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Electronic Scientific Notebook No.165E: Analyze the Stability of Emplacement Drifts Excavated in a Jointed Rock Mass, Under In Situ and Thermal Stress Fields to Develop an Understanding of the Load that May Be Generated by Rock Movement and Rock Fall

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SCIENTIFIC NOTEBOOK

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by

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March 19, 1996

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1. INITIAL ENTRIES

Scientific NoteBook: # 165

Issued to: Mikko Ahola

Issue Date: January 31, 1996

Printing Period: January 31, 1996 to March 31, 1996

Project Title: Thermal-Mechanical (TM) Modeling of Emplacement Drift Stability

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By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

1.1 Objectives

The specific objectives for this activity are to analyze the stability of emplacement drifts excavated in a jointed rock mass, under *in situ* and thermal stress fields, and to develop an understanding of the load that may be generated by rock movement and rock fall that will have an impact on the waste packages. This activity will provide a basis for assessing the acceptable range of thermal loads for the proposed repository, considering preclosure performance objectives as well as postclosure performance objectives. The Yucca Mountain (YM) rock properties will be used in the simulations, based on information available from borehole drilling. The UDEC code Version 2.01 will be used to model different scenarios. The range of thermal loads that will be used in this study will span the DOE "hot" and "cold" repository concepts. Using a rock joint network, as realistic as possible for the proposed repository at YM, this activity will investigate the effect of different thermal load regimes on the stability of the emplacement drifts and the corresponding load on the waste packages. It is realized that the current information on thermal degradation of rock properties is limited at best.

Installation test run of UDEC Version 2.01 was conducted by duplicating a given example problem (see page 2.1 of UDEC 2.0 User's Manual Volume I. That includes inserts for the new UDEC revision 2.01). This example problem provides the basic steps of operating the code. Our installation test run indicated that we have the reported capabilities of the code.

This activity will continue over a period of two years. In the first year, this study will focus on simulating the scenarios without any backfill in the emplacement drifts. Effects of backfill will be studied in the second year.

1.2 Technical Approaches

The technical approach for this project will be to utilize the discrete element code UDEC (ITASCA, 1993) to conduct a series of numerical modeling analyses to investigate the thermal-mechanical response of a typical repository waste emplacement drift assuming realistic ranges of joint geometries,

geomechanical properties, and areal thermal loadings. The intent is to characterize the size of the damage region around the drifts and independently assess DOE's choices of thermal loadings. A second objective is to evaluate the extent to which failure of the rock mass around the drift and movement along joints may lead to rock loading or impact to the waste canister itself for assessments of the long term canister performance.

1.3 Computers, Computer Codes, and Data Files

Table 0-1: Computing equipment

Machine Name	Type	Operating System	Location
PCs	Pentium & 486	OS2	Bldg. 189
Sun Workstations	SPARC 10	Solaris	Bldg. 189

1.4 Mathematical Theory

1.5 Assumptions

1.6 Initial/Boundary Conditions

For the UDEC modeling analyses, the vertical boundaries are taken to be lines of symmetry based on the repository design having parallel drifts. As a result, the x-velocity is set to zero along the vertical boundaries simulating rollers, and also zero heat flux is applied to the two vertical boundaries. The lateral extent of the model is governed by the drift to drift spacing which itself depends on the areal thermal loading chosen. For this analysis, four different areal thermal loadings were analyzed. These are listed in Table 2, where the areal thermal loading is given in units of MTU's/acre.

Table 2. Drift and Waste Package Spacing Corresponding to Range of Thermal Loadings

Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Waste Package Spacing (m)
100.0	22.5	18.0
80.0	25.0	20.0
40.0	30.0	33.7
20.0	40.0	50.6

Table 2 shows the drift and waste package spacings associated with each of the above areal mass loadings for the UDEC analyses. The parameters in Table 2 lie within the ranges considered by DOE (TRW Environmental Safety Systems Inc., 1994), however, as stated by DOE in that report, the areal mass loadings of 20 and 40 MTU's/Acre are less favorable since they lead to waste package spacings greater than the drift to drift spacings.

The vertical extent of the UDEC models was determined such that the ambient temperatures applied along the upper and lower boundaries did not artificially impact the results, for the total selected simulation time of 100 years. The method suggested by St. John (1985) was applied to determine the distance of influence of a single waste container on rock temperatures as a function of time in order to determine the vertical extent of the UDEC 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)

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

where

i = imaginary number
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

$$\exp\ (-R^2/4\kappa t) \qquad (2)$$

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

$$R \geq 4\sqrt{\kappa t} \qquad (3)$$

where *t* is time in years.

Applying the above equation to the present UDEC model for a simulation time period of 100 years and a thermal diffusivity of 31.3 m^2/yr, the vertical extent of thermal influence, *R*, is determined to be approximately 225 m. Thus, in all the UDEC runs, both the upper and lower boundaries are located 225 m from the drift centerline.

The initial temperature at the repository horizon was selected at 29 °C (Christianson and Brady, 1989), with gradient of 0.02 °C/m. The *in situ* vertical stress at the repository horizon was taken to be 7.0 MPa (Christianson and Brady, 1989) with a gradient of 0.0225 MPa/m. The *in situ* horizontal stress was assumed to be related to the vertical stress by the following equation

$$\sigma_h = \frac{\nu}{(1-\nu)}\sigma_v \qquad (4)$$

where the horizontal gradient was determined to be 0.0059 MPa/m.

1.7 Baseline Mechanical and Thermal Rock Properties

The baseline mechanical and thermal properties used in the UDEC modeling were as follows:

Intact Rock

Young's Modulus	32.3 GPa
Poisson's Ratio	0.21
Density	2297.0 kg/m^3
Uniaxial Compressive Strength	166.0 MPa
Cohesion	2.1 MPa
Tensile Strength	1.05 MPa
Angle of Internal Friction	49.0 ^{o}
Thermal Conductivity	2.1 W/m-K
Coeff. of Thermal Expansion	8.8E-6 /K
Specific Heat	932.0 J/kg-K

Rock Joints

Joint Normal Stiffness	1.0E5 MPa/m
Joint Shear Stiffness	1.0E5 MPa/m
Joint Cohesion	0.08 MPa
Joint Tensile Strength	0.04 MPa
Joint Angle of Friction	38.0 ^{o}

1.8 Thermal Flux Input

For the UDEC analysis, it was decided to model the volumetric heat generation due to the decaying in-drift waste package as a thermal flux applied directly to the wall of the circular emplacement drift. In reality, in a unbackfilled drift, heat transfer from the waste package to the surrounding rock would be a combination of radiation heat transfer to the wall of the emplacement drift as well as conduction heat transfer to the tunnel floor depending on how the waste package is supported in the drift. Because Version 2.01 of UDEC has limitations in modeling cavity radiation (i.e., currently is set up for boundary radiation), it was decided to neglect modeling of the waste package itself and apply the volumetric heat generation directly as a heat flux to the drift wall. In essence, the analysis neglects heat removal from ventilation. The entire series of UDEC runs are based on the fuel within the MPC being 20 years old at the time of waste emplacement. The C^{++} source code subroutine (Manteufel, 199?) that generates the time decaying heat flux is provided in Appendix A along with a Figure showing the total heat output in Watts as a function of time. The surface heat flux (W/m^2) applied to the tunnel wall in the 2-D UDEC models is calculated by dividing the total waste package heat output (W) by the perimeter length of the drift and the waste package spacing. For the UDEC analyses, the emplacement drift diameter was taken to be 5 m. The decaying heat generation curve for the waste package given in Appendix A is comprised of a number of exponentially decaying terms. Version 2.01 of UDEC has limitations in that for the thermal flux boundary condition input, it cannot read in a table such as that used to create Figure A-1. Also, in specifying an exponentially decaying flux boundary condition, UDEC only allows a single decay function of the form where q_o is the initial surface heat flux (W/m^2) applied to the drift wall at time of emplacement (assuming 20 year old fuel) and α is the decay constant (1/s). As a result, a best exponential fit to the true decay

$$q = q_o \exp(-\alpha t) \quad (5)$$

curve was made with a single decay constant for the UDEC runs. Table 3 shows the values for q_o and α for the different areal mass loadings

Table 3. Heat flux decay parameters (see Equ. 5) for 20 year old fuel

Areal Mass Loading (MTU's/Acre)	q_o (W/m^2)	α (1/s)
100	28.570	3.2197E-10
80	25.459	3.2197E-10
40	15.260	3.2197E-10
20	10.163	3.2197E-10

2. IN-PROCESS ENTRIES

2.1 Introduction

The objective of this activity is to conduct a series of discrete element computer analyses using the e UDEC to independently assess DOE's repository thermal loading strategies and their impact on the near field thermal-mechanical response of the fractured rock surrounding the emplaced waste. A progress report documenting the details of this activity will be submitted to the NRC to fulfill the intermediate milestone "Stability of Emplacement Drifts under Range of Thermal Loads - Phase I Report" (IM 5702-623-601). This work is conducted under the scope of RDCO Element Subtask 2.3.

2.2 Benchmark Comparison of UDEC Thermal Results with ABAQUS

As an independent check to assure that the decaying thermal flux input into the UDEC correct, a comparison of temperatures predicted by UDEC were made with a similar 2D ABAQUS analysis. Although the comparison was made assuming an areal mass loading of 80 MTU's/Acre, the drift spacing in UDEC was set at 25 m while the drift spacing in ABAQUS was 22.5 m. Consequently, the waste package spacings for the two separate analyses were also slightly different to arrive at the same areal mass loading. This was not thought to result in significant differences in the temperature profiles between the two codes. The ABAQUS analysis was done for a separate study on surface ground heave, and it was felt not necessary to rerun ABAQUS (which would have resulted in modifying the finite element mesh) at the same drift spacing chosen for the UDEC study. Figures 2-1 and 2-2 show the input heat flux to the emplacement drift wall and corresponding temperature calculated as a function of time at the crown of

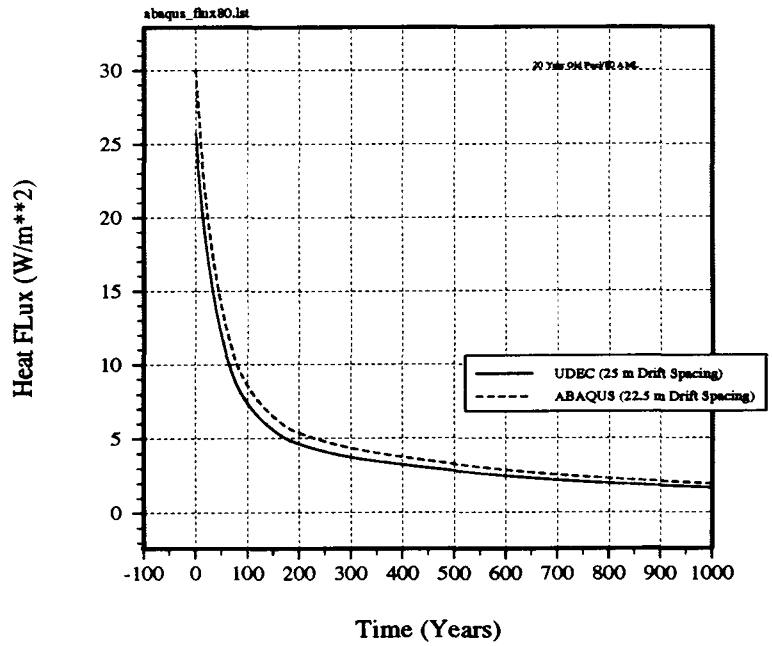

Figure 2-1. Heat fluxes used in the ABAQUS and UDEC analyses for benchmark comparison of calculated temperature

the drift. Note that the ABAQUS analysis used a multiplier of 1.16 to the input heat flux, which is why the initial ABAQUS heat flux is 29 W/m^2 versus 25.4 W/m^2 for the UDEC run. The resulting temperature at the roofline between the two codes compares quite well, both giving a peak temperature of about 163 C (Figure 2-2). The slight overestimation of temperature calculated by ABAQUS at early times is due to the fact that a slightly higher flux was input due to this multiplier.

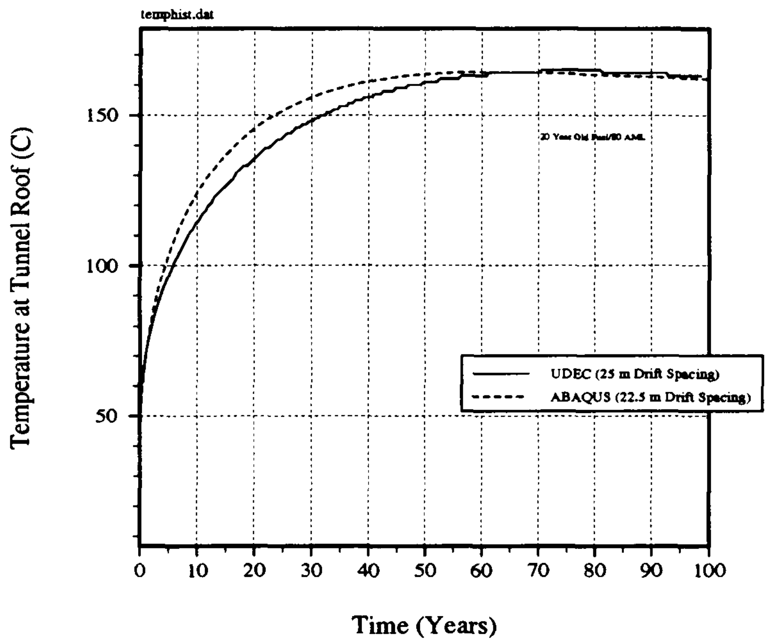

Figure 2-2. Comparison of calculated temperatures between UDEC and ABAQUS at the tunnel crown for 80 MTU/Acre areal mass loading

2.3 UDEC Thermal-Mechanical Runs

Due to the large number of variables for conducting a thermal-mechanical drift stability parametric study with UDEC, it was decided that in the first set of runs the mechanical properties of the rock matrix and joints as well as thermal properties remain fixed at the base case values given in Section 1. As a result, the first set of UDEC runs analyzed the near-field thermal mechanical response based on 5 distinct joint patterns under low and high thermal loadings (20 and 100 MTU's/Acre, respectively). Each of the 5 joint patterns contained at least two joint sets, namely one subhorizontal and one subvertical joint set. Several cases contained an additional subvertical or ubiquitous joint set. The subhorizontal joint set orientation varied between 0-10^o with a constant spacing of 1.25 m. For the cases with only one subvertical joint set, the orientation varied between 85-90^o with a constant spacing of 0.625 m. For the cases with an additional subvertical joint set (i.e., 3 joint sets total) the orientations were 70^o or 60^{o}and spacing fixed at 1.25 m. This joint geometry data was extracted from Christianson and Brady (1989) as well as borehole mappings from the North Ramp geotechnical study. In essence, the published results show the primary jointing being near vertical with some horizontal jointing due to bedding foliations within the tuff. As the orientations approach vertical, the published data shows the joint frequency also increases. Table 4 shows the matrix of UDEC runs for the first set of analyses.

Table 4. UDEC run matrix for 20 and 100 MTU/Acre thermal loadings with different fracture geometry.

AML (MTU/acre)	File Name	Spacing		Thermal Load		Joint Sets*			E (GPa)	Joint Friction Angle
		Drift (m)	Waste Package (m)	Initial Strength (W/m^2)	Exponent (s^{-1})	Joint Set No.1	Joint Set No.2	Joint Set No.3		
100	TM100a.dat	22.5	18.0	28.4701	$-3.2197e^{-10}$	90° 0.625 m	0° 1.25 m	-	32.3	38°
	TM100b.dat					85° 0.625 m	10° 1.25 m	-		
	TM100c.dat							70° 1.25 m		
	TM100d.dat							60° 1.25 m		
	TM100f.dat					85° ubiquitous		70° 1.25 m		
20	TM20a.dat	40.0	50.6	10.1633	$-3.2197e^{-10}$	90° 0.625 m	0° 1.25 m	-		
	TM20b.dat					85° 0.625 m	10° 1.25 m	-		
	TM20c.dat							70° 1.25 m		
	TM20d.dat							60° 1.25 m		
	TM20f.dat					85° ubiquitous		70° 1.25 m		

2.3.1 UDEC Case TM100F

Appendix B contains the input deck for the UDEC run for Case TM100F. A plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure B-1. In addition to the to distinct joint sets around the drift, a ubiquitous joint material property set was assigned to the blocks themselves oriented at 85°. The analysis was run up to a thermal time of 100 years. Figures B-2 and B-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 3 mm to 1.7 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures B-4 and B-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum principal compressive strength is 13.0 MPa. After 100 years of heating, the maximum principal compressive stress increases to approximately 56.2 MPa in the immediate roof and floor of the excavation. No tensile stresses are predicted for this case. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to the thermal expansion. For this 100 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the right rib of the tunnel as evidenced by the gridpoint velocity vectors in Figure B-5 for this particular fracture orientation.

Figures B-6 and B-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure B-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 11 cm upward (Figure B-9). The temperature of the rock at the tunnel roof increases to approximately 190° after 75 years for the 100 MTU/Acre case (Figure B-10). Figure B-11 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table B-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table B-2 lists the temperatures at specific locations with time used to generate Figures B-10 and B-11.

2.3.2 UDEC Case TM20F

Appendix C contains the input deck for the UDEC run for Case TM20F. The UDEC discrete element mesh is provided in Figure C-1, and contains the same joint sets as that described in Section 2.3.1 for Case TM100F. The only difference is that the lateral dimensions have been increased to simulate the lower 20 MTU/acre heat loading. Figures C-2 and C-3 show the shear displacements after excavation and 100 years of heating, respectively. The maximum shear displacements increase from about 3.4 mm to approximately 3.0 cm. Unlike the 100 MTU/acre loading, little to no shearing takes place along the subhorizontal joints. Figures C-4 and C-5 show the principle stress and velocity vector plots after excavation and 100 years of heating. After excavation, the maximum principal stress is 13.65 MPa increasing to 22.34 MPa after 100 years. Again, the thermal loading results in increased compressive stress in the roof and floor of the excavation. Similarly, the walls of the tunnel become distressed leading to block instability along the right sidewall (Figure C-5).

Figures C-6 and C-7 depict the horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively, at several time periods. Figures C-8 shows the vertical

displacement with distance above the center of the tunnel. As shown in Figure B-9, the upward displacement of the tunnel roof for the 20 MTU/acre loading reaches 2.23 cm versus 10.69 cm for the 10 MTU/acre loading. Likewise, as shown previously in Figure B-10 the maximum temperature of the tunnel roof only reaches 64.4 °C for the 20 MTU/acre case versus 190 °C for the 100 MTU/acre case. Figure C-9 shows the temperature with vertical distance above the tunnel centerline at various times. Tables 7 and 8 give the tabulated values for the temperatures, displacements, and stresses at discrete points around the tunnel.

2.3.3 UDEC Case TM100A

Appendix D contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure D-1. There are two distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures D-2 and D-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 8 mm to 1.057 cm. The thermal loading results primarily in increased shear displacements along the horizontal joints. Figures D-4 and D-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 15 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 86 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures D-4 and D-5. The maximum tensile stress is 0.7 MPa after the excavation and it is located near roof and floor of the excavation. The maximum tensile stress increases to 1.5 MPa after 100 years of heating and the location of the maximum tensile stresses moved to the ribs of the excavation. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 100 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure D-5 for this particular fracture orientation.

Figures D-6 and D-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure D-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 13 cm upward. Figure D-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table D-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table D-2 lists the temperatures at specific locations with time used to generate Figure D-9.

2.3.4 UDEC Case TM100B

Appendix E contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure E-1. There are two distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures E-2 and E-3 show the joint shear displacements after excavation and

100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 2 mm to 14 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures E-4 and E-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 11.5 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 75 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures E-4 and E-5. The maximum tensile stress is 0.7 MPa after the excavation and it is located near roof and floor of the excavation. The maximum tensile stress increases to 4 MPa after 100 years of heating and the location of the maximum tensile stresses moved to the ribs of the excavation. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 100 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure E-5 for this particular fracture orientation.

Figures E-6 and E-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure E-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 12 cm upward. Figure E-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table E-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table E-2 lists the temperatures at specific locations with time used to generate Figure E-9.

2.3.5 UDEC Case TM100C

Appendix F contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure F-1. There are three distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures F-2 and F-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 3.7 mm to 14.7 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures F-4 and F-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 20 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 63 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted around the excavation immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures F-4 and F-5. The maximum tensile stress is 1.6 MPa after the excavation. The maximum tensile stress increases to 6.4 MPa after 100 years of heating. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 100 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure F-5 for this particular fracture orientation.

Figures F-6 and F-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure F-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 12.5 cm upward. Figure F-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table F-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table F-2 lists the temperatures at specific locations with time used to generate Figure F-9.

2.3.6 UDEC Case TM100D

Appendix G contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure G-1. There are three distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures G-2 and G-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 3.8 mm to 16 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures G-4 and G-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 20 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 61 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted around the excavation immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures G-4 and G-5. The maximum tensile stress is 1.5 MPa after the excavation. The maximum tensile stress increases to 5 MPa after 100 years of heating. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 100 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure G-5 for this particular fracture orientation.

Figures G-6 and G-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure G-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 12 cm upward. Figure G-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table G-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table G-2 lists the temperatures at specific locations with time used to generate Figure G-9.

2.3.7 UDEC Case TM20A

Appendix H contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC

discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure H-1. There are two distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures H-2 and H-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 1.852 mm to 16.87 cm. The thermal loading results primarily in increased shear displacements along the horizontal joints. Figures H-4 and H-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 14.87 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 21 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures H-4 and H-5. The maximum tensile stress is 0.75 MPa after the excavation and it is located near roof and floor of the excavation. The maximum tensile stress increases to 0.82 MPa after 100 years of heating and the location of the maximum tensile stresses moved to the ribs of the excavation. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 20 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure H-5 for this particular fracture orientation.

