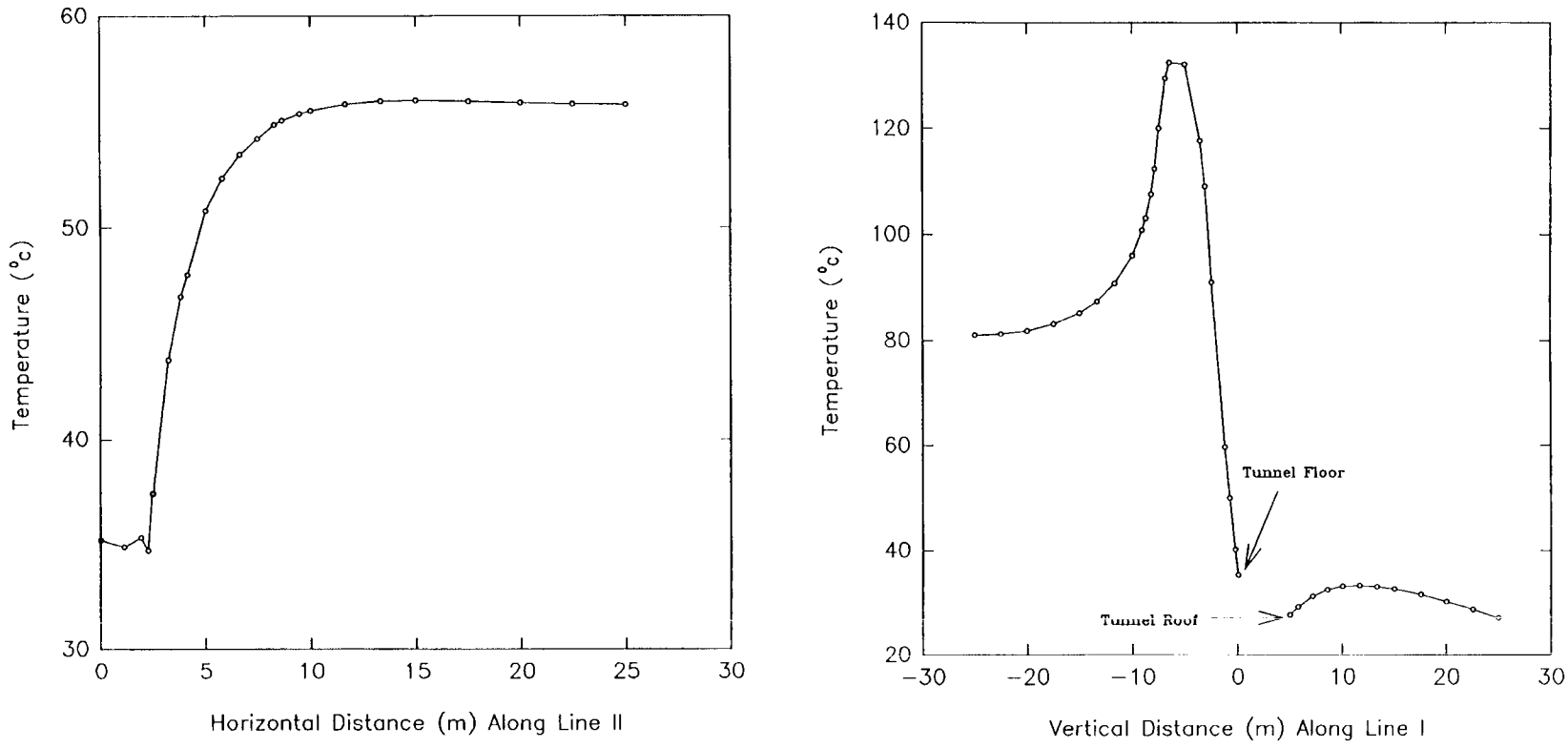


Figure C-6. UDEC results for Case A after 30 yr of heating ($t = t^* + 30$ yr) showing temperature contours (°C)