Figures H-6 and H-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure H-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 2.4 cm upward. Figure H-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table H-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table H-2 lists the temperatures at specific locations with time used to generate Figure H-9.

2.3.8 UDEC Case TM20B

Appendix I contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure I-1. There are two distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures I-2 and I-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 2.58 mm to 7.93 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures I-4 and I-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 10.90 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 19.36 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures I-4 and I-5. The maximum tensile stress is 0.77 MPa after the excavation and it is located near roof and floor of the excavation. The maximum tensile stress increases to 0.98 MPa after 100 years of heating and the location of the maximum tensile stresses moved to the ribs of the excavation. From the two figures, it can be noticed that the circumferential stress increases in the

roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 20 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure I-5 for this particular fracture orientation.

Figures I-6 and I-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure I-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 2.2 cm upward. Figure I-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table I-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table I-2 lists the temperatures at specific locations with time used to generate Figure I-9.

2.3.9 UDEC Case TM20C

Appendix J contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure J-1. There are three distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures J-2 and J-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 5.38 mm to 7.60 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures J-4 and J-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 21.27 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 19.21 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted around the excavation immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures J-4 and J-5. The maximum tensile stress is 1.05 MPa after the excavation. The maximum tensile stress increases to 3.01 MPa after 100 years of heating. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 20 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure J-5 for this particular fracture orientation.

Figures J-6 and J-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure J-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 2.12 cm upward. Figure J-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table J-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table J-2 lists the temperatures at specific locations

with time used to generate Figure J-9.

2.3.10 UDEC Case TM20D

Appendix K contains the input deck for the UDEC runs for Case TM100A. The plot of the UDEC discrete element mesh around the emplacement drift based on the joint geometry given in Table 4 is shown in Figure K-1. There are three distinct joint sets around the drift. The analysis was run up to a thermal time of 100 years. Figures K-2 and K-3 show the joint shear displacements after excavation and 100 years, respectively. As noted in the two figures, the maximum joint shear displacements increase from around 3.78 mm to 1.92 cm. The thermal loading results primarily in increased shear displacements along the subhorizontal joints. Figures K-4 and K-5 show the corresponding principal stress and velocity vector plots at the same two time periods. After excavation, the maximum compressive stress is 18.69 MPa and it is located in the ribs of the excavation. After 100 years of heating, the maximum principal compressive stress increases to approximately 16.60 MPa in the immediate roof and floor of the excavation. Tensile stresses are predicted around the excavation immediately after the excavation as well as after 100 years of heating for this case as indicated by the diamonds in Figures K-4 and K-5. The maximum tensile stress is 1.41 MPa after the excavation. The maximum tensile stress increases to 3.42 MPa after 100 years of heating. From the two figures, it can be noticed that the circumferential stress increases in the roof with heating, while it decreases in the ribs of the tunnel due to thermal expansion. For this 20 MTU/Acre loading case, the right and left tunnel ribs become almost completely distressed. This results in unstable rock along the ribs of the tunnel as evidenced by the gridpoint velocity vectors in Figure K-5 for this particular fracture orientation.

Figures K-6 and K-7 depict horizontal and vertical stress profiles along vertical and horizontal sections through the tunnel centerline, respectively. These are plotted at several time periods. Except for the roof, the peak stress is shifted somewhat into the rock mass due to slip along joints intersecting the tunnel. Figure K-8 shows the vertical displacement (heave) with distance above the center of the tunnel. After 100 years, the displacement at the tunnel roof is approximately 2.13 cm upward. Figure K-9 shows the temperature with vertical distance above the tunnel centerline at various times. It should be noted that for these runs, no ventilation is assumed.

Table K-1 gives the values of displacement at the tunnel roof and floor as well as the stresses at two particular points around the tunnel at various times. Table K-2 lists the temperatures at specific locations with time used to generate Figure K-9.

2.4 Comparison of UDEC Runs

2.4.1 Effect of Thermal Load and Joint Pattern on Displacement

Figure L-1 compares vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for different joint patterns for the thermal load of 100 MTU/Acre. The distribution of vertical displacement for different joint patterns is similar, i.e., upward expansion increases with increasing vertical distance from the tunnel. However, the magnitude of vertical expansion is slightly different for different joint patterns. Vertical expansion at a given depth is the largest for Case F (ubiquitous joint model with a subvertical and a subhorizontal joint sets, see Table 4) and it is the smallest for Case B (a subvertical and a subhorizontal joint sets with orientations similar to those in Case F, see Table 4). For the thermal load of 20 MTU/Acre, vertical displacement at a given depth is the highest for Case A and the lowest for Case C. These two figures show that the effect of joint pattern on the

magnitude of vertical displacement is rather arbitrary and not consistent for the high and low thermal load strategies considered in this analysis (i.e., 100 MTU/Acre and 20 MTU/Acre).

Figures L-3 through L-7 compare vertical expansion for different thermal loads for the five joint patterns considered (i.e., Cases A through F in Table 4), respectively. The maximum vertical expansion of the high thermal load (100 MTU/Acre) is about 5 times higher than that of the low thermal load (20 MTU/Acre).

Figures L-8 and L-9 compare vertical displacement at roof and floor, respectively, as a function of time for different joint patterns for the thermal load of 100 MTU/Acre. An interesting observation from these two figures is that the ubiquitous model (Case F) has the highest floor expansion, while it has the lowest roof expansion. For ubiquitous model, floor expansion after 100 years heating is about 25% higher than the roof expansion (see Table L-1). For all other joint patterns, the difference between roof and floor expansion is rather nominal, although in general, roof expands more than the floor. In general, joint pattern does not have significant effect on neither roof expansion nor floor expansion, except in the case of ubiquitous joint model.

Table L-1 compares roof displacement, floor displacement, and the maximum joint shear displacement after excavation and after 100 years of heating for different cases. This table shows that case TM100D has the highest maximum joint shear displacement for 100 MTU/Acre thermal loading case and case TM20A has the highest maximum joint shear displacement for 20 MTU/Acre thermal loading case joint shear displacement after 100 years of heating is, in general, a magnitude higher than joint shear displacement right after excavation. Neither the magnitude of thermal loads nor joint pattern appear to have altered the maximum joint shear displacement in a consistent way.

Figures L-10 and L-11 compare vertical displacement at roof and floor, respectively, as a function of time for different joint patterns for the thermal load of 20 MTU/Acre. Joint patterns show very little effect on the roof and floor displacement. An interesting observation for this low thermal loading strategy, which is rather different from the high thermal loading strategy (100 MTU/Acre), is that the floor displacement is always larger than the roof displacement (see Table L-1). Also, case F behaves in a way which is similar to other cases

2.4.2 Effect of Thermal Load and Joint Pattern on Stresses

Figure L-12 compares horizontal stress after 100 years of heating along a vertical section through the tunnel for the five joint patterns listed in Table 4 for the 100 MTU/acre thermal loading case. Joint patterns do not seem to affect neither the magnitude nor the distribution of horizonal stresses significantly, except in the immediate roof and floor. In the immediate roof and floor, Cases TM100C and TM100D appear to have the highest compressive horizontal stress and the largest stress variation along the vertical section (also see Figures L-14 through L-18). Similar effects can also be observed in the case of 20 MTU/acre thermal loading (Figure L-13). Case TM100F has the highest compressive horizontal stress in the immediate roof and floor areas for 20 MTU/Acre thermal loading case. These observations lead to a reasonable general conclusion: the more complex the joint pattern, the more fluctuation in the stress and the higher the maximum stress magnitude.

Figurês L-14 through L-18 compare horizontal stresses after 100 years of heating along a vertical section through the tunnel resulting from the 100 MTU/Acre and 20 MTU/Acre loading cases for the five joint patterns considered in this study, respectively. In general, increasing thermal load from 20 MTU/Acre

to 100 MTU/Acre would increase horizontal compressive stress 4 to 6 times in the roof and floor areas. Figure L-19 compares vertical stress after 100 years of heating along a horizontal section through the tunnel for the five joint patterns listed in Table 4 for the 100 MTU/acre thermal loading case. Due to the short distance and high fluctuation in the magnitude of the vertical stresses, it is difficult to observe the effect of joint patten on the magnitude and distribution of stresses. Figure L-20 shows the similar figure for the case of 20 MTU/Acre thermal loading. This figure shows that joint pattern does not significantly alter either the magnitude or the distribution of vertical stresses along this horizontal section. However, it appears that the simpler joint patters (e.g. cases A and B) result in smoother stress curves.

Figures L-21 through L-25 compare vertical stresses after 100 years of heating along a horizontal section through the tunnel resulting from the 100 MTU/Acre and 20 MTU/Acre loading cases for the five joint patterns considered in this study, respectively. In general, the maximum vertical compressive stress along this horizontal section is higher for the higher thermal load (the 100 MTU/Acre thermal loading case).

Table L-2 summarizes the maximum tensile stresses and the maximum compressive stresses for each UDEC run. There are tensile stresses right after excavation for all the cases except for the ubiquitous joint model. The maximum tensile stress is the highest for cases with three joint sets (i.e., Cases D and C) for both thermal loading cases.

2.4.3 Summary of Temperature and Temperature Distribution

Figures L-26 and L-27 depict temperature histories on tunnel wall at roof for all of the joint patterns under thermal loads of 100 MTU/Acre and 20 MTU/Acre, respectively. In 100 MTU/Acre loading case, temperature at tunnel wall increases to a maximum of 180 to 190°C and it reaches the maximum at about 80 years after heating. In 20 MTU/Acre loading case, temperature at tunnel wall increases to a maximum of 62 to 63°C and it reaches the maximum at about 60 years after heating. Since in UDEC, thermal analysis is independent of mechanical analysis, joint pattern should not affect temperature. The slight differences in the magnitude of temperature shown in Figures L-26 and L-27 for different joint patters is, therefore, due to the computational accuracy and errors induced in applying thermal flux at tunnel wall using UDEC.

3. References

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St. John, C.M. 1985. *Thermal Analysis of Spent Fuel Disposal in Vertical Boreholes in a Welded Tuff Repository.* SAND84-7207. Albuquerque, NM: Sandia National Laboratories.

TRW Environmental Safety Systems Inc. 1994. *Initial Summary Report for Repository/Waste Package Advanced Conceptual design.* Prepared for the U.S. Department of Energy. Document No. B00000000-01717-5705-00015 Rev. 00. Volume I. Las Vegas, NV.

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Appendix A

C++ Subroutine to calculate decaying volumetric heat generation rate assuming waste package diameter of 1.5 m and length of 6 m

```
#include <stdlib.h>
#include <iostream.h>
#include <math.h>
#include <iomanip.h>
#include <fstream.h>

double time_decaying_hs(double tyr)
{
/* All entered times must be in years and should include the time out of
the reactor    */

  static double time[38] =
                {1,2,3,4,5,6,7,8,9,10,16,18,20,25,30,40,50,60,70,80,
                 90,100,200,300,400,500,1000,2000,3000,5000,10000,
                 30000,40000,50000,100000,200000,500000,1000000};
  static double pwr[38] =
            {9740.0,5050.0,3170.0,2270.0,1800.0,1530.0,1370.0,1270.0,
             1200.0,1140.0,949.0,908.0,871.0,791.0,723.0,612.0,525.0,
             455.0,398.0,353.0,316.0,286.0,160.0,126.0,108.0,93.8,54.7,
             29.2,22.8,18.8,13.5,5.19,3.71,2.8,1.05,0.618,0.525,0.392};

  static double bwr[38] =
         {7070.0,3700.0,2360.0,1710.0,1380.0,1190.0,1080.0,1000.0,
          951.0,911.0,773.0,742.0,713.0,652.0,599.0,511.0,440.0,383.0,
          338.0,300.0,270.0,245.0,142.0,114.0,97.2,85.0,49.9,26.8,21.0,
          17.4,12.6,4.88,3.49,2.63,0.943,0.530,0.458,0.351};

  double timevalue = tyr;
  double exponent;
  double qp,qb;
  double hsvalue;
  double ahsvalue;


  double MTU = 10.0;  /* Number of Metric Tons of Uranium   */

  if((timevalue < time[0]) || (timevalue > time[37])){
    cout<<"left_ahs : Time is out of range"<<endl;
    exit(0);
```

```
  }

  for(int jj = 0;(jj < 38) && (timevalue >= time[jj]);jj++);

  if(jj == 38)
    jj = 36;
  else
    jj -= 1;

  exponent = log10(pwr[jj]/pwr[jj+1]) / log10(time[jj+1]/time[jj]);

  qp = pwr[jj] * pow(time[jj]/timevalue,exponent);

  exponent = log10(bwr[jj]/bwr[jj+1]) / log10(time[jj+1]/time[jj]);

  qb = bwr[jj] * pow(time[jj]/timevalue,exponent);

  hsvalue = (0.6*qp + 0.4*qb)*(MTU);
  ahsvalue = hsvalue/((3.141592654*1.5*1.5*6.0)/4.0);

/*   hsvalue is in Watts */

  return ahsvalue;

}

void main(int argc,char *argv[])
{

  float yearsofcooling;

  float time;
  double heat;
  float timeS;
  int count = 1;
  char str[50];

  if(argc != 2){
    cerr<<argv[0]<<" #of years"<<endl;
    exit(1);
  }
  yearsofcooling = atoi(argv[1]);
  time = yearsofcooling;
  sprintf(str,"%dyearsTDecayVHS\0",atoi(argv[1]));
```

```
 ofstream outfile(str);
 if (!outfile){
   cout<<“Unable to create the outfile”<<endl;
   exit(1);
 }


 cout<<“************ ”<<yearsofcooling<<“  Year Old Fuel ************”<<endl;


 while (time<1000000.0){
   heat = time_decaying_hs(time);
   timeS = (time-yearsofcooling)*365.25*24*3600;
   if (count<4){
     outfile<<setprecision(4)<<timeS<<“,”;
     outfile<<setprecision(5)<<heat<<“,”;
     count++;
   }
   else{
     outfile<<setprecision(4)<<timeS<<“,”;
     outfile<<setprecision(5)<<heat<<endl;
     count=1;
   }
   if ((time-yearsofcooling)<10.0) time+=0.5;
   else
     if ((time-yearsofcooling)<1000.0) time+=2.5;
     else
       if ((time-yearsofcooling)<10000.0) time+=35.0;
       else
         if ((time-yearsofcooling)<100000.0) time+=750.0;
         else
           if ((time-yearsofcooling)<1100000.0) time+=7500;
   if (time>1000000) time=1000000;
 }

 if (time==1000000){
   heat = time_decaying_hs(time);
   timeS = (time-yearsofcooling)*365.25*24*3600;
     outfile<<timeS<<“,”<<heat<<endl;
 }

 outfile.close();

}
```

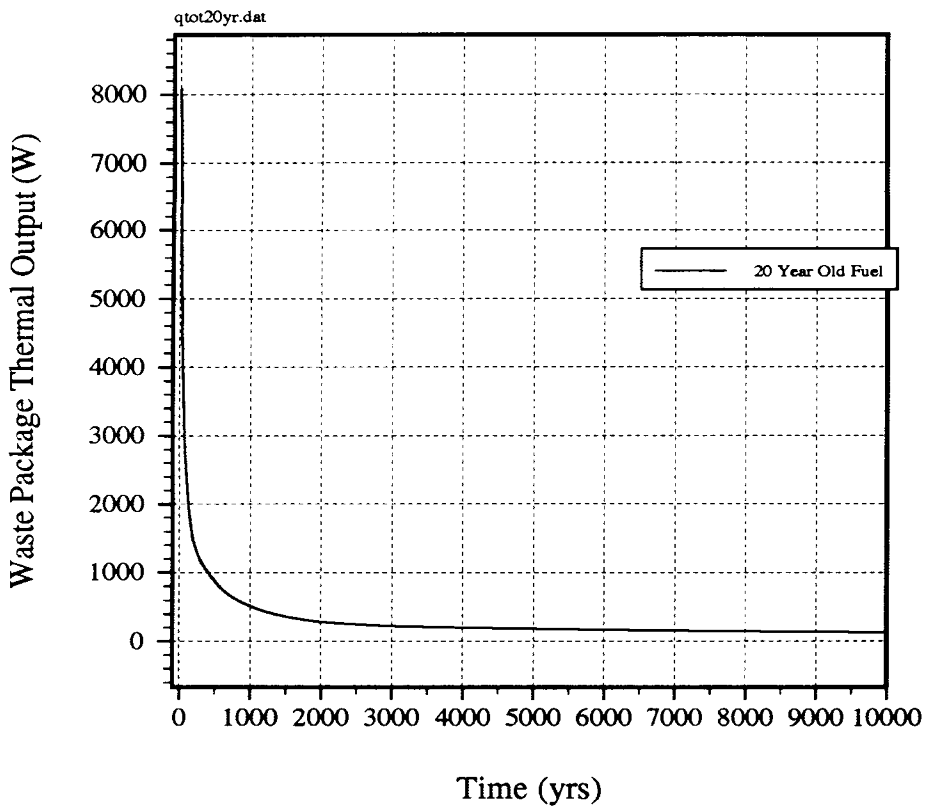

Figure A-1. Total MPC waste package heat generation assuming 20-year-old fuel at time of emplacement.

Appendix B - Case TM100F.DAT

UDEC Input Deck - TM100F.DAT

```
set log on
set plot po
start
head
Thermal-Mechanical Analysis - 20 Yr Old Fuel/100 AML - ubiquitous model
* Data File - **** tm100f.dat ****
*
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set - 10 degrees ccw from horizontal - 1.25 m spacing
* 2nd joint set - 70 degrees ccw from horizontal - 1.25 m spacing
* 3rd joint set - 90 degrees - ubiquitous joint model
**
*
* Size of problem domain is -11.25<x<11.25 -222<y<222
* - Vertical boundaries are located along symmetry lines assuming
*   22.5 m drift spacings
* - Upper and lower horizontal boundaries set based on extent
*   of thermal front at 100 years of heating
*
* input block, tunnel, and joint geometry
round 0.025
set ovtol 1.0
block -11.25 -225 -11.25 225 11.25 225 11.25 -225
split -13 -25 13 -25
split -13 25 13 25
split -13 50 13 50
split -13 -50 13 -50
*
* create jointing
*
** outer problem domain
*
jregion -13 25 -13 50 13 50 13 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.625 0.0 -11.25 25.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -11.25 25.0
*
jregion -13 50 -13 225 13 225 13 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 7.5 0.0 -11.25 50.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -11.25 50.0
*
jregion -13 -50 -13 -25 13 -25 13 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.625 0.0 -11.25 -25.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -11.25 -25.0
```

```
*
jregion -13 -225 -13 -50 13 -50 13 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 7.5 0.0 -11.25 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -11.25 -50.0
*
** inner problem domain
*
jregion -13 -25 -13 25 13 25 13 -25
jset 70.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -11.25 -22
jset 10.0 0.0 50.0 0.0 0.0 0.0 2.5 0.0 -11.25 -22
*
** detailed jointing around tunnel
*
jregion -12.5 -10.0 -12.5 8.75 12.5 12.75 12.5 -6.0
jset 70.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -11.25 -22
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -11.25 -22
*
tunnel 0 0 2.5 24
jd
del area 3.0e-2
*
gen region -5 -5 -5 5 5 5 5 -5 edge 1.5
gen region -12.5 -10.0 -12.5 8.75 12.5 12.5 12.5 -6.0 edge 2.75
gen region -12.5 -25.0 -12.5 25.0 12.5 25.0 12.5 -25.0 edge 6.0
gen region -12.5 -50.0 -12.5 50.0 12.5 50.0 12.5 -50.0 quad 6.0
gen region -12.5 -225.0 -12.5 225.0 12.5 225.0 12.5 -225.0 quad 12.0
*
pr max
*
damp auto
*
* apply mechanical boundary conditions (units, MPa)
*
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86  &
zgrad 0.0 0.00599
bound -13 13 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 -226 -224 yvel=0.0
bound -12 -11 -226 226 xvel=0.0
bound 11 12 -226 226 xvel=0.0
*
* define mechanical and thermal material properties for joints/intact blocks
*
*   material 1 = rock
*
change -13 13 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
```

```
zone region -13 -25 -13 25 13 25 13 -25 model ubiquitous b=1.856e4 &
c=2.1 d=25.0 f=49.0 ja=85.0 jc=0.08 jf=38.0 jt=0.04 sh=1.335e4 t=1.05
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
cycle 3000
save tm100f_insit.sav
win -12.5 12.5 -12.5 12.5
*pl bl st iw hold
*pl hi 5 6 hold
*
* remove tunnel blocks
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4500
*pl bl st iw hold
*pl bl dis iw hold
*pl bou mohr hold
*pl hi 3 hold
*pl hi 5 hold
*pl hi 7 hold
*pl bou sh hold
*
sav tm100f_exc.sav
*********************************************************************
*
* apply decaying heat flux to tunnel wall boundary
*
*********************************************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
```

```
* - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -13 13 -226.0 -224.0
tfix 25.0 -13 13 224.0 226.0
*
print bound
reset time
*
initem 29.0 -13 13 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
* apply heat flux to tunnel wall
*
thapp ann 0.0 0.0 2.4 2.55 flux 28.4701 -3.2197e-10
*
* run thermal time to 1 week
*
run age=6.048e5 temp=10000  step=1000000 tol=0.005
reset damp
*pl bl tem hold
*pl this 1 2 3 4 5 hold
cycle 2500
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 temp=10000 step=1000000 tol=0.005
reset damp
cycle 2500
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
```

```
cycle 2500
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=1.0e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
save tm100f_t1yr.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=5.0e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=8.64e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm100f_t2yr.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=1.728e5  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
sav tm100f_t3yr.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=8.64e5  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm100f_t4yr.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e5  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm100f_t5yr.sav
*
* run thermal time to 7.5 years
```

```
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm100f_t10yr.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 40 years
*
run age=1.26144e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm100f_t50yr.sav
*
* run thermal time to 75  years
*
run age=2.3652e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 5000
pr max
*
* run thermal time to 100  years
```

```
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 5000
save tm100f_t100yr.sav
return
```