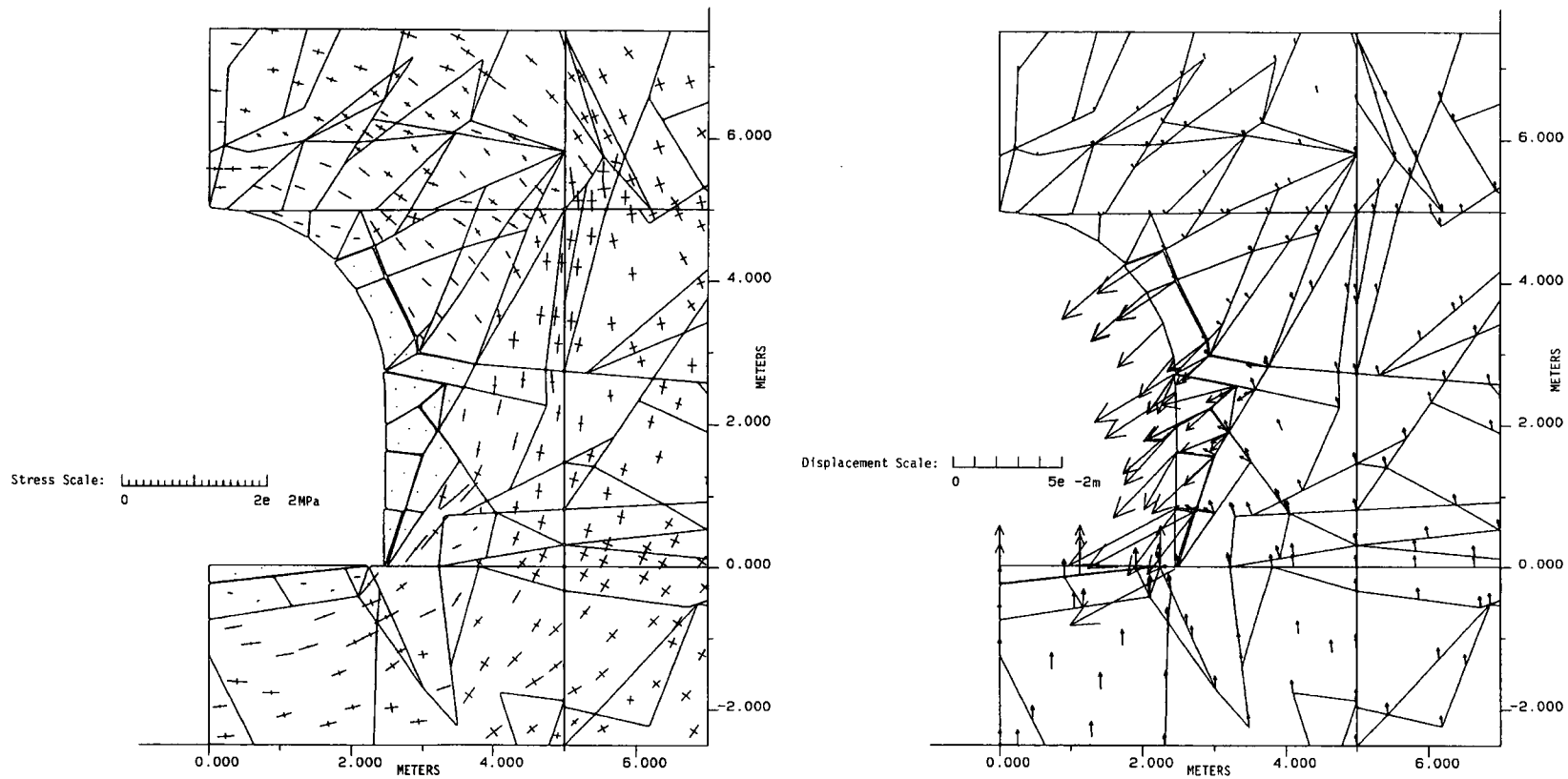
(a) (b)

Figure C-7. UDEC results for Case A after 30 yr of heating ($t = t^* + 30$ yr) (a) normal stress (σ_{yy}) along line II, and (b) normal stress (σ_{xx}) along line I



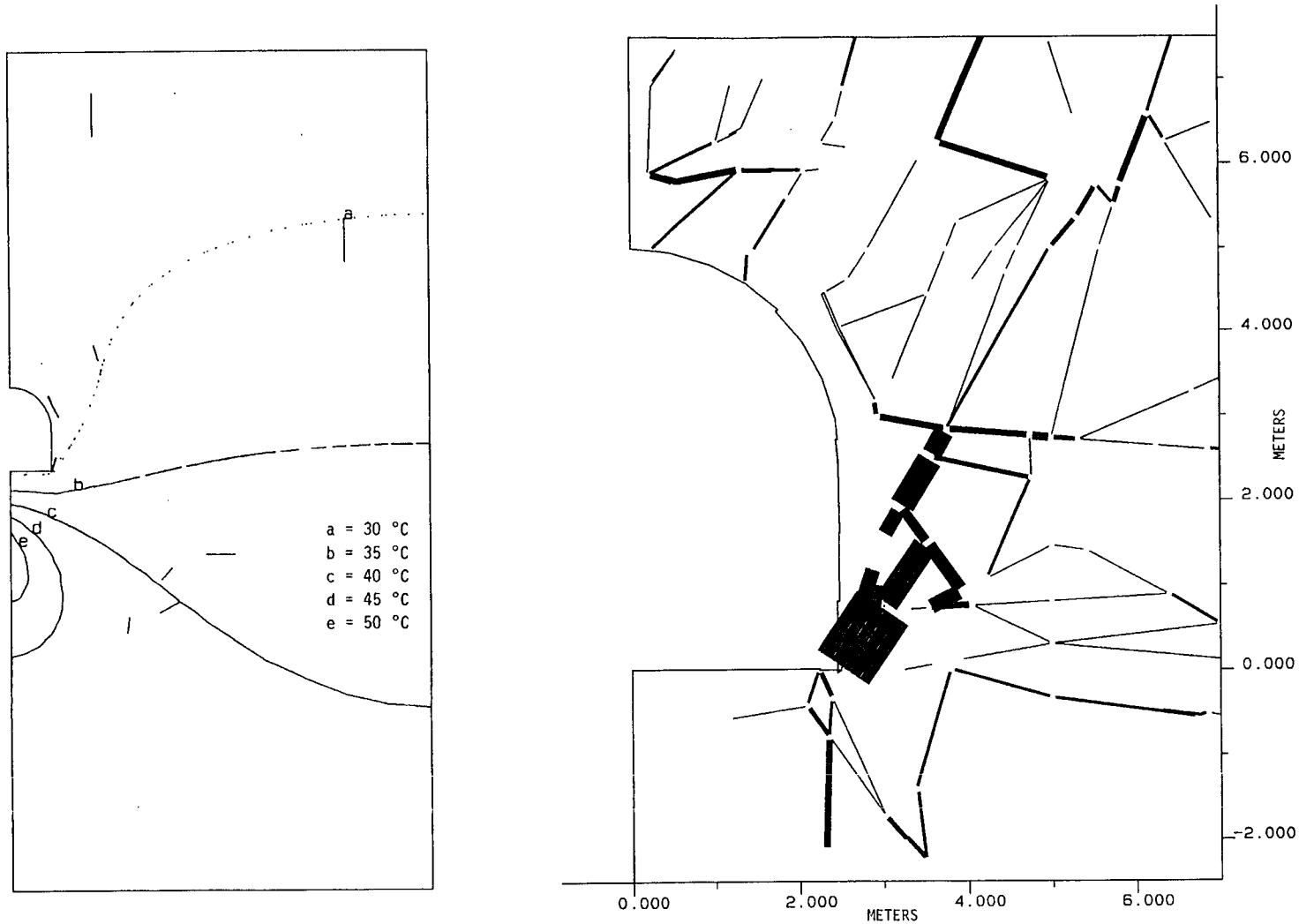
(a) (b)

Figure C-8. UDEC results for Case A after 30 yr of heating ($t = t^* + 30$ yr) (a) temperature (°C) along line II, and (b) temperature (°C) along line I