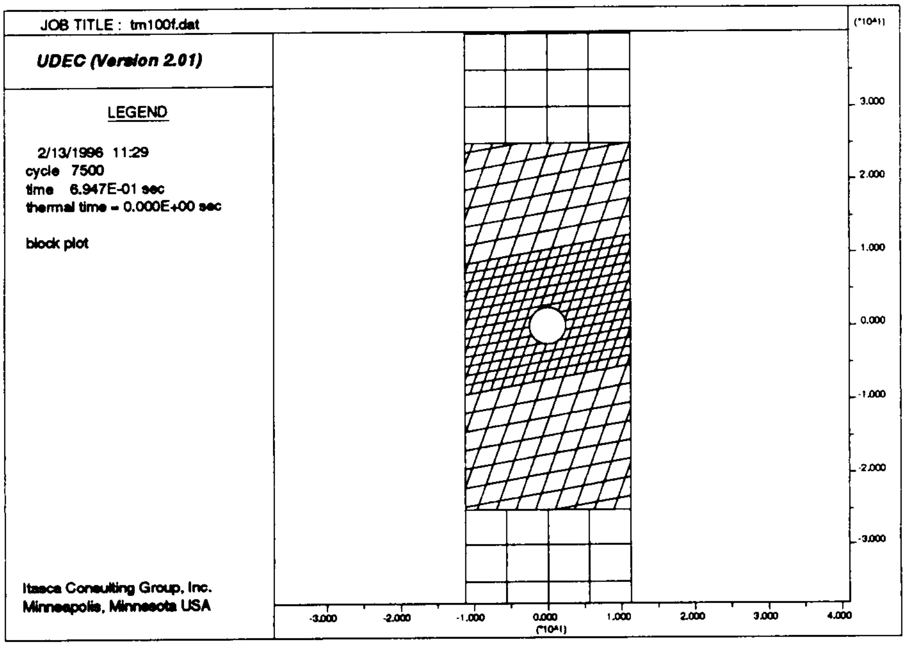

Figure B-1. UDEC discrete element mesh plot - Case TM100F

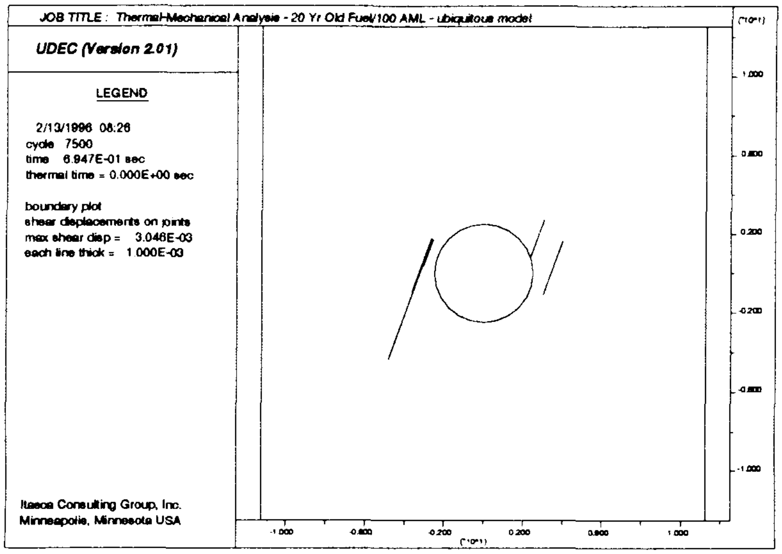

Figure B-2 Joint shear displacements after excavation (maximum = 3.046 mm) - Case TM100F

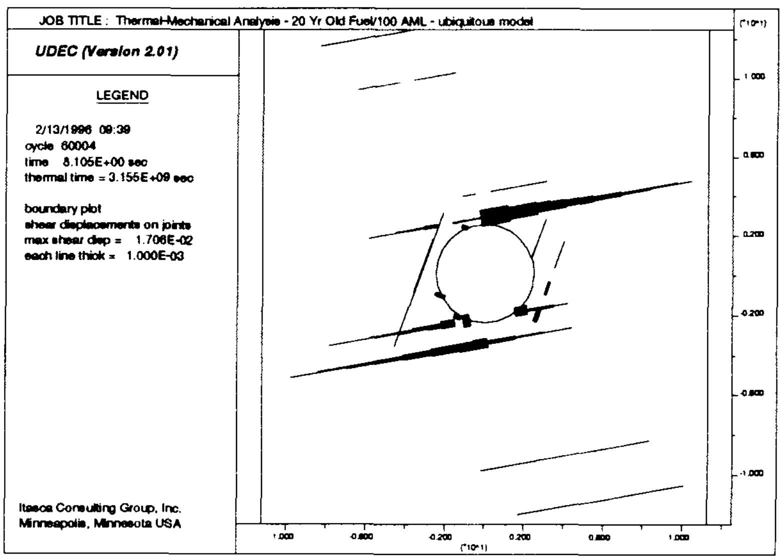

Figure B-3 Joint shear displacements after 100 years (Maximum = 1.706 cm) - Case TM100F

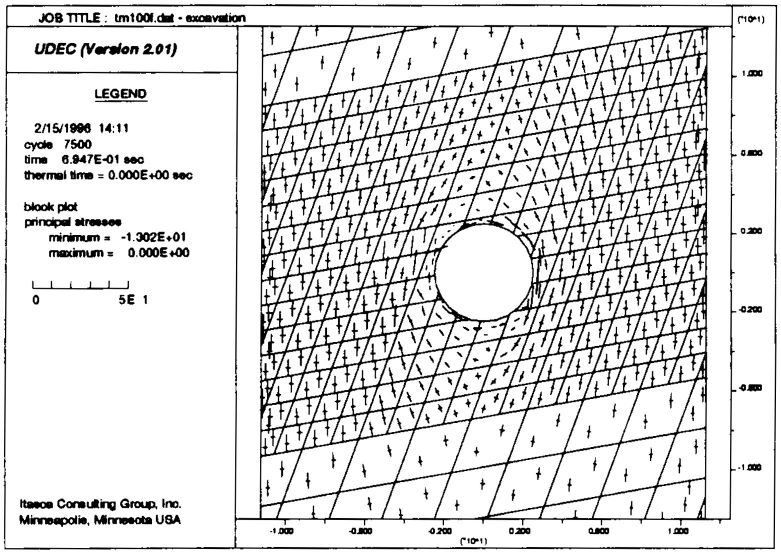

Figure B-4 Principal stress distribution after excavation (maximum= -13.02 MPa) Case Tm100F

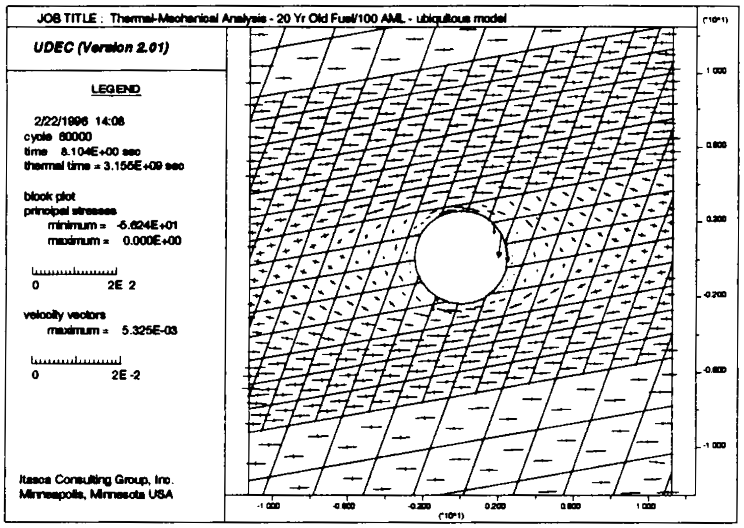

Figure B-5 Principal stress and velocity vectors after 100 years (Maximum stress = 56.24 MPa) Case TM100F

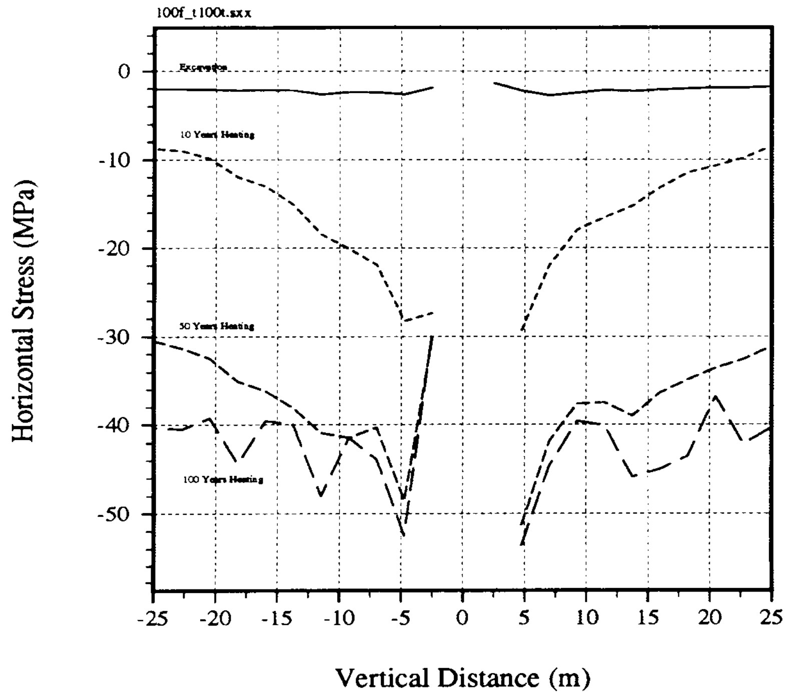

Figure B-6 Horizontal stress along a vertical section through center of tunnel - Case TM100F

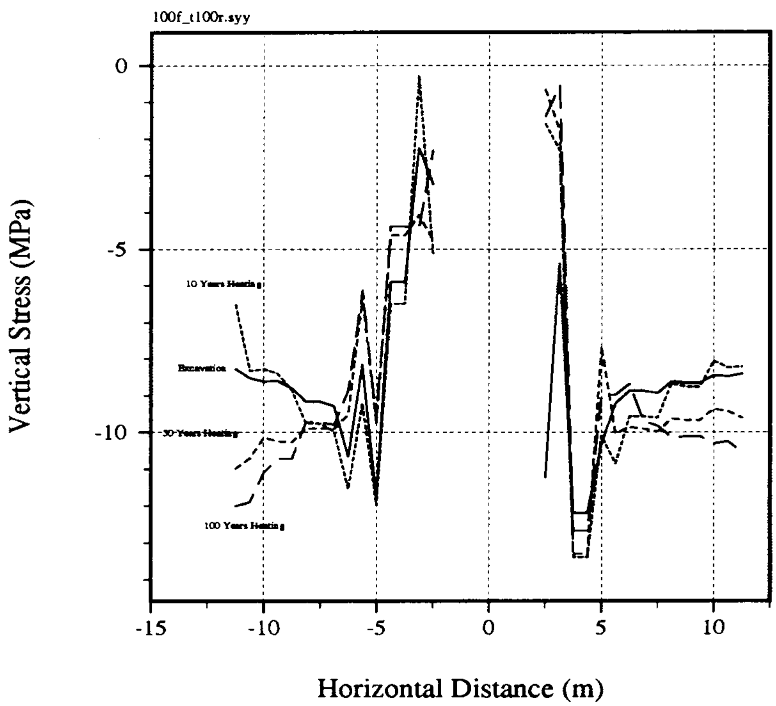

Figure B-7 Vertical stress along horizontal section through center of tunnel - Case TM100F

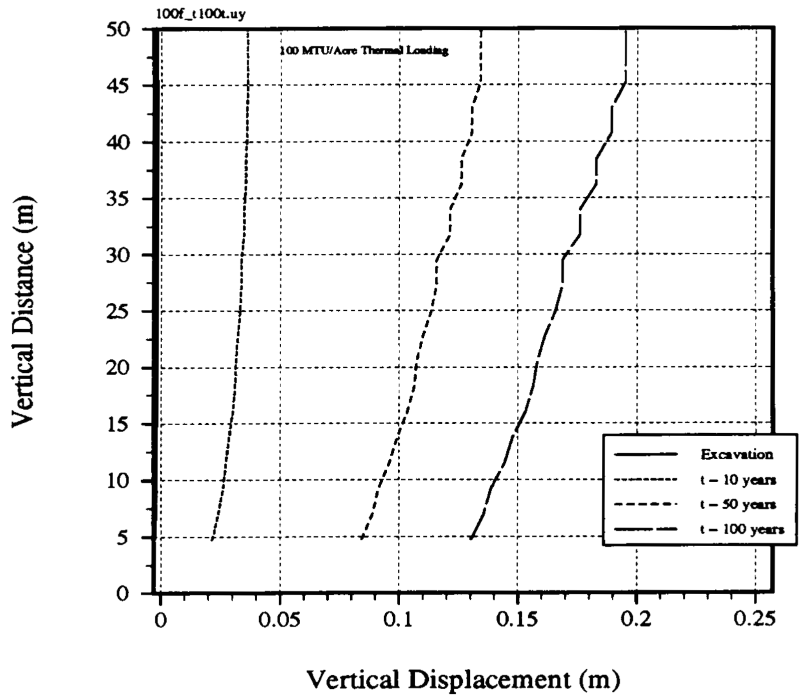

Figure B-8 Vertical expansion with distance at select time periods - Case Tm100F

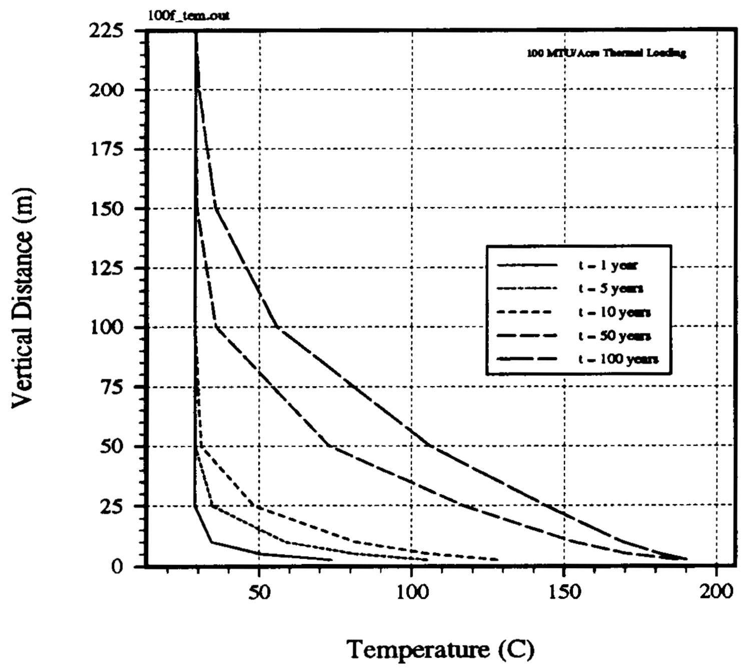

Figure B-9 Temperature with vertical distance above the tunnel roof at select times - Case Tm100F

Table B-1. Temperature at select points above tunnel roof with time - Case TM100F

Time (yrs)	TEMPERATURE (°C)								
	(0,2.5)	(0,5)	(0,10)	(0,25)	(0,50)	(0,100)	(0,150)	(0,200)	(0,225)
0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
1	73.7	50.3	34.4	29.0	29.0	29.0	29.0	29.0	29.0
2	84.8	60.7	41.6	29.6	29.0	29.0	29.0	29.0	29.0
3	92.9	68.7	48.0	30.9	29.0	29.0	29.0	29.0	29.0
4	100.0	75.8	54.1	32.9	29.0	29.0	29.0	29.0	29.0
5	105.0	80.8	58.6	34.8	29.1	29.0	29.0	29.0	29.0
10	128.0	105.0	81.5	48.4	31.0	29.0	29.0	29.0	29.0
50	187.0	170.0	153.0	117.0	73.0	35.8	29.5	29.0	29.0
100	190.0	181.0	169.0	144.0	106.0	55.8	35.6	30.0	29.1

Table B-2. Displacements and stresses at select points around tunnel with time - Case TM100F

Time* (yrs)	TM100F.DAT		TM20F.DAT	
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3.0,0.0)
0	-0.288	0.135	-2.89	-13.53
1	0.0	0.378	-7.29	-16.51
2	0.190	0.533	-8.72	-16.85
3	0.371	0.706	-9.79	-16.82
4	0.531	0.873	-10.61	-16.66
5	0.689	1.046	-11.35	-16.48
10	1.468	1.995	-13.85	-15.55
50	6.491	8.573	-19.99	-11.93
100	10.69	13.36	-20.08	-10.68

* Time after initiation of heating (Time = 0 yr → Excavation)

Appendix C - Case TM20F.DAT

UDEC Input Deck - TM20F.DAT

```
set log on tm20f.log
res tm20f_exc.sav
*****************************************************************
*
* apply decaying heat flux to tunnel wall boundary
*
******************************************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
reset time
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
* apply heat flux to tunnel wall
*
thapp ann 0.0 0.0 2.4 2.56 flux 10.1633 -3.2197e-10
*
* run thermal time to 1 week
*
run age=6.048e5 temp=10000  step=1000000 tol=0.05
reset damp
*pl bl tem hold
*pl this 1 2 3 4 5 hold
cycle 2500
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 temp=10000 step=1000000 tol=0.05
reset damp
cycle 2500
pr max
```

```
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
save tm20f_t6mo.sav
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
save tm20f_t1yr.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t2yr.sav
*
* run thermal time to 3 years
```

```
*
run age=9.4608e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
sav tm20f_t3yr.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t4yr.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t5yr.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t10yr.sav
*
* run thermal time to 15 years
*
run age=4.7304e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 20 years
*
```

```
run age=6.3072e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t20yr.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 40 years
*
run age=1.26144e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 2500
pr max
sav tm20f_t50yr.sav
*
* run thermal time to 75  years
*
run age=2.3652e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 5000
pr max
*
* run thermal time to 100  years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 5000
save tm20f_t100yr.sav
return
****************************************************************
set plot po
start
head
Thermal-Mechanical Analysis - 20 Yr Old Fuel/20 AML - ubiquitous model
```

```
* Data File - **** tm20f.dat ****
*
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  10 degrees ccw from horizontal  - 1.25 m spacing
* 2nd joint set -  70 degrees ccw from horizontal  - 1.25 m spacing
* 3rd joint set -  90 degrees - ubiquitous joint model
**
*
* Size of problem domain is -20<x<20 -222<y<222
*  - Vertical boundaries are located along symmetry lines assuming
*    40 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent
*    of thermal front at 100 years of heating
*
* input block, tunnel, and joint geometry
round 0.025
set ovtol 1.0
block -20 -225 -20 225 20 225 20 -225
split -20 -25 20 -25
split -20  25 20  25
split -20  50 20  50
split -20 -50 20 -50
*
* create jointing
*
** outer problem domain
*
jregion -20 25 -20 50 20 50 20 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -20 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -20 25.0
*
jregion -20 50 -20 225 20 225 20 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -20 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -20 50.0
*
jregion -20 -50 -20 -25 20 -25 20 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -20 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -20 -25.0
*
jregion -20 -225 -20 -50 20 -50 20 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -20 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -20 -50.0
*
** inner problem domain
```

```
*
jregion -20 -25 -20 25 20 25 20 -25
jset 70.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -20 -22
jset 10.0 0.0 50.0 0.0 0.0 0.0 2.5 0.0 -20 -22
*
** detailed jointing around tunnel
*
jregion -20 -12.0 -20 8.0 20 15.0 20 -5.0
jset 70.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -20 -22
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -20 -22
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
gen region -5 -5 -5 5 5 5 5 -5 edge 1.5
gen region -20 -10.0 -20 10.0 20 10.0 20 -10.0 edge 2.75
gen region -20 -25.0 -20 25.0 20 25.0 20 -25.0 edge 5.5
gen region -20 -50.0 -20 50.0 20 50.0 20 -50.0 quad 5.5
gen region -20 -225.0 -20 225.0 20 225.0 20 -225.0 quad 10.5
*
pr max
*
damp auto
*
* apply mechanical boundary conditions (units, MPa)
*
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86  &
zgrad 0.0 0.00599
bound -21 21 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -21 21 -226 -224 yvel=0.0
bound -21 -19 -226 226 xvel=0.0
bound 19 21 -226 226 xvel=0.0
*
* define mechanical and thermal material properties for joints/intact blocks
*
*   material 1 = rock
*
change -21 21 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
zone region -21 -25 -21 25 21 25 21 -25 model ubiquitous b=1.856e4 &
c=2.1 d=25.0 f=49.0 ja=85.0 jc=0.08 jf=38.0 jt=0.04 sh=1.335e4 t=1.05
```

```
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
cycle 3000
save tm20f_insit.sav
win -12.5 12.5 -12.5 12.5
*pl bl st iw hold
*pl hi 5 6 hold
*
* remove tunnel blocks
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4500
*pl bl st iw hold
*pl bl dis iw hold
*pl bou mohr hold
*pl hi 3 hold
*pl hi 5 hold
*pl hi 7 hold
*pl bou sh hold
*
sav tm20f_exc.sav
*******************************************************************
*
* apply decaying heat flux to tunnel wall boundary
*
*******************************************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
```

```
*
* Initial temperature at repository horizon taken to be 29 C
* - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
reset time
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
* apply heat flux to tunnel wall
*
thapp ann 0.0 0.0 2.4 2.56 flux 10.1633 -3.2197e-10
*
* run thermal time to 1 week
*
run age=6.048e5 temp=10000  step=1000000 tol=0.005
reset damp
*pl bl tem hold
*pl this 1 2 3 4 5 hold
cycle 2500
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 temp=10000 step=1000000 tol=0.005
reset damp
cycle 2500
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
```

```
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=3600.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
save tm20f_t1yr.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=7200.0  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t2yr.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=4.32e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
sav tm20f_t3yr.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=4.32e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t4yr.sav
```

```
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e4  temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t5yr.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t10yr.sav
*
* run thermal time to 15 years
*
run age=4.7304e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t20yr.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 40 years
```

```
*
run age=1.26144e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 2500
pr max
sav tm20f_t50yr.sav
*
* run thermal time to 75  years
*
run age=2.3652e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 5000
pr max
*
* run thermal time to 100  years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.005 impl
reset damp
cycle 5000
save tm20f_t100yr.sav
return
```