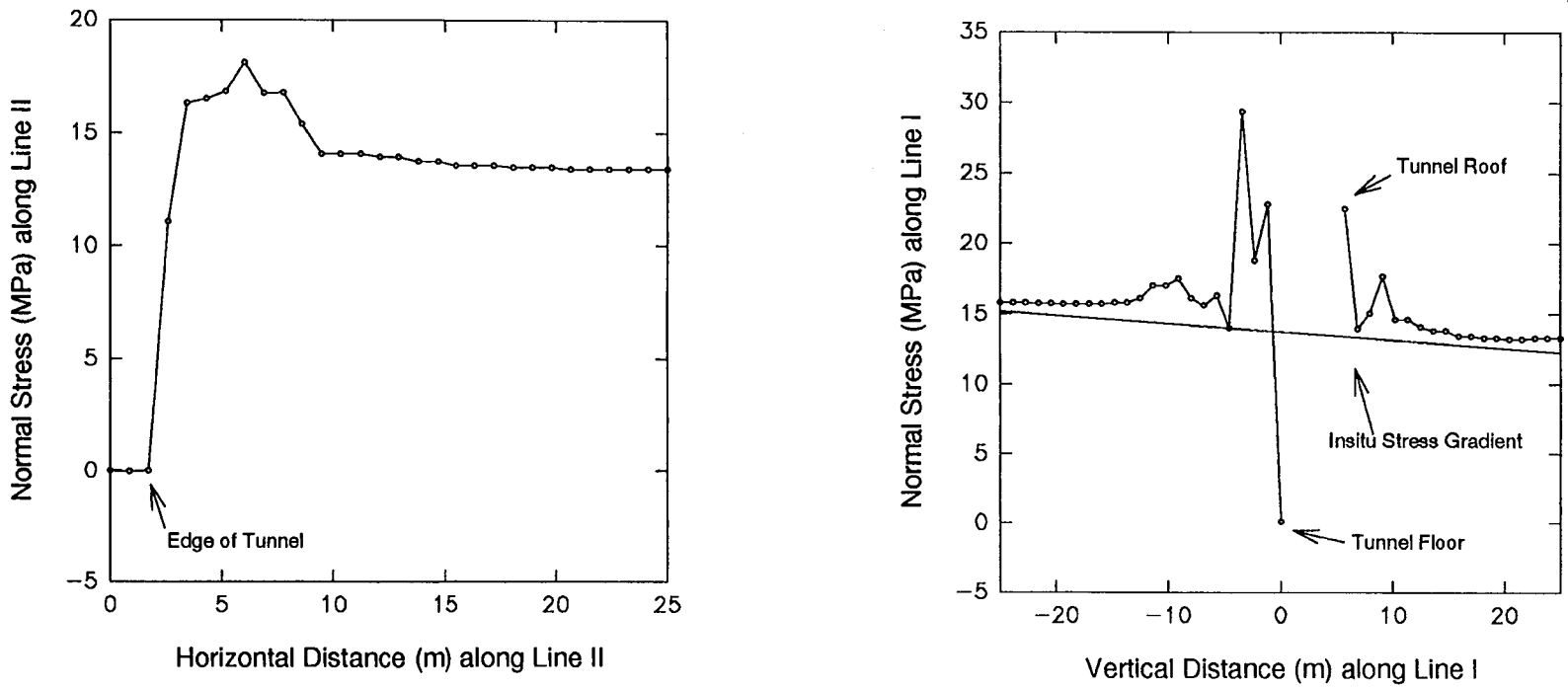
(a) (b)

Figure C-9. UDEC results for Case A after 100 yr of heating ($t = t^* + 100$ yr) (a) principal stress vectors [maximum principal stress (compression) = 60.80 MPa; minimum principal stress (tension) = 7.24 MPa], and (b) displacement vectors (maximum displacement = 5.601×10^{-2} m)



(a) (b)

Figure C-10. UDEC results for Case A after 100 yr of heating ($t = t^* + 100$ yr) (a) temperature contours (°C), and (b) fracture flowrates (tunnel inflow = 1.808×10^{-8} m^3/s).