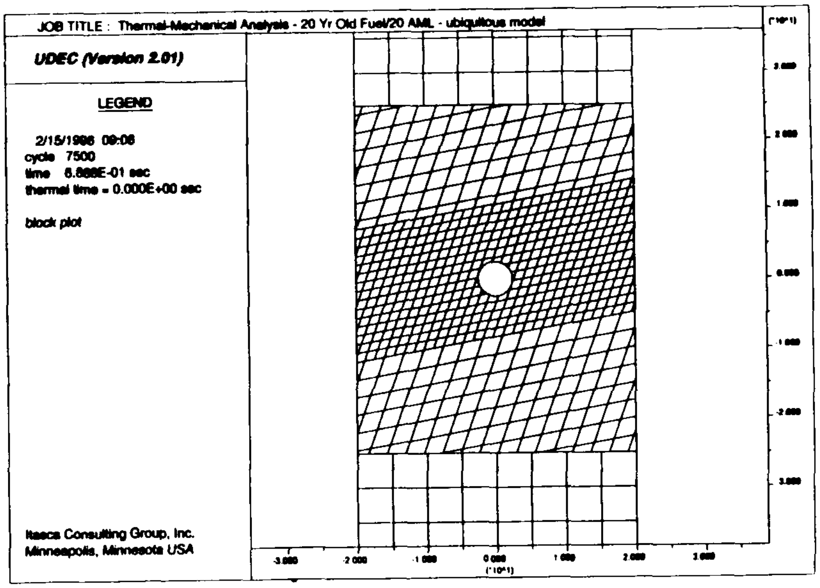

Figure C-1. **UDEC discrete element mesh plot-Case TM20F**

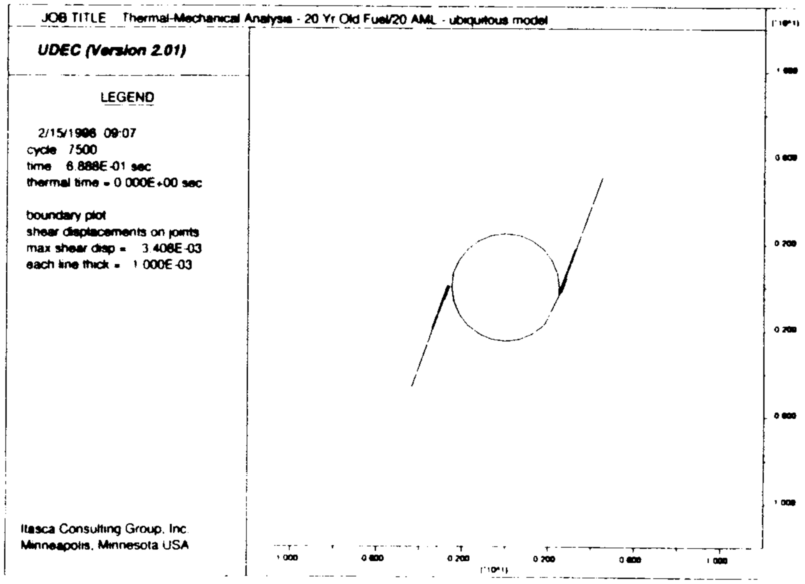

Figure C-2. **Joint shear displacements after excavation (Maximum = 3.046 mm) - Case TM20F**

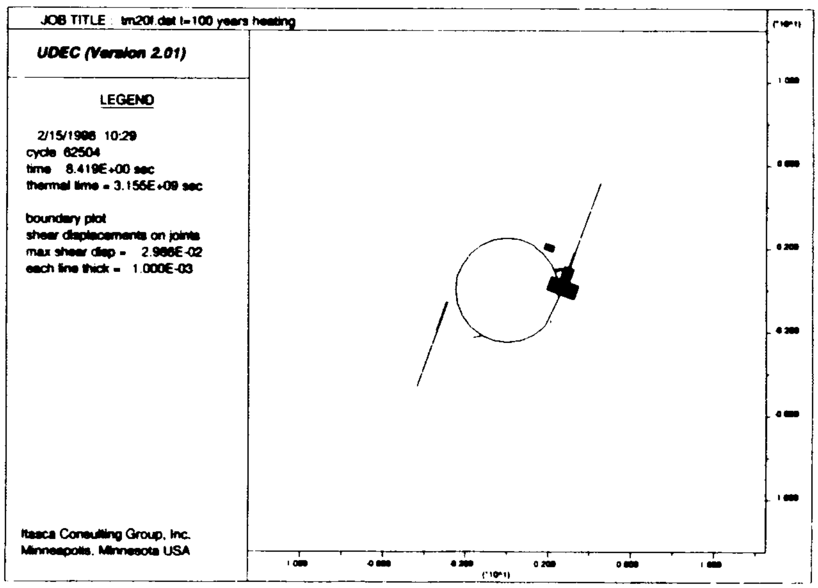

Figure C-3. **Joint shear displacements after 100 years (maximum = 1.706 cm) - Case TM20F**

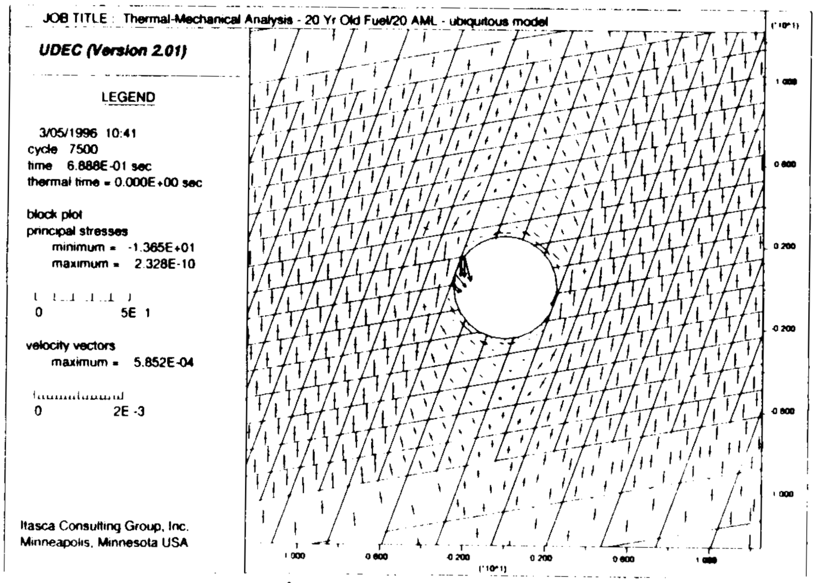

Figure C-4. Principal stress distribution after excavation (maximum = 13.65 MPa) - Case TM20F

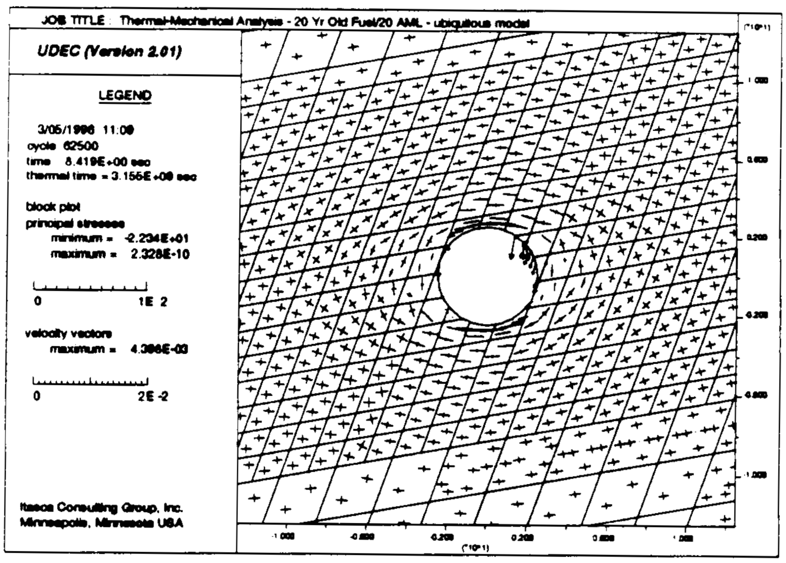

Figure C-5. Principal stress and velocity vectors after 100 years (maximum stress =22.34 MPa) - Case TM20F.

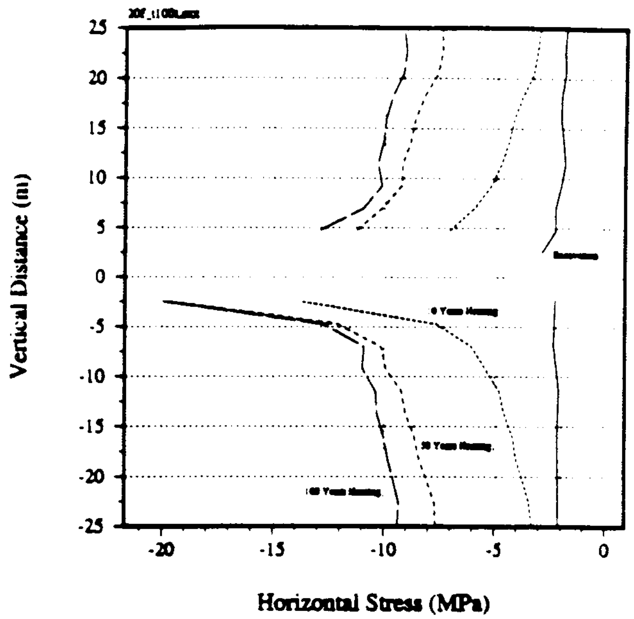

Figure C-6. Horizontal stress along a vertical section through center of tunnel - Case TM20F

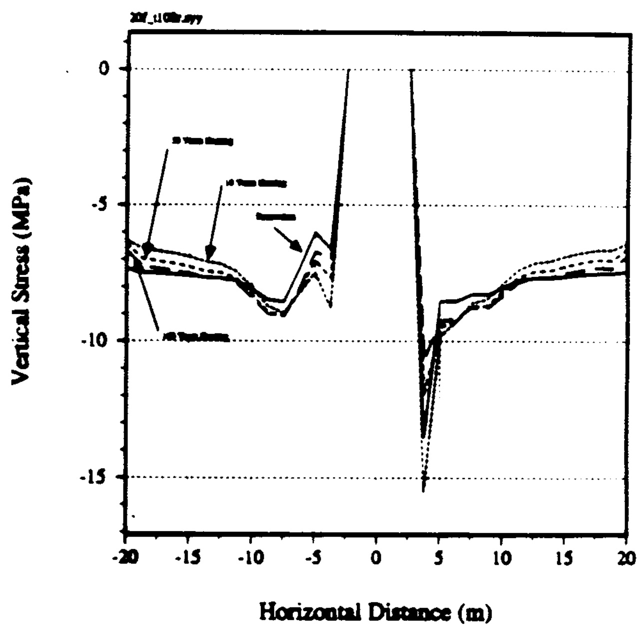

Figure C-7. Vertical stress along horizontal section through center of tunnel - Case TM20F

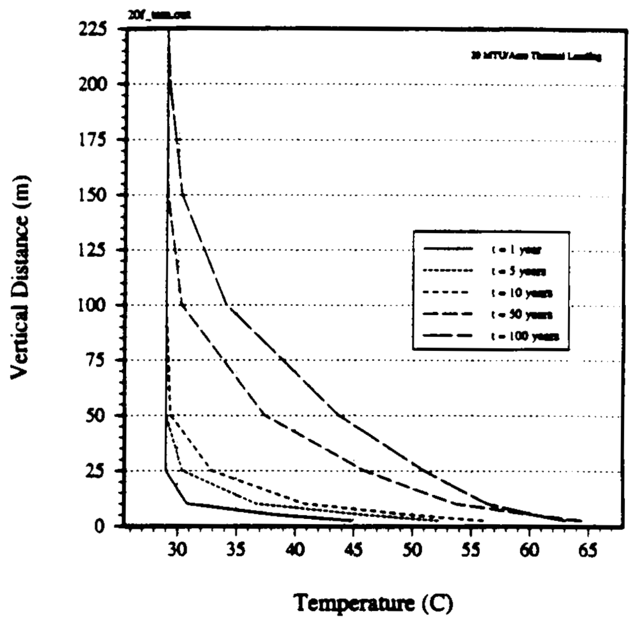

Figure C-8. Vertical expansion with distance at select time periods - Case TM20F

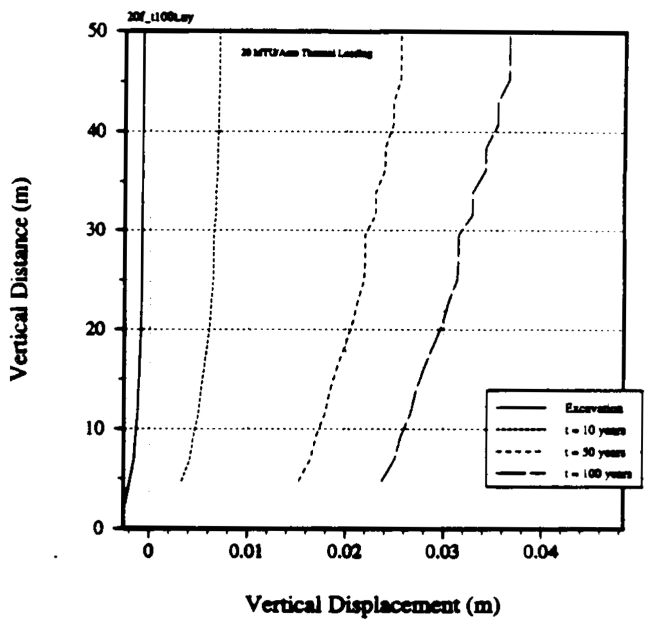

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Figure C-9. Temperature with vertical distance above the tunnel roof at selected times - Case TM20F

Appendix D - Case TM100A.DAT

UDEC Input Deck - TM100A.DAT

```
set log tm100a.log
set plot po
start
************************************************************************
* Title and block definition for AML100 with Lwp=18 m, Ldrift=22.5 m
************************************************************************
head
Case 2 - TM Analysis - 20 Yr Old Fuel/TM100a.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  90 degrees from horizontal - 2.5 m spacing
* 2nd joint set -   0 degrees - 5.0 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4
*
* Size of problem domain is -11.25<x<11.25 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent of thermal front at
*    100 years of heating.
*
round 0.025
set ovtol 1.0
block -11.25 -225 -11.25 225 11.25 225 11.25 -225
split -13 -25 13 -25
split -13  25 13  25
split -13  50 13  50
split -13 -50 13 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -13 25 -13 50 13 50 13 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -13 50 -13 225 13 225 13 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -13 -50 -13 -25 13 -25 13 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
```

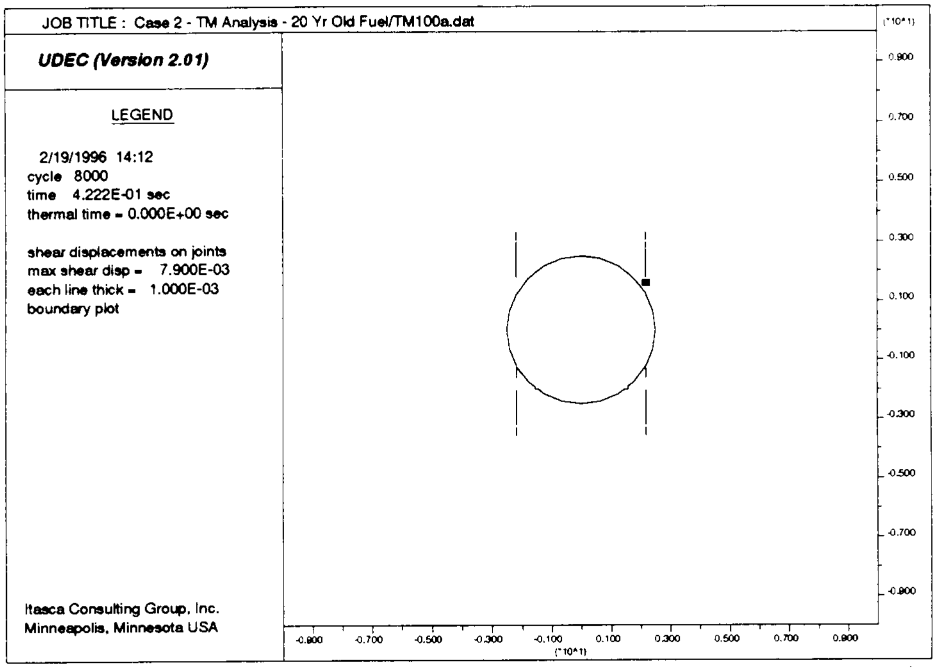
```
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -13 -225 -13 -50 13 -50 13 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ---------------------
*  inner problem domain
* ---------------------
jregion -13 -25 -13 25 13 25 13 -25
jset 90.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 0.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
*
* --------------------------------
*  detailed jointing around tunnel
* --------------------------------
*
jregion -12.5 -10.0 -12.5 10.0 12.5 10.0 12.5 -10.0
jset 90.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 0.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
* ****************************
*  auto generation of zones
* ****************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -11.25 -10.0 -11.25 10.0 11.25 10.0 11.25 -10.0 edge 2.5
gen region -11.25 -25.0 -11.25 25.0 11.25 25.0 11.25 -25.0 edge 5.5
gen region -11.25 -50.0 -11.25 50.0 11.25 50.0 11.25 -50.0 quad 5.5
gen region -11.25 -225.0 -11.25 225.0 11.25 225.0 11.25 -225.0 quad 10.5
*
pr max
*
damp auto
*
****************************************************
* apply mechanical boundary conditions (units, MPa)
****************************************************
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -13 13 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 -226 -224 yvel=0.0
bound -12 -11 -226 226 xvel=0.0
bound 11 12 -226 226 xvel=0.0
*
**************************************************************************
* define mechanical and thermal material properties for joints/intact blocks
```

```
******************************************************************************
*
*   material 1 = rock
*
change -13 13 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
*****************************
* initial cycling equilibrium
*****************************
cycle 4000
save 100a_ini.sav
*
***********************
* remove tunnel blocks
***********************
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 100a_exc.sav
*
************************************
* set thermal boundary and histories
```

```
************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -13 13 -226.0 -224.0
tfix 25.0 -13 13 224.0 226.0
*
print bound
*
initem 29.0 -13 13 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 12.5 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.3 2.54 flux 28.4701 -3.2197e-10
*
* run initial thermal time by explicit scheme for 100 steps
*
run age=3600 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*save 100a_10sd.sav
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
save 100a_1wk.sav
*
* run thermal time to 1 month
*
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
```

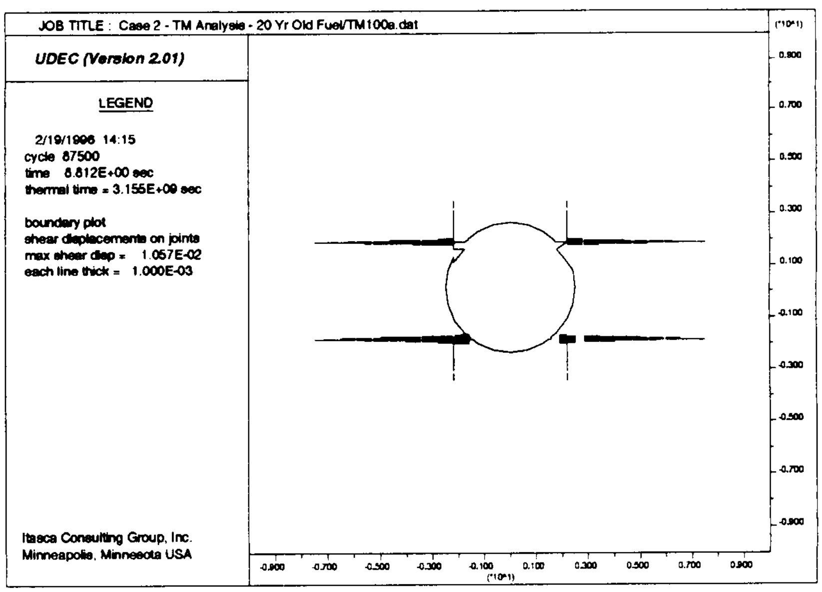
```
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100a_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=5.0e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 100a_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
```

```
cycle 4000
pr max
sav 100a_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_20y.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_40y.sav
*
```



7.90 MAA 3/29/96

Figure D-2. Joint shear displacements after excavation (maximum = ~~3.046~~ 7.90 mm) - Case TM100A



1.057 MPA 3/29/96

Figure D-3. Joint shear displacements after 100 years (Maximum = ~~1.706~~ 1.057 cm) - Case TM100A

```
* run thermal time to 50 years
*
run age=1.5768e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100a_50y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
sav 100a_100.sav
return
```

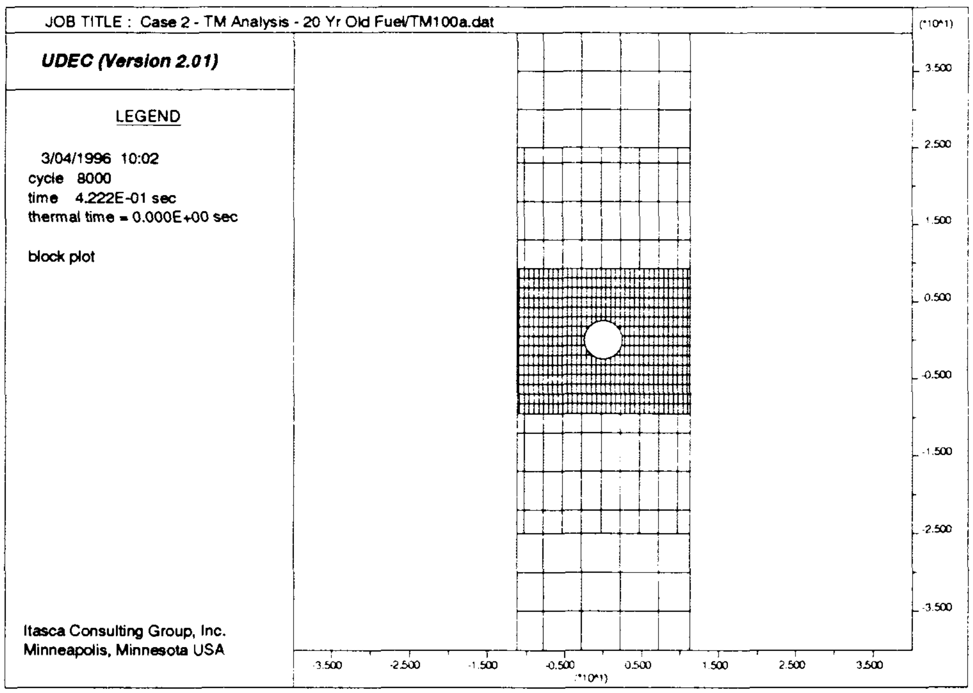
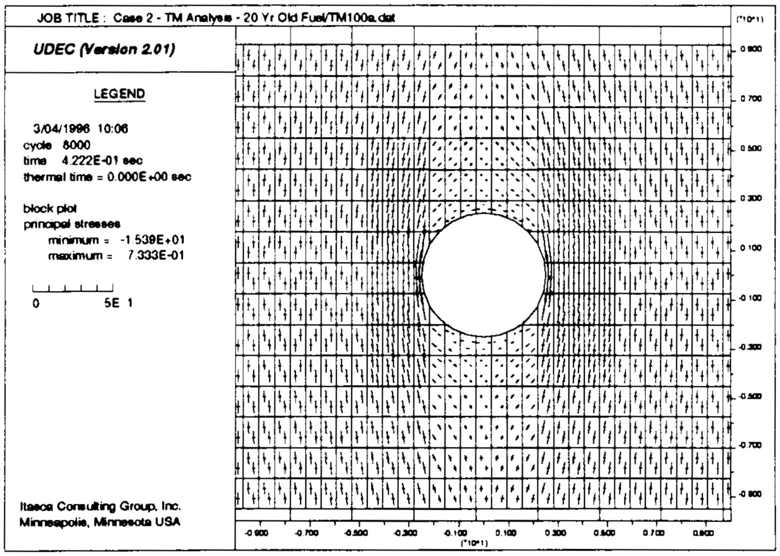
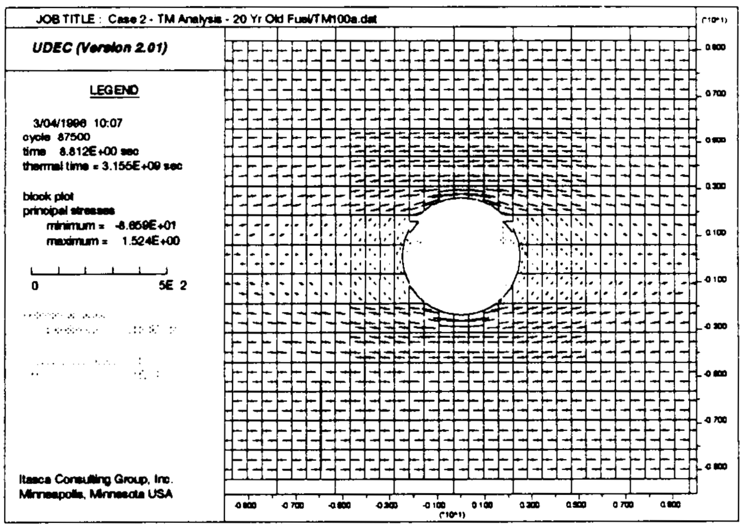


Figure D-1. UDEC discrete element mesh plot - Case TM100A



15.39 MPA 3/29/96

Figure D-4. Principal stress distribution after excavation (maximum= ~~-13.02~~ 15.39 MPa) Case TM100A



MPA 3/29/96

86.59

Figure D-5. Principal stress and velocity vectors after 100 years (Maximum stress = ~~56.24~~ 86.59 MPa) Case TM100A

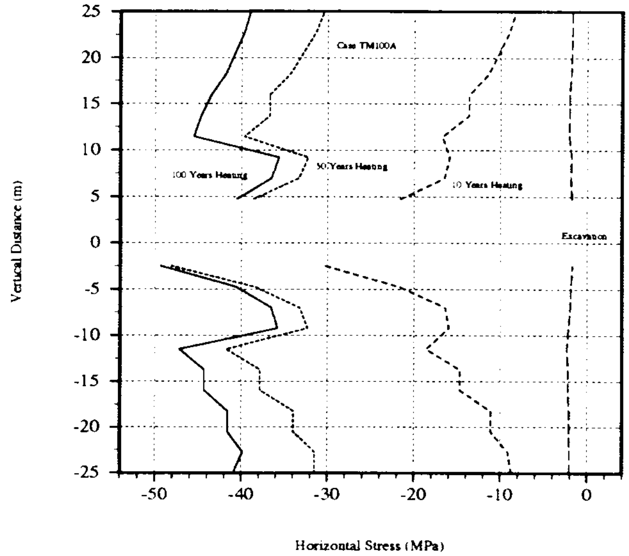


Figure D-6. Horizontal stress along a vertical section through center of tunnel - Case TM100A

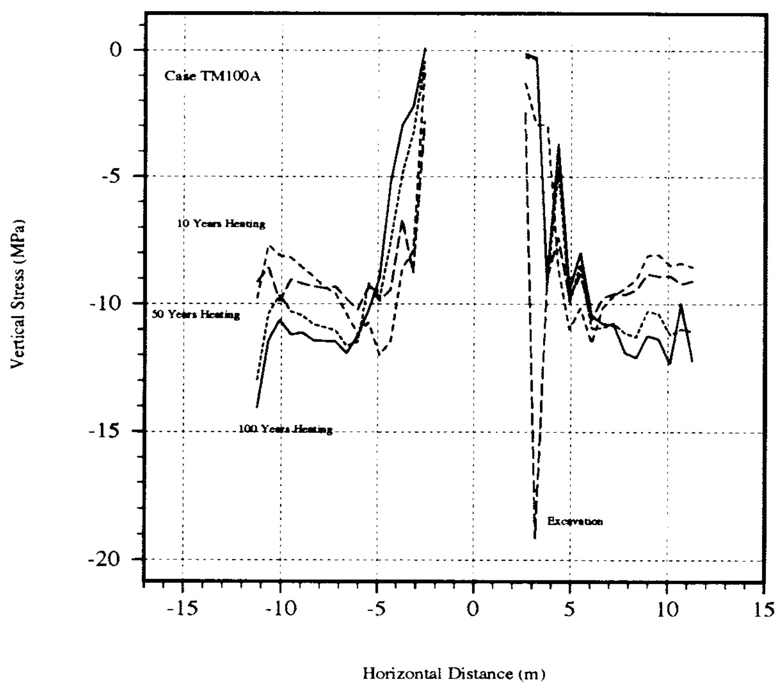


Figure D-7. Vertical stress along horizontal section through center of tunnel - Case TM100A

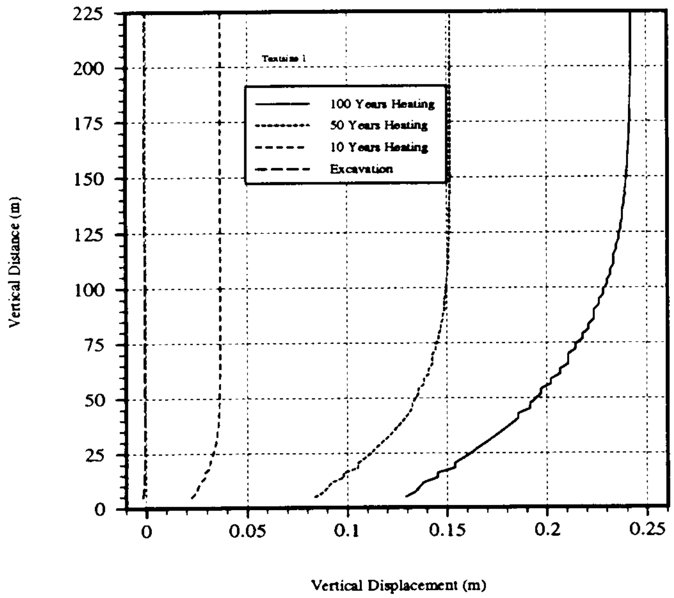


Figure D-8. Vertical expansion with distance at select time periods - Case Tm100A

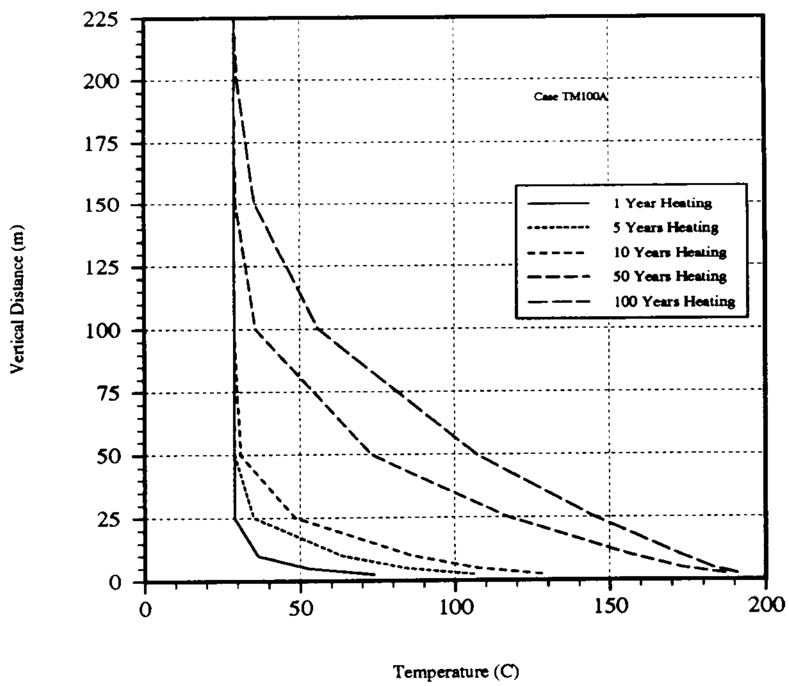


Figure D-9. ~~Vertical displacement at tunnel roof with time~~ - Case TM100A MPA 3/25/96. Temperature with vertical distance above tunnel roof at select times.

Temperature along vertical line above tunnel (x=0.0)
Case TM100A: Time(years) vs y-coord (m)

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y-coord	~~0yr~~ y coord	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3 years	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	100 years
1	2.5	29.0	73.8	84.6	92.9	99.7	106	128	187	191
2	5.0	29.0	52.7	63.1	71.4	78.2	84.4	107	173	183
3	10.0	29.0	36.5	44.4	51.5	57.7	63.5	86.0	157	173
4	25.0	29.0	29.0	29.6	31.0	32.9	35.2	48.4	117	145
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	31.0	73.1	107
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	35.8	55.9
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.5	35.6
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.0
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1

Time (yrs)	TM100A.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3,0,0.0)
0	-0.2325	-0.1552	-1.849	-9.994
1	0.08773	0.3760	-12.59	-13.86
2	0.3314	0.520	-17.08	-13.58
3	0.5653	0.6746	-20.58	-13.25
4	0.7845	0.8277	-23.52	-12.99
5	0.9975	0.9839	-26.08	-12.75
10	2.009	1.792	-35.42	-1[illegible]9
50	8.028	7.345	-57.56	-8.109
100	12.55	11.82	-59.55	-7.534

Appendix E - Case TM100B.DAT

UDEC Input Deck - TM100B.DAT

```
set log tm100b.log
set plot po
start
********************************************************************
* Title and block definition for AML100 with Lwp=18 m, Ldrift=22.5 m
********************************************************************
head
Case 2 - TM Analysis - 20 Yr Old Fuel/TM100b.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees from horizontal - 1.25 m spacing
* 2nd joint set -   0 degrees - 5.0 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4
*
* Size of problem domain is -11.25<x<11.25 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent of thermal front at
*     100 years of heating.
*
round 0.025
set ovtol 1.0
block -11.25 -225 -11.25 225 11.25 225 11.25 -225
split -13 -25 13 -25
split -13  25 13  25
split -13  50 13  50
split -13 -50 13 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -13 25 -13 50 13 50 13 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -13 50 -13 225 13 225 13 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -13 -50 -13 -25 13 -25 13 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
```

```
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -13 -225 -13 -50 13 -50 13 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ----------------------
*  inner problem domain
* ----------------------
jregion -13 -25 -13 25 13 25 13 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
*
* --------------------------------
*  detailed jointing around tunnel
* --------------------------------
*
jregion -12.5 -10.0 -12.5 10.0 12.5 10.0 12.5 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
* ****************************
*  auto generation of zones
* ****************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -11.25 -10.0 -11.25 10.0 11.25 10.0 11.25 -10.0 edge 2.5
gen region -11.25 -25.0 -11.25 25.0 11.25 25.0 11.25 -25.0 edge 4.5
gen region -11.25 -50.0 -11.25 50.0 11.25 50.0 11.25 -50.0 quad 5.5
gen region -11.25 -225.0 -11.25 225.0 11.25 225.0 11.25 -225.0 quad 10.5
*
pr max
*
damp auto
*
****************************************************
* apply mechanical boundary conditions (units, MPa)
****************************************************
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -13 13 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 -226 -224 yvel=0.0
bound -12 -11 -226 226 xvel=0.0
bound 11 12 -226 226 xvel=0.0
*
**************************************************************************
* define mechanical and thermal material properties for joints/intact blocks
```

```
******************************************************************************
*
*   material 1 = rock
*
change -13 13 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.3e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
******************************
* initial cycling equilibrium
******************************
cycle 4000
save 100b_ini.sav
*
************************
* remove tunnel blocks
************************
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 100b_exc.sav
*
*************************************
* set thermal boundary and histories
```

```
*************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -13 13 -226.0 -224.0
tfix 25.0 -13 13 224.0 226.0
*
print bound
*
initem 29.0 -13 13 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.4 2.54 flux 28.4701 -3.2197e-10
*
* run initial thermal time by explicit scheme for 100 steps
*
run age=3600 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*save 100b_10sd.sav
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* save 100b_1wk.sav
*
* run thermal time to 1 month
*
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
* save 100b_1m.sav
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
```

```
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100b_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 100b_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
sav 100b_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_40y.sav
*
```

```
* run thermal time to 50 years
*
run age=1.5768e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100b_50y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
sav 100b_100.sav
return
```

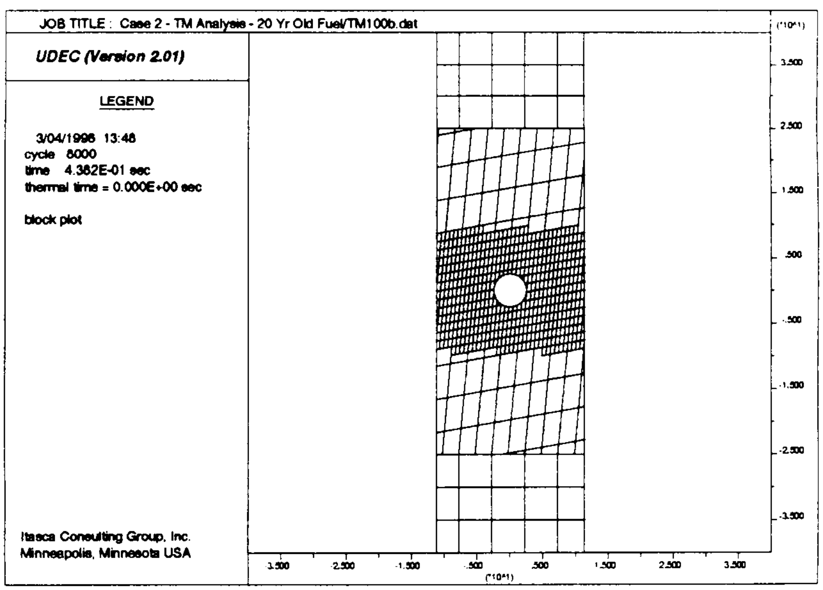

Figure E-1. UDEC discrete element mesh plot - Case TM100B

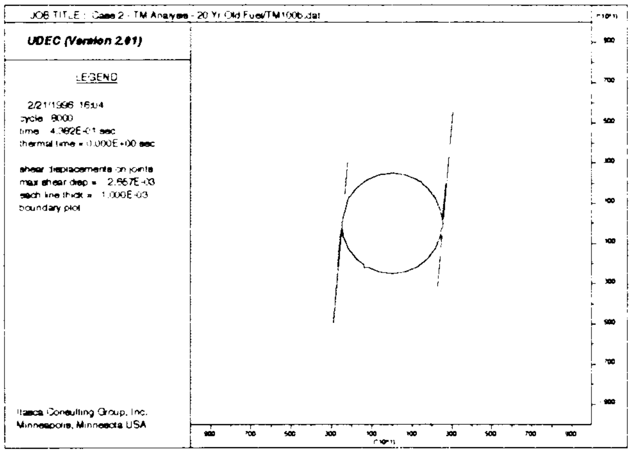

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Figure E-2 Joint shear displacements after excavation (maximum = ~~3.046~~ 2.657 mm) - Case TM100B

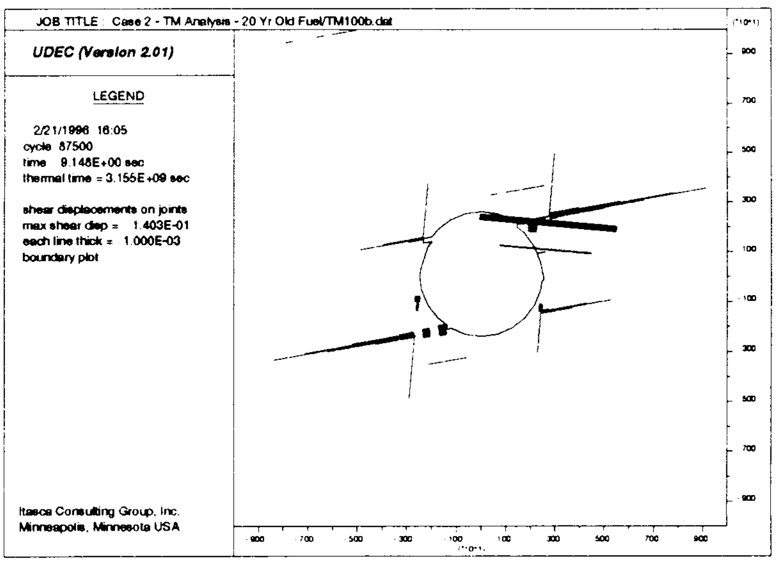

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Figure E-3 Joint shear displacements after 100 years (Maximum = ~~1.706~~ 14.03 cm) - Case TM100B

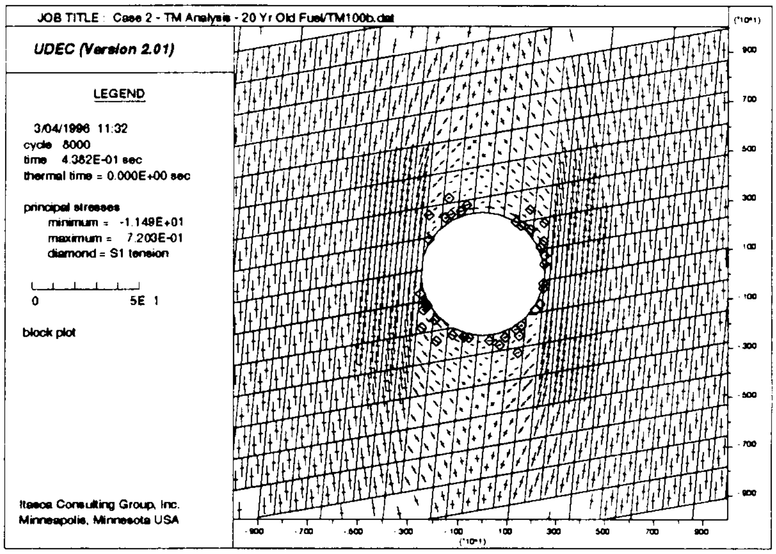

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Figure E-4 Principal stress distribution after excavation (maximum= ~~-13.02~~ 11.49 MPa) Case TM100B