(a) (b)

Figure C-11. UDEC results for Case A after 100 yr of heating ($t = t^* + 100$ yr) (a) normal stress (σ_{yy}) along line II, and (b) normal stress (σ_{xx}) along line I

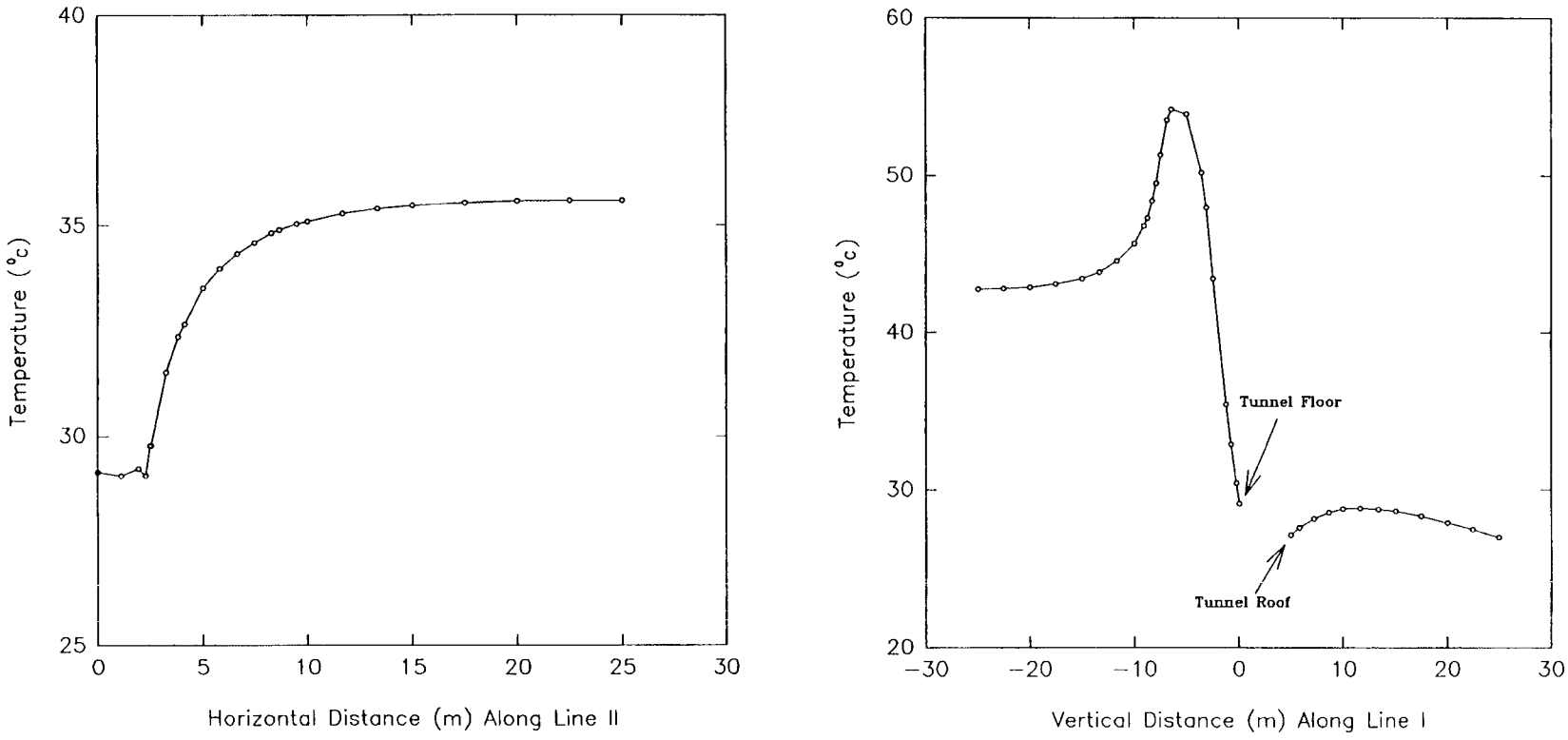
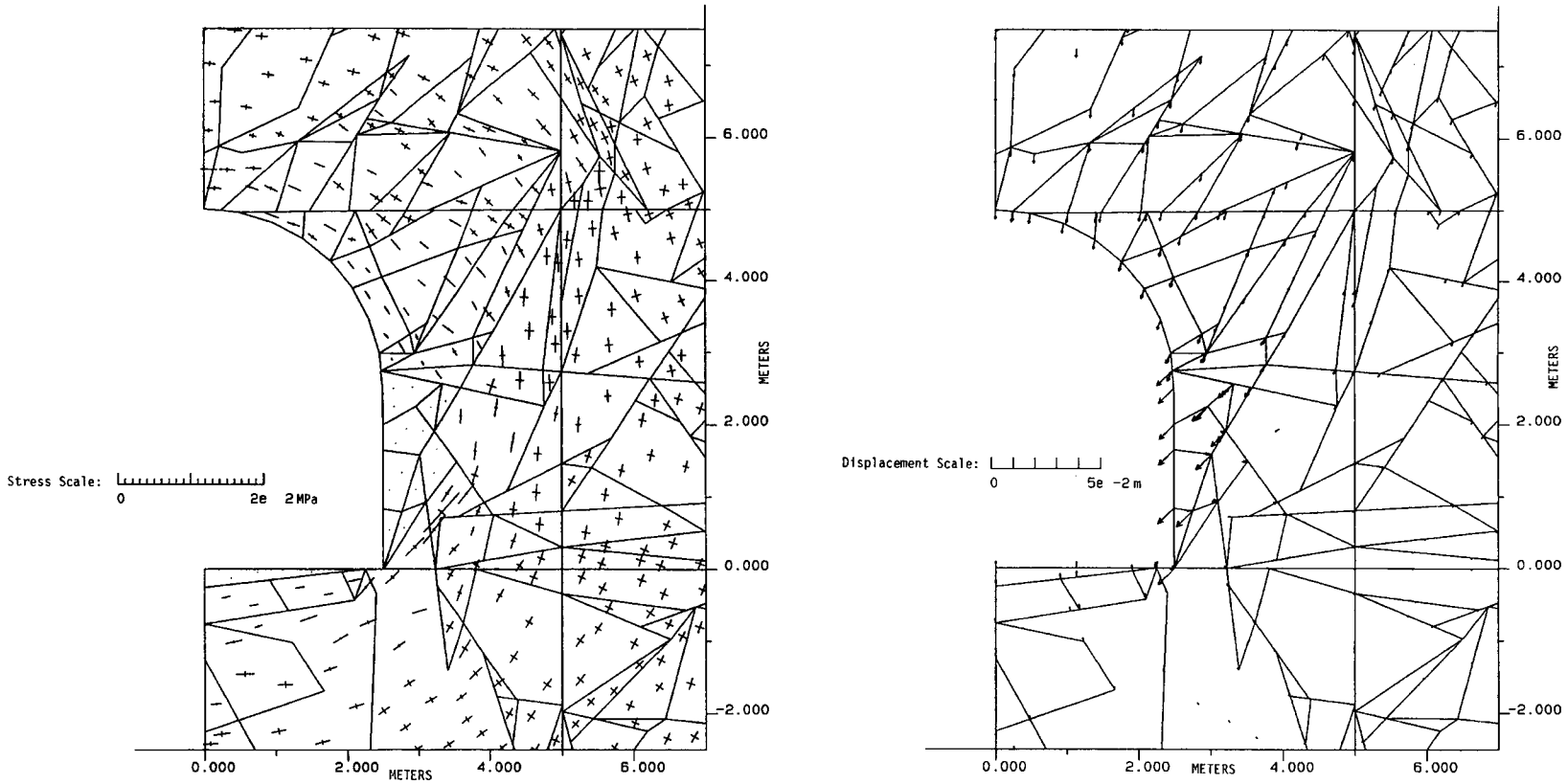
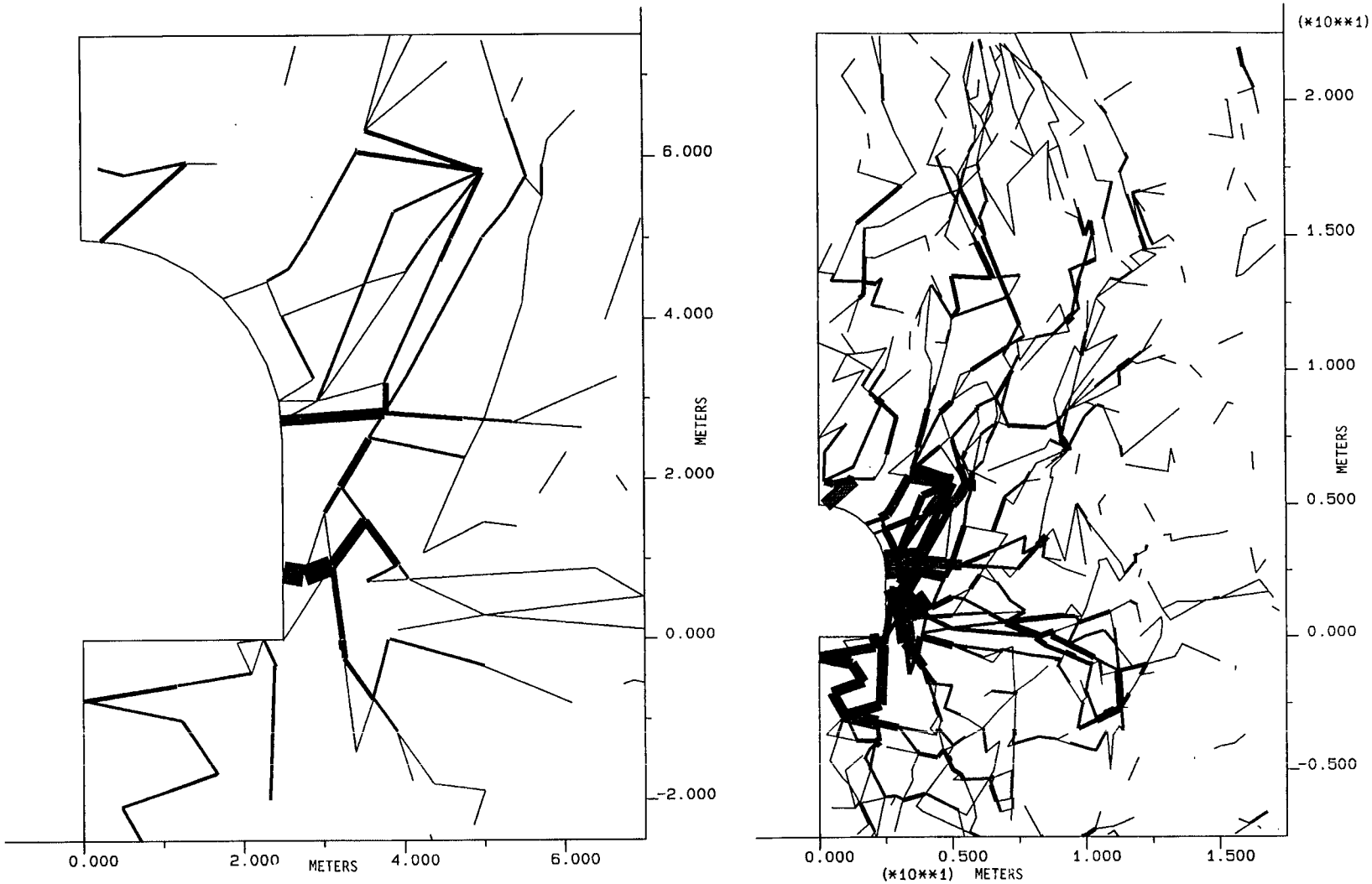


Figure C-12. UDEC results for Case A after 100 yr of heating ($t = t^* + 100$ yr) (a) temperature (°C) along line II, and (b) temperature (°C) along line I



(a) (b)

Figure C-13. UDEC results for Case B after excavation of tunnel ($t = t^*$) (a) principal stress vectors [maximum principal stress (compression) = 71.83 MPa, minimum principal stress (tension) = 4.63 MPa], and (b) displacement vectors (maximum displacement 1.058×10^{-2}m)



(a) (b)

Figure C-14. UDEC results for Case B after excavation of tunnel ($t = t^*$) (a) fracture flowrates in vicinity of tunnel (tunnel inflow = 3.293×10^{-8} m^3/s; minimum line thickness represents flowrate of 5.0×10^{-10} m^3/s) and (b) fracture flowrates for entire model (minimum line thickness represents flowrate of 2.0×10^{-10} m^3/s)

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