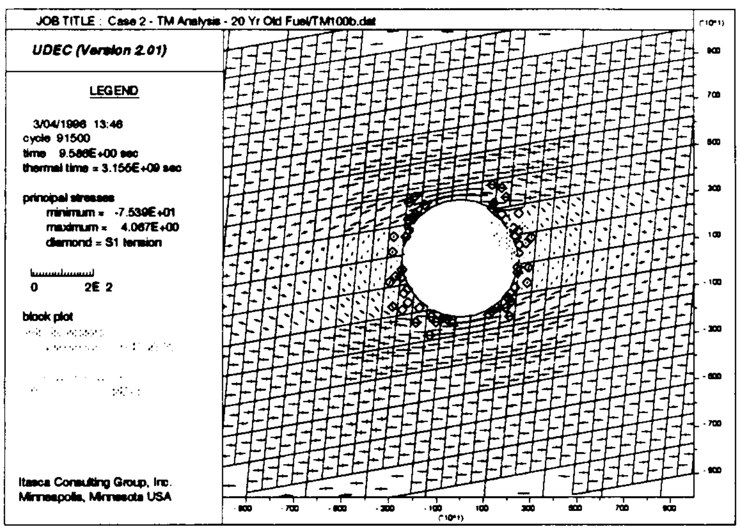

Figure E-5 Principal stress and velocity vectors after 100 years (Maximum stress = ~~56.24~~ 75.39 MPa) Case TM100B

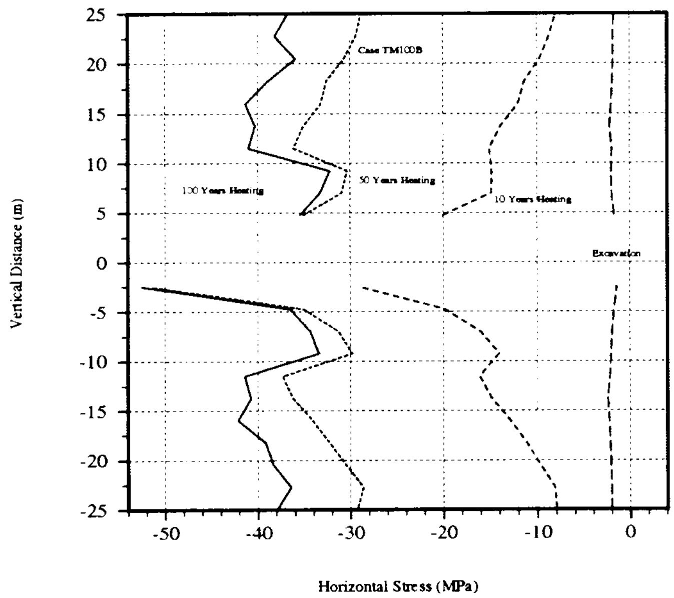

Figure E-6 Horizontal stress along a vertical section through center of tunnel - Case TM100B

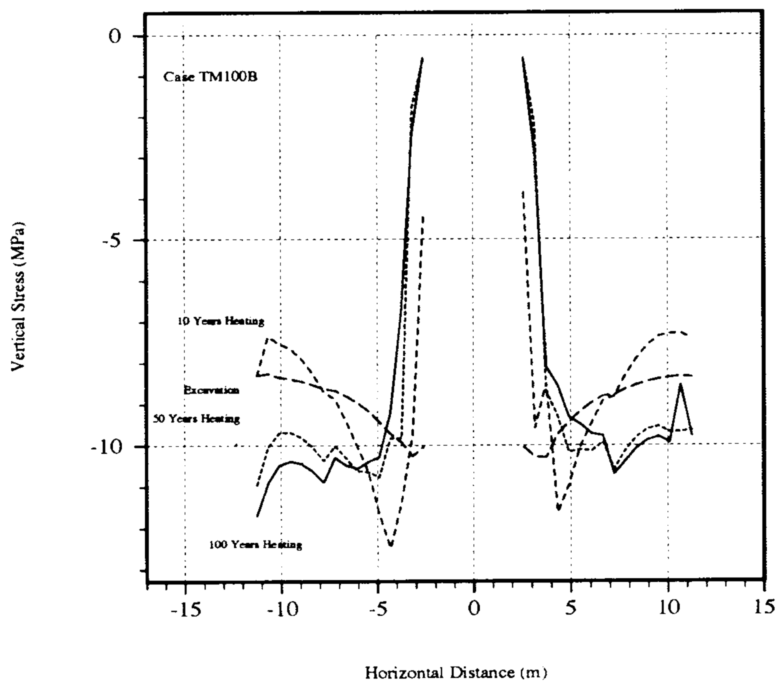

Figure E-7 Vertical stress along horizontal section through center of tunnel - Case TM100B

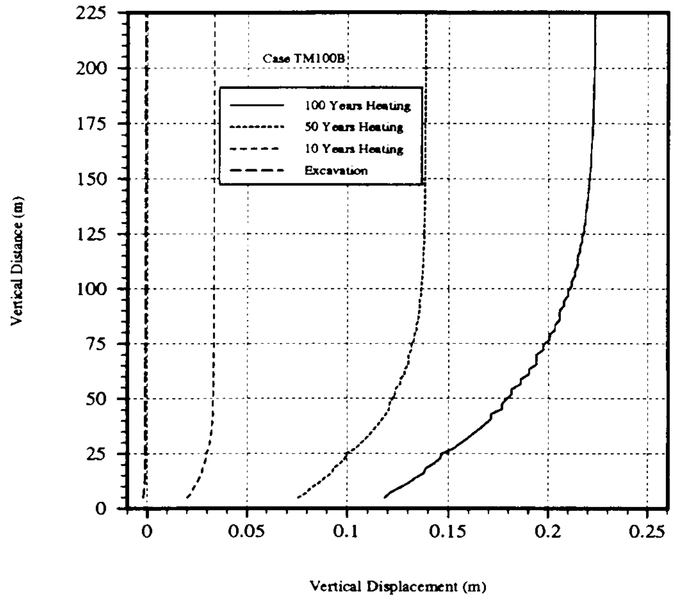

Figure E-8 Vertical expansion with distance at select time periods - Case Tm100B

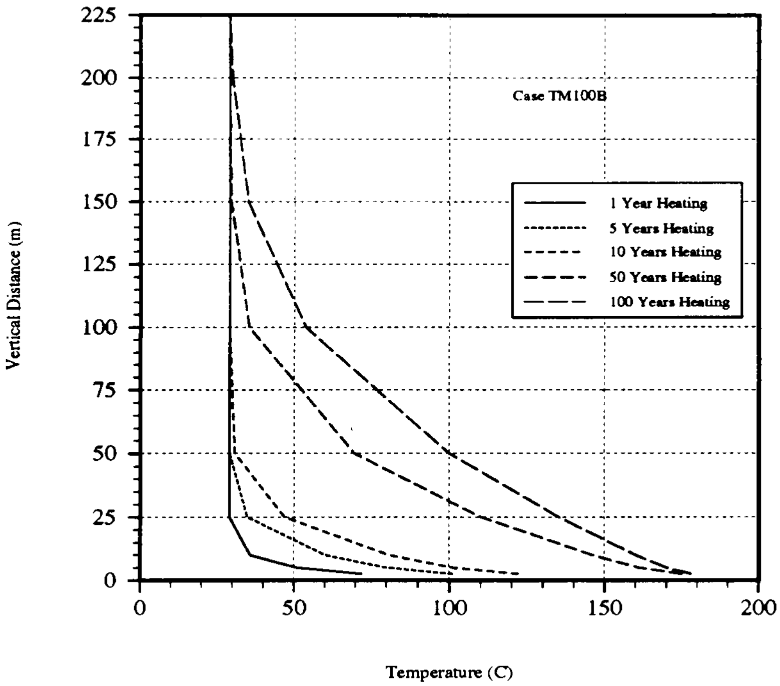

Figure E-9 ~~Vertical displacement at tunnel roof with time~~ - Case TM100B

Temperature with ~~time~~ ~~at~~ ~~a~~ vertical distance above roof at select times. MPA

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Temperature along vertical line above tunnel (x=0.0)
Case TM100B: Time(years) vs y-coord (m)

y-coord	~~0yr~~	~~1~~ 0	~~2~~ 1	years ~~3~~ 2	~~4~~ 3	~~8~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	100 years
1	2.5	29.0	71.9	82.0	89.5	95.8	101	122	175	178
2	5.0	29.0	50.9	60.6	68.1	74.3	80.0	101	161	170
3	10.0	29.0	35.8	43.0	49.3	54.9	60.1	80.7	146	160
4	25.0	29.0	29.0	29.6	30.8	32.6	34.8	46.9	110	135
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	30.8	69.6	100
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	35.3	53.7
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.5	35.0
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.9
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1

Time (yrs)	TM100B.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3.0,0.0)
0	-0.2645	-01652	-1.628	-10.04
1	0.01966	0.3756	-10.60	-12.27
2	0.2407	0.5066	-14.44	-10.69
3	0.4518	0.6469	-17.45	-9.328
4	0.6512	0.7883	-20.14	-8.77
5	0.8455	0.9326	-22.75	-7.196
10	1.761	1.676	-32.62	-3.862
50	7.205	6.732	-57.01	-0.5492
100	11.48	10.93	-58.96	-0.5591

Appendix F - Case TM100C.DAT

UDEC Input Deck - TM100C.DAT

```
TM100C.DAT
set log tm100c.log
set plot po
start
***********************************************************************
* Title and block definition for AML100 with Lwp=18 m, Ldrift=22.5 m
***********************************************************************
head
Case 2 - TM Analysis - 20 Yr Old Fuel/TM100c.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees from horizontal - 2.5 m spacing
* 2nd joint set -  10 degrees - 5.0 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4
*
* Size of problem domain is -11.25<x<11.25 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent of thermal front at
*    100 years of heating.
*
round 0.025
set ovtol 1.0
block -11.25 -225 -11.25 225 11.25 225 11.25 -225
split -13 -25 13 -25
split -13  25 13  25
split -13  50 13  50
split -13 -50 13 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -13 25 -13 50 13 50 13 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -13 50 -13 225 13 225 13 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
```

```
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -13 -50 -13 -25 13 -25 13 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -13 -225 -13 -50 13 -50 13 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ----------------------
*  inner problem domain
* ----------------------
jregion -13 -25 -13 25 13 25 13 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25
*
* --------------------------------
*  detailed jointing around tunnel
* --------------------------------
*
jregion -12.5 -10.0 -12.5 10.0 12.5 10.0 12.5 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
* ****************************
*  auto generation of zones
* ****************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -11.25 -10.0 -11.25 10.0 11.25 10.0 11.25 -10.0 edge 2.5
gen region -11.25 -25.0 -11.25 25.0 11.25 25.0 11.25 -25.0 edge 5.5
gen region -11.25 -50.0 -11.25 50.0 11.25 50.0 11.25 -50.0 quad 5.5
gen region -11.25 -225.0 -11.25 225.0 11.25 225.0 11.25 -225.0 quad 10.5
*
pr max
*
damp auto
*
****************************************************
* apply mechanical boundary conditions (units, MPa)
****************************************************
```

```
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 -226 -224 yvel=0.0
bound -12 -11 -226 226 xvel=0.0
bound 11 12 -226 226 xvel=0.0
*
**************************************************************************
* define mechanical and thermal material properties for joints/intact blocks
**************************************************************************
*
*   material 1 = rock
*
change -13 13 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
******************************
* initial cycling equilibrium
******************************
cycle 4000
save 100c_ini.sav
*
************************
* remove tunnel blocks
************************
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
```

```
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 100c_exc.sav
*
*************************************
* set thermal boundary and histories
*************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -13 13 -226.0 -224.0
tfix 25.0 -13 13 224.0 226.0
*
print bound
*
initem 29.0 -13 13 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.4 2.58 flux 28.4701 -3.2197e-10
*
* run initial thermal time by explicit scheme for 100 steps
*
run age=7200 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
cycle 4000
```

```
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100c_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
```

```
run age=6.3072e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100c_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 100c_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100c_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100c_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100c_10y.sav
*
* run thermal time to 20 years
*
```

```
run age=6.3072e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100c_20y.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100c_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100c_40y.sav
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100c_50y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
sav 100c_100.sav
return
```

TM100C1.DAT

```
set log tm100c1.log
set plot po
start
* rerun tm100c.log from 100c_50y to 100 years
res 100c_50y.sav
*
* run thermal time to 100 years
```

```
*
run age=3.1536e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
sav 100c_100.sav
return
```

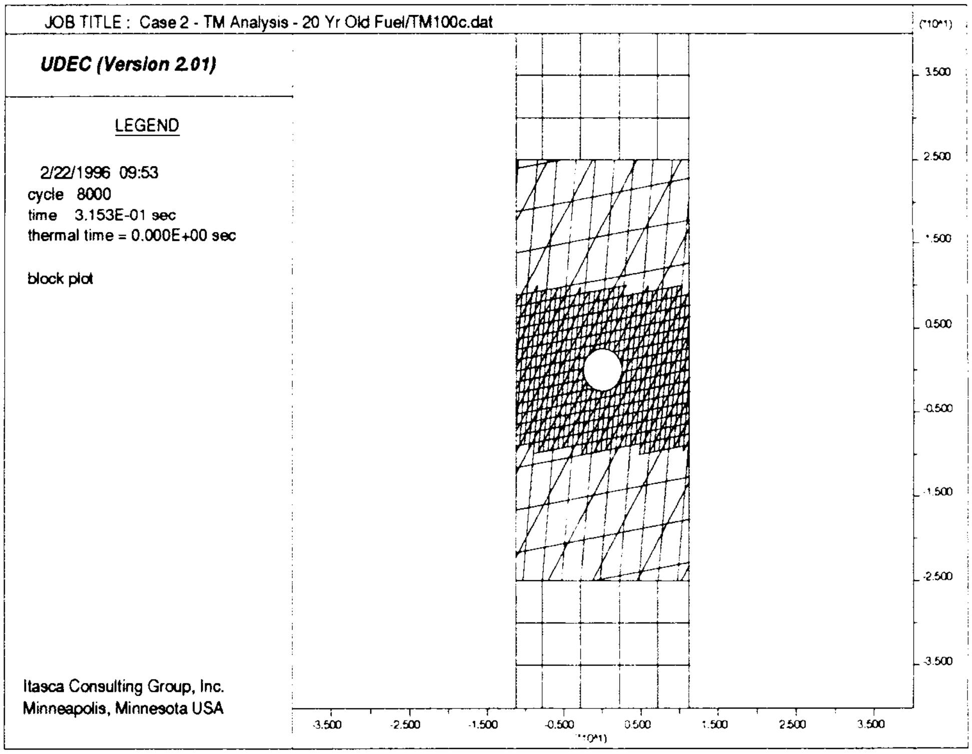

Figure F-1. UDEC discrete element mesh plot - Case TM100C

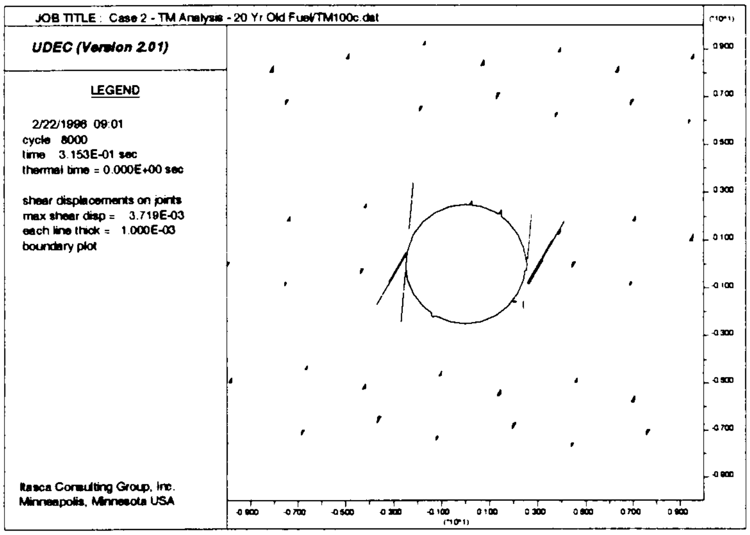

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Figure F-2 Joint shear displacements after excavation (maximum = ~~3.046~~ 3.719 mm) - Case TM100C

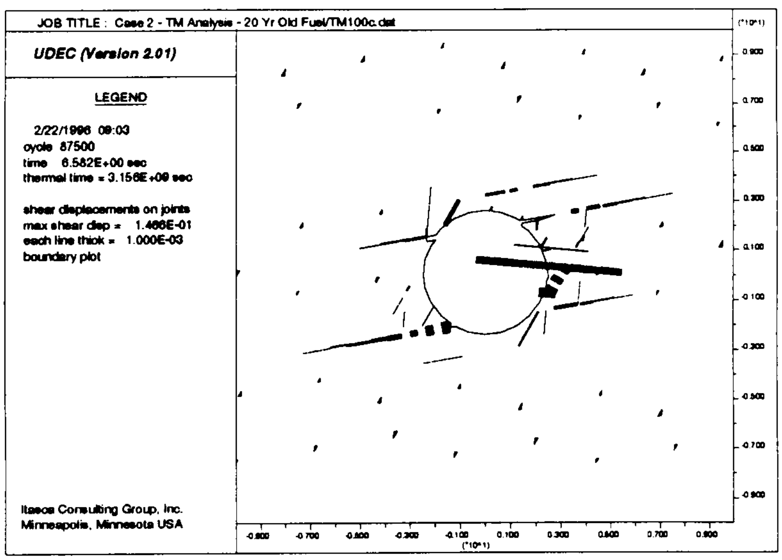

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Figure F-3 Joint shear displacements after 100 years (Maximum = ~~1.706~~ 14.66 cm) - Case TM100C

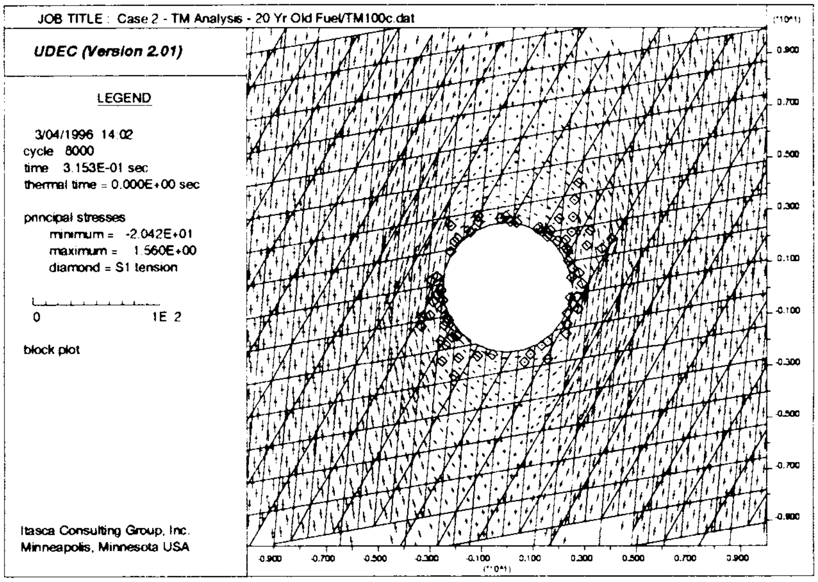

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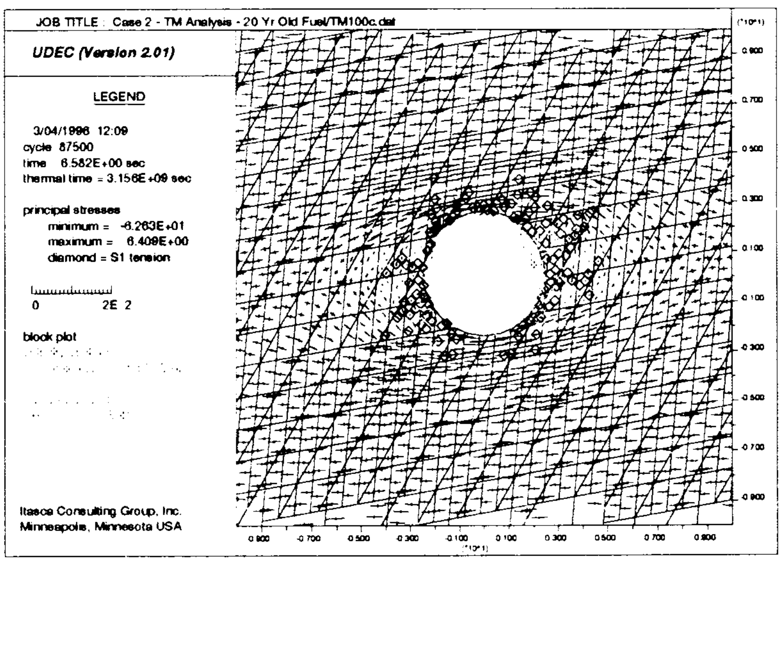
Figure F-4 Principal stress distribution after excavation (maximum= ~~13.02~~ MPa) Case TM100C



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62.03

Figure F-5 Principal stress and velocity vectors after 100 years (Maximum stress = ~~56.24~~ MPa) Case TM100C

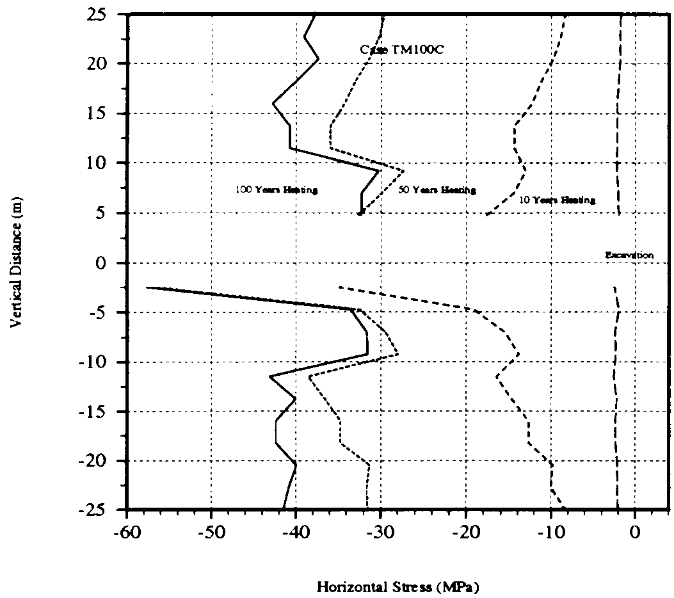

Figure F-6 Horizontal stress along a vertical section through center of tunnel - Case TM100C

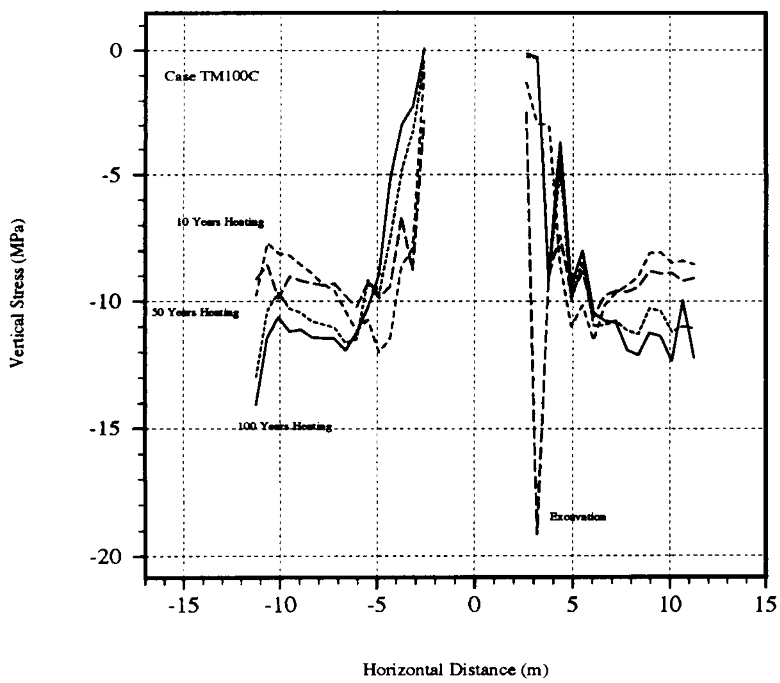

Figure F-7 Vertical stress along horizontal section through center of tunnel - Case TM100C

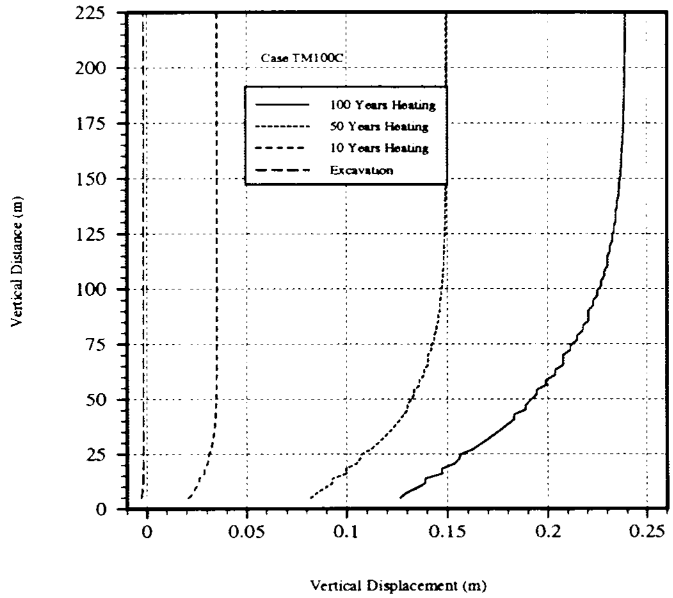

Figure F-8 Vertical expansion with distance at select time periods - Case Tm100C

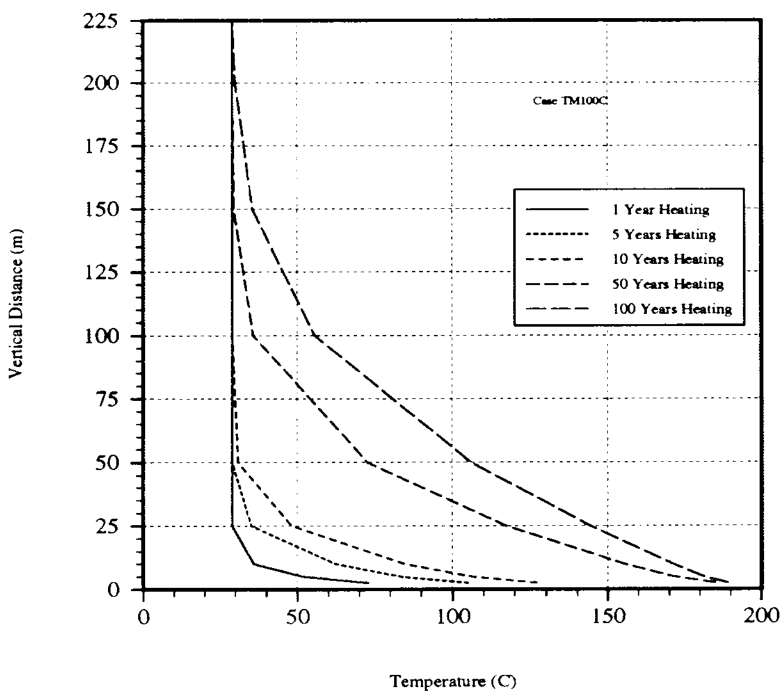

Figure F-9 ~~Vertical displacement at tunnel roof with time - C~~ase TM100C
Temperature with vertical distance above tunnel roof at select times

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Temperature along vertical line above tunnel (x=0.0)
Case TM100C: Time(years) vs y-coord (m)

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Years

y-coord	0yr	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	~~years~~ 100
1	2.5	29.0	73.0	83.7	91.9	98.7	105	127	185	189
2	5.0	29.0	51.9	62.3	70.3	77.2	83.2	106	171	181
3	10.0	29.0	36.0	43.8	50.6	56.7	62.3	84.6	155	171
4	25.0	29.0	29.0	29.6	31.0	32.9	35.2	48.2	117	144
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	31.0	72.7	106
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	35.8	55.6
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.5	35.5
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.0
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1

Time (yrs)	TM100C.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3.0,0.0)
0	-0.3443	-0.1580	-2.188	-19.17
1	-0.0385	0.3883	-7.407	-25.66
2	0.1991	0.5324	-9.958	-26.02
3	0.4288	0.6888	-11.97	-26.05
4	0.6399	0.8395	-14.11	-25.94
5	0.8445	0.9933	-15.91	-25.73
10	1.826	1.803	-22.65	-24.68
50	7.741	7.352	-42.86	-1.594
100	12.17	11.17	-45.28	-0.1110

Appendix G - Case TM100D.DAT

UDEC Input Deck - TM100D.DAT

```
TM100D.DAT
set log tm100d.log
set plot po
start
*********************************************************************
* Title and block definition for AML100 with Lwp=18 m, Ldrift=22.5 m
*********************************************************************
head
Case 2 - TM Analysis - 20 Yr Old Fuel/TM100d.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees from horizontal - 1.25 m spacing
* 2nd joint set -  10 degrees - 5.0 m spacing
* 3rd joint set - 60 degrees - 5.0 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4
*
* Size of problem domain is -11.25<x<11.25 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent of thermal front at
*    100 years of heating.
*
round 0.03
set ovtol 1.0
block -11.25 -225 -11.25 225 11.25 225 11.25 -225
split -13 -25 13 -25
split -13  25 13  25
split -13  50 13  50
split -13 -50 13 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -13 25 -13 50 13 50 13 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -13 50 -13 225 13 225 13 50
```

```
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -13 -50 -13 -25 13 -25 13 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -13 -225 -13 -50 13 -50 13 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ----------------------
*  inner problem domain
* ----------------------
jregion -13 -25 -13 25 13 25 13 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25
*
* ---------------------------------
*  detailed jointing around tunnel
* ---------------------------------
*
jregion -12.5 -10.0 -12.5 10.0 12.5 10.0 12.5 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
* ****************************
*  auto generation of zones
* ****************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -11.25 -10.0 -11.25 10.0 11.25 10.0 11.25 -10.0 edge 2.5
gen region -11.25 -25.0 -11.25 25.0 11.25 25.0 11.25 -25.0 edge 4.3
gen region -11.25 -50.0 -11.25 50.0 11.25 50.0 11.25 -50.0 quad 5.5
gen region -11.25 -225.0 -11.25 225.0 11.25 225.0 11.25 -225.0 quad 10.5
*
pr max
*
damp auto
*
*****************************************************
* apply mechanical boundary conditions (units, MPa)
```

```
*****************************************************
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -13 13 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -13 13 -226 -224 yvel=0.0
bound -12 -11 -226 226 xvel=0.0
bound 11 12 -226 226 xvel=0.0
*
******************************************************************************
* define mechanical and thermal material properties for joints/intact blocks
******************************************************************************
*
*   material 1 = rock
*
change -13 13 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
******************************
* initial cycling equilibrium
******************************
cycle 4000
save 100d_ini.sav
*
************************
* remove tunnel blocks
************************
*
del ann 0 0 0 2.5
```

```
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 100d_exc.sav
*
*************************************
* set thermal boundary and histories
*************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -13 13 -226.0 -224.0
tfix 25.0 -13 13 224.0 226.0
*
print bound
*
initem 29.0 -13 13 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 11.25 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.4 2.56 flux 28.4701 -3.2197e-10
*
*
* run initial thermal time by explicit scheme for 100 steps
*
run age=3600 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
```

```
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100d_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 100d_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
sav 100d_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 100d_20y.sav
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_40y.sav
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
sav 100d_50y.sav
*
* run thermal time to 60 years
run age=1.89216e9 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
* sav 100d_60.sav
*
* run thermal time to 70 years
*
run age=2.20752e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 5000
pr max
* sav 100d_70.sav
*
* run thermal time to 80 years
*
run age=2.52288e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
* sav 100d_80.sav
*
* run thermal time to 90 years
*
run age=2.83824e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
* sav 100d_90.sav
*
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_100.sav
return
```

TM100D1.DAT

```
set log tm100d1.log
set plot po
start
res 100d_50y.sav
*
* run thermal time to 60 years
run age=1.89216e9 delt=1.3e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_60.sav
*
* run thermal time to 70 years
*
run age=2.20752e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 5000
pr max
sav 100d_70.sav
*
* run thermal time to 80 years
*
run age=2.52288e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_80.sav
*
* run thermal time to 90 years
*
run age=2.83824e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_90.sav
*
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=2.61e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 100d_100.sav
return
```

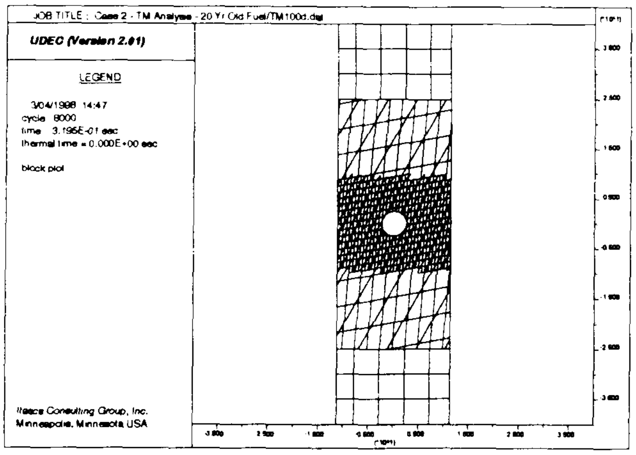
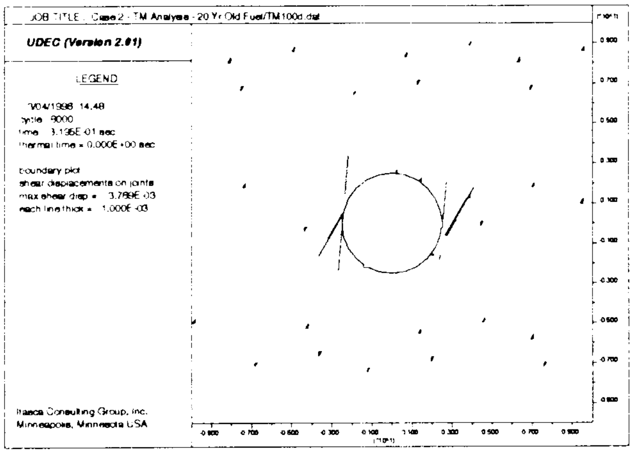
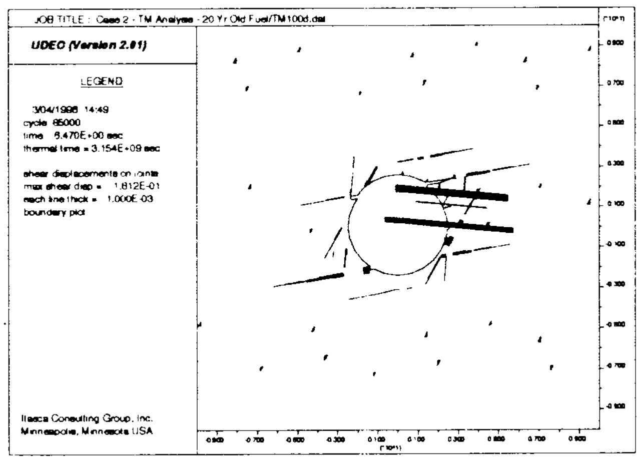


Figure G-1. UDEC discrete element mesh plot - Case TM100D



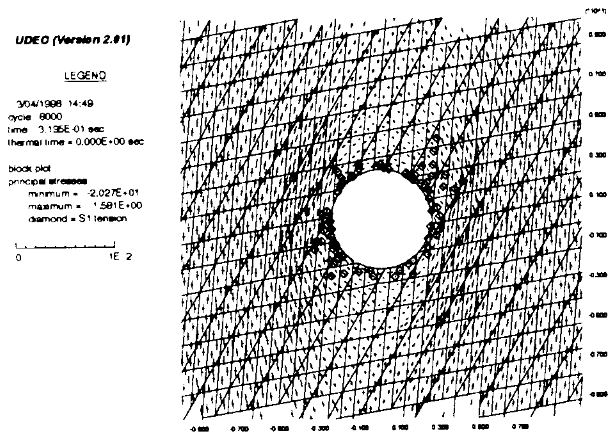
MPA 3/29/96

Figure G-2 Joint shear displacements after excavation (maximum = ~~3.046~~ 3.769 mm) - Case TM100D



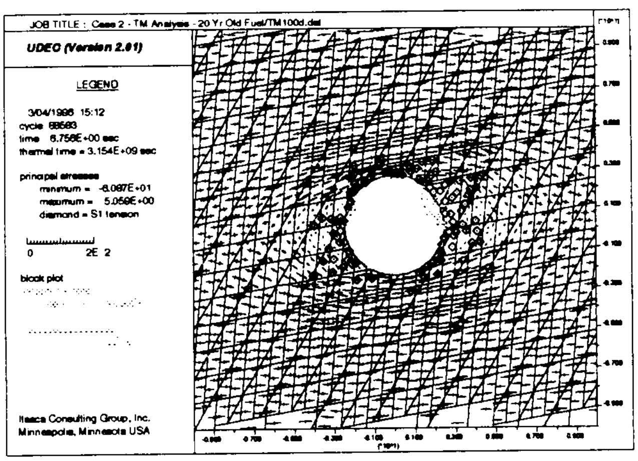
MPA 3/29/96

Figure G-3 Joint shear displacements after 100 years (Maximum = ~~1.706~~ 16.12 cm) - Case TM100D



MPA 3/29/96

Figure G-4 Principal stress distribution after excavation (maximum= ~~-13.02~~ 20.27 MPa) Case TM100D



MPA 3/29/96

Figure G-5 Principal stress and velocity vectors after 100 years (Maximum stress = ~~56.24~~ 60.87 MPa) Case TM100D

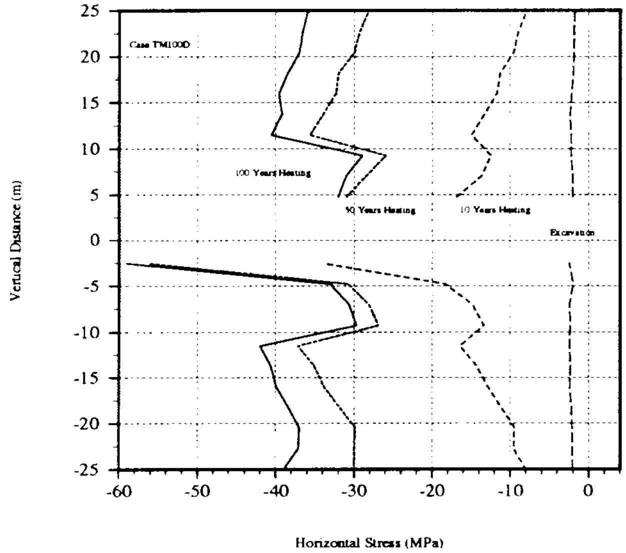


Figure G-6 Horizontal stress along a vertical section through center of tunnel - Case TM100D

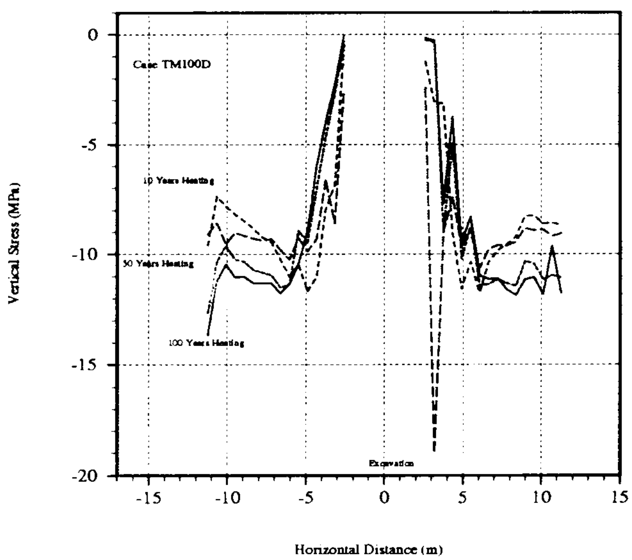


Figure G-7 Vertical stress along horizontal section through center of tunnel - Case TM100D

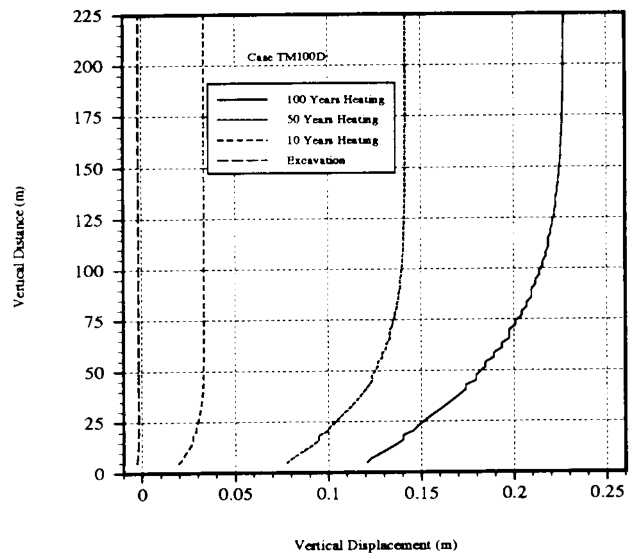
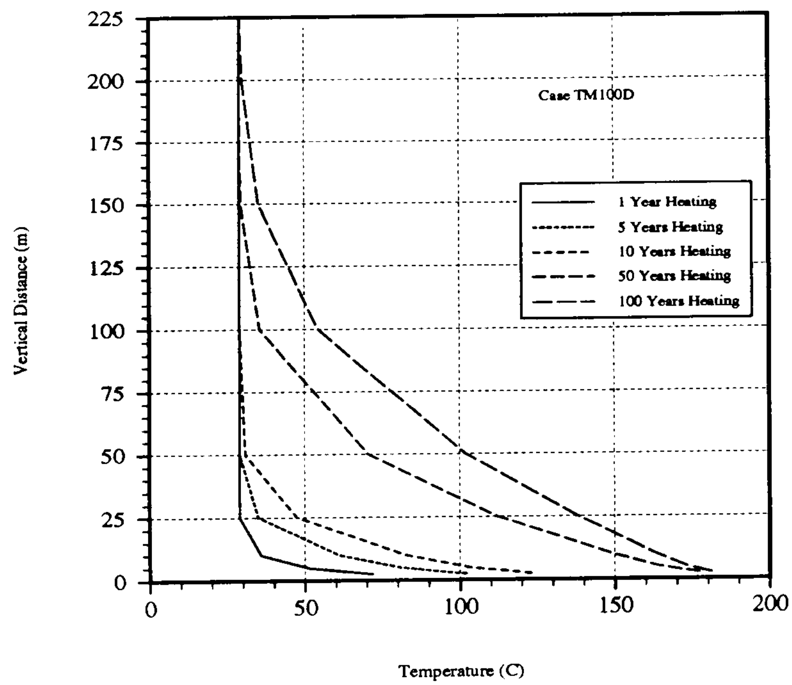


Figure G-8 Vertical expansion with distance at select time periods - Case Tm100D



MPA 3/25/96

Figure G-9 ~~Vertical displacement at tunnel roof with time~~ - Case TM100D Temperature with vertical distance above tunnel roof at select times.

Temperature along vertical line above tunnel (x=0.0)
Case TM100D: Time(years) vs y-coord (m)

MPA 3/29/96

y-coord	~~0yr~~	~~1~~ 0	~~2~~ 1	~~3~~ 2	years ~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	100 years
1	2.5	29.0	71.8	81.9	89.7	96.3	102	123	177	181
2	5.0	29.0	51.2	60.9	68.6	75.2	80.9	103	164	173
3	10.0	29.0	35.9	43.3	49.8	55.7	61.0	82.2	149	163
4	25.0	29.0	29.0	29.6	30.9	32.8	35.0	47.5	112	138
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	30.9	70.6	102
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	35.5	54.3
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.5	35.2
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.0
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1

Time (yrs)	TM100D.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3,0,0.0)
0	-0.3475	-0.1599	-2.200	-18.99
1	-0.05313	-0.3984	-7.175	-25.46
2	-0.1662	-0.5264	-9.593	-25.84
3	0.3861	0.6764	-11.46	-25.87
4	0.5875	0.8208	-13.48	-25.80
5	0.7835	0.9680	-15.23	-25.60
10	1.721	1.745	-21.49	-24.69
50	7.332	7.026	-40.64	-1.391
100	11.63	11.24	-43.23	-1.352

APPENDIX H - CASE TM20A.DAT

UDEC Input Deck - TMA20A. DAT

```
set log tm20a.log
set plot po
start
head
Case 1 - Thermal-Mechanical Analysis - 20 Yr Old Fuel/20 AML
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  90 degrees ccw from horizontal  - 1.25 m spacing
* 2nd joint set -   0 degrees - 2.5 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4
*
* Size of problem domain is -20<x<20 -222<y<222
*  - Vertical boundaries are located along symmetry lines assuming 25 m drift spacings
*  - Upper and lower horizontal boundaries set based on extent of thermal front at
*    100 years of heating.
*
* input block, tunnel, and joint geometry
round 0.025
set ovtol 1.0
block -20 -225 -20 225 20 225 20 -225
split -21 -25 21 -25
split -21  25 21  25
split -21  50 21  50
split -21 -50 21 -50
*
* create jointing
*
** outer problem domain
*
jregion -21 25 -21 50 21 50 21 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -21 50 -21 225 21 225 21 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
```

```
*
jregion -21 -50 -21 -25 21 -25 21 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -21 -225 -21 -50 21 -50 21 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
** inner problem domain
*
jregion -21 -25 -21 25 21 25 21 -25
jset 90.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
jset 0.0 0.0 50.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -22
*
** detailed jointing around tunnel
*
jregion -20 -10.0 -20 10.0 20 10.0 20 -10.0
jset 90.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 0.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -20 -10.0 -20 10.0 20 10.0 20 -10.0 edge 2.5
gen region -20 -25.0 -20 25.0 20 25.0 20 -25.0 edge 5.5
gen region -20 -50.0 -20 50.0 20 50.0 20 -50.0 quad 5.5
gen region -20 -225.0 -20 225.0 20 225.0 20 -225.0 quad 10.5
*
pr max
*
damp auto
*
* apply mechanical boundary conditions (units, MPa)
*
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -21 21 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -21 21 -226 -224 yvel=0.0
bound -21 -19 -226 226 xvel=0.0
bound 19 21 -226 226 xvel=0.0
```

```
*
* define mechanical and thermal material properties for joints/intact blocks
*
*   material 1 = rock
*
change -21 21 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &
 kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
cycle 4000
save tm20a_in.sav
win -20 20 -20 20
*pl bl st iw hold
*pl hi 5 6 hold
*
* remove tunnel blocks
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 3500
*pl bl st iw hold
*pl bl dis iw hold
```

```
*pl bou mohr hold
*pl hi 3 hold
*pl hi 5 hold
*pl hi 7 hold
*pl bou sh hold
*
sav 20a_exc.sav
********************************************************************
*
* apply decaying heat flux to tunnel wall boundary
*
********************************************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
reset time
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 12.5 0
*
* apply heat flux to tunnel wall
*
thapp ann 0.0 0.0 2.40 2.54 flux 10.1633 -3.2197e-10
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
*pl bl tem hold
*pl this 1 2 3 4 5 hold
cycle 4000
pr max
*
* run thermal time to 1 month
*
```

```
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 20a_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
sav 20a_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 20a_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20a_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=8.64e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20a_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20a_10y.sav
*
```

```
* run thermal time to 20 years
*
run age=6.3072e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 40 years
*
run age=1.26144e9 delt=8.64e6 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20a_50y.sav
*
* run thermal time to 100  years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
save 20a_100y.sav
return
```

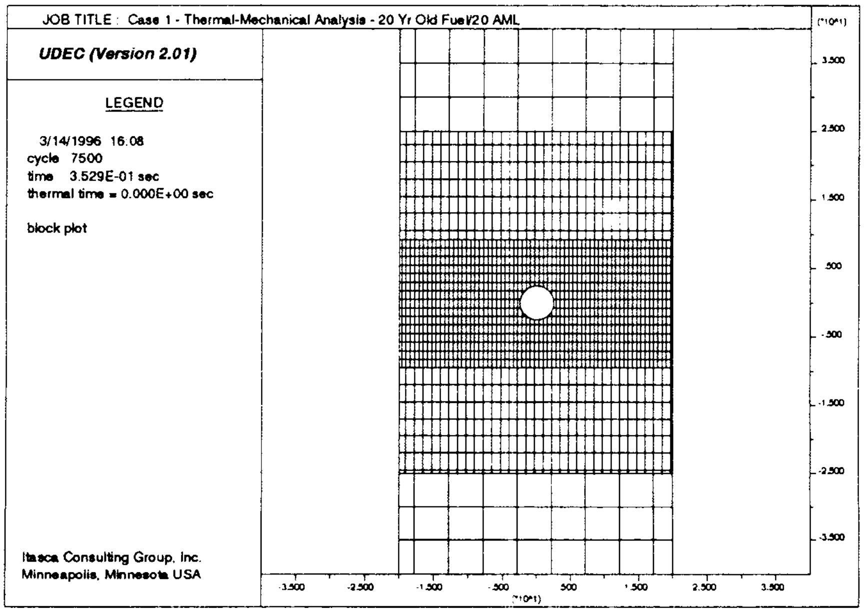


Figure H-1. UDEC discrete element mesh plot - Case TM20A

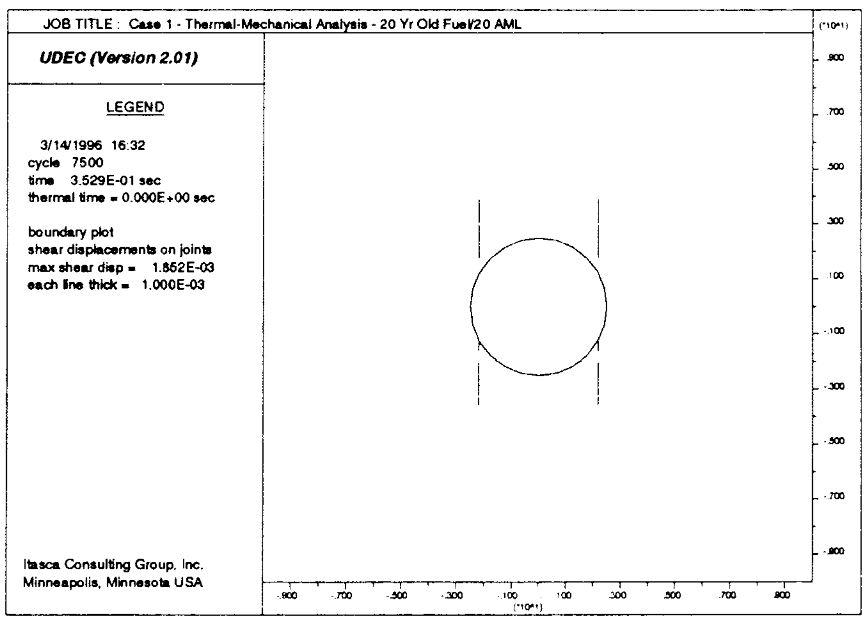


Figure H-2. Joint shear displacements after excavation (maximum = ~~3.046~~ 1.852 mm) - Case TM20A MPA 3/29/96

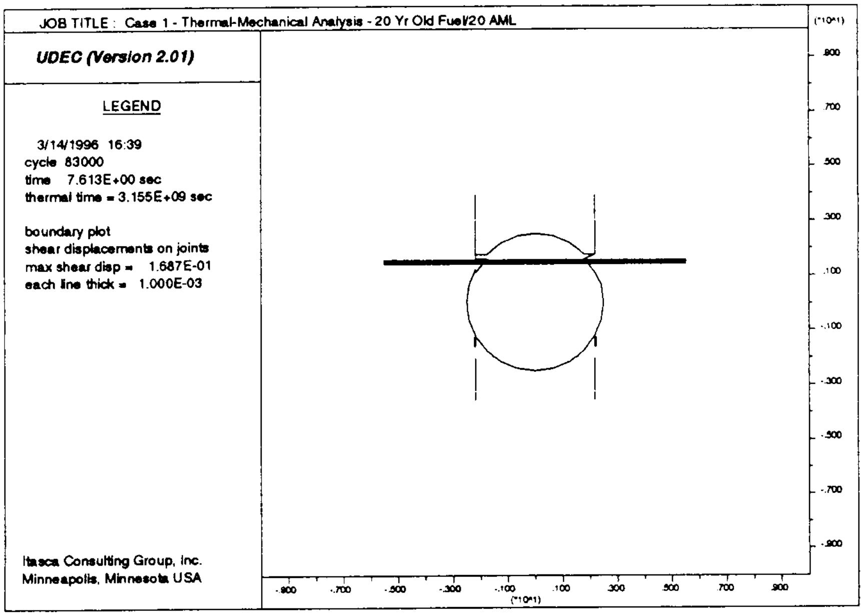


Figure H-3. Joint shear displacements after 100 years (maximum = ~~1.706~~ 16.87 cm) - Case TM20A MPH 3/25/96

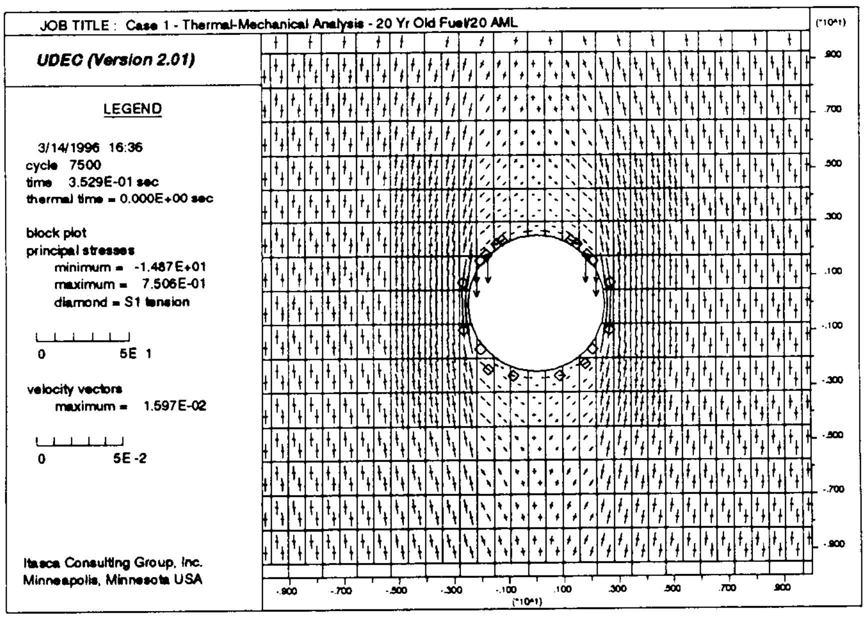


Figure H-4. Principal stress distribution after excavation (maximum = ~~>13.02~~ 14.87 MPa) Case TM20A MPA 3/25/96

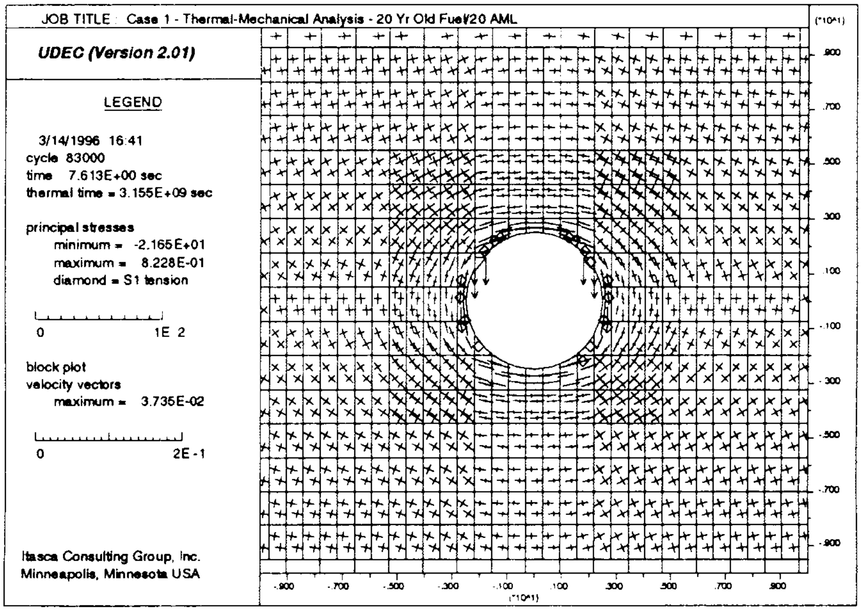


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Figure H-5. Principal stress and velocity vectors after ~~excavation~~ 100 years (maximum stress = ~~56.24~~ 21.65 MPa) Case TM20A

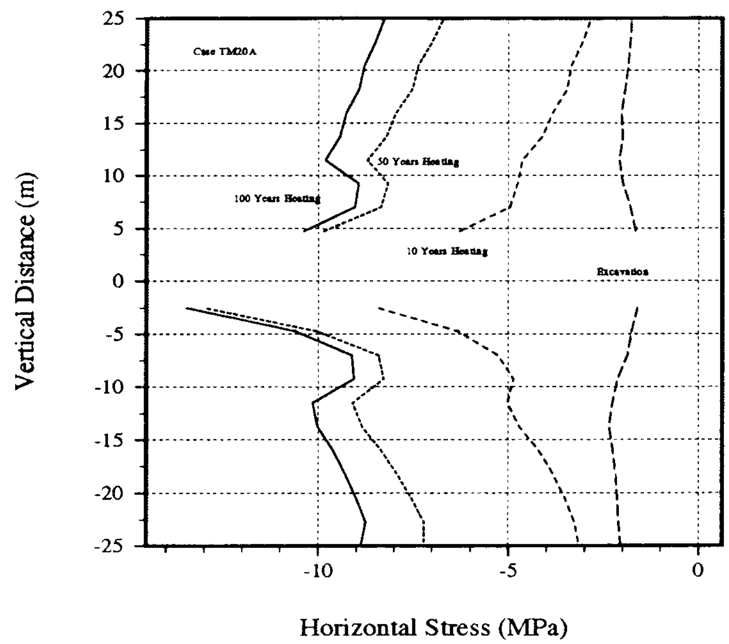

Figure H-6. Horizontal stress along a vertical section through center of tunnel - Case TM20A

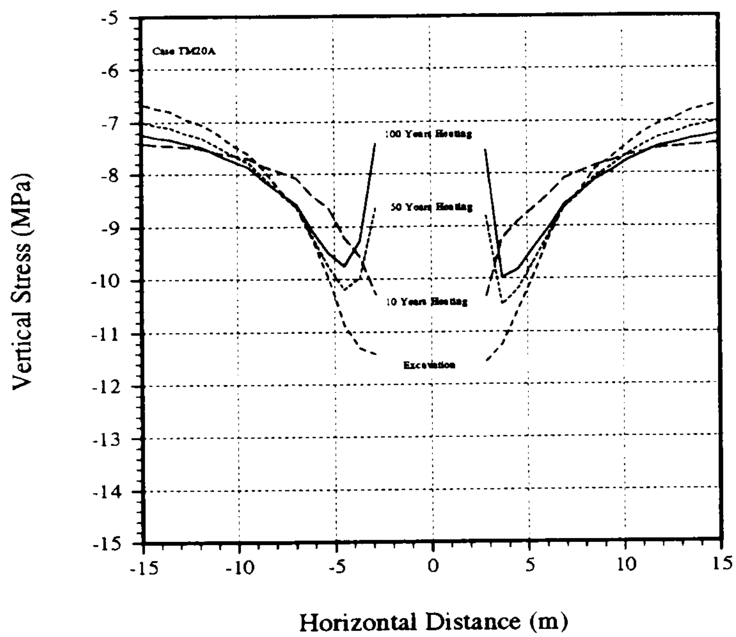

Figure H-7. Vertical stress along a vertical section through center of tunnel - Case TM20A

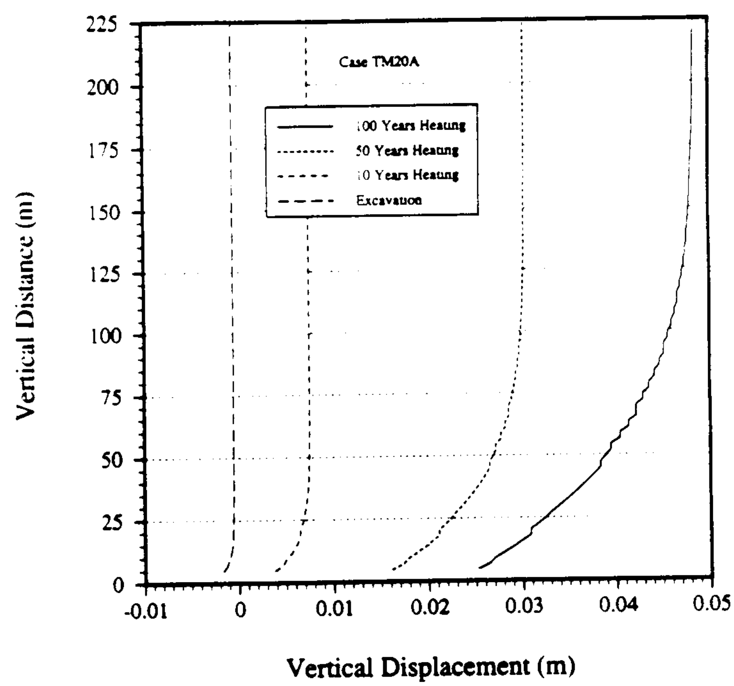

Figure H-8. Vertical expansion with distance at select time periods - Case TM20A

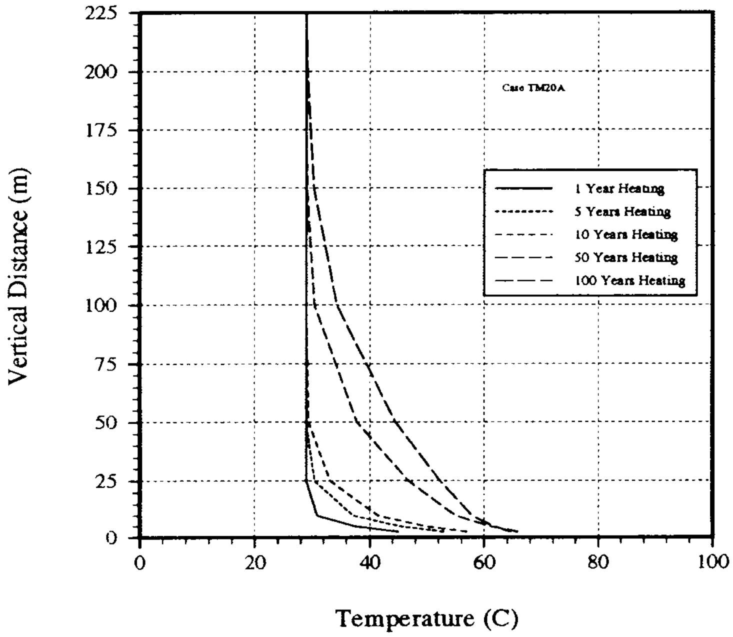

Figure H-9. ~~**Vertical displacement at tunnel roof with time**~~ **- Case TM20A**

Temperature with vertical distance above roof at select times.

Temperature along vertical line above tunnel (x=0.0)
Case TM20A: Time(years) vs y-coord (m)

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y-coord	~~0yr~~	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	100 years
1	2.5	29.0	45.0	48.2	50.2	51.7	52.8	56.9	65.8	64.6
2	5.0	29.0	37.5	40.6	42.6	44.1	45.3	49.7	61.0	61.6
3	10.0	29.0	30.9	33.1	34.7	36.1	37.2	41.5	55.0	57.9
4	25.0	29.0	29.0	29.2	29.5	30.0	30.4	33.1	46.7	52.2
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	30.9	37.8	44.5
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.4	34.3
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1	30.3
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.2
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Time (yrs)	TM20A.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3,0,0.0)
0	-0.2147	-0.1665	-1.735	-9.618
1	-0.09626	0.2793	-4.966	-11.74
2	-0.05206	0.3111	-5.929	-12.05
3	-0.007168	0.343	-6.648	-12.11
4	0.03565	0.3734	-7.249	-12.09
5	0.0778	0.4039	-7.774	-12.04
10	0.2818	0.5618	-9.749	-11.73
50	1.496	1.64	-15.04	-10.32
100	2.407	2.523	-15.62	-9.52

APPENDIX I - CASE TM20B.DAT

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UDEC Input Deck - TMA20B. DAT

```
set log tm20b.log
set plot po
start
*******************************************************************
* Title and block definition for AML20 with Lwp=50.6 m, Ldrift=40 m
*******************************************************************
head
Case 1 - TM Analysis - 20 Yr Old Fuel/TM20b.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees from horizontal - 1.25 m spacing
* 2nd joint set -  10 degrees - 5.0 m spacing
*
**  around tunnel orientations kept the same and spacings reduced by 1/4 *
* Size of problem domain is -20<x<20 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings *  - Upper and lower horizontal boundaries set based on extent of thermal front at *    100 years of heating.
*
round 0.025
set ovtol 1.0
block -20 -225 -20 225 20 225 20 -225
split -20 -25 20 -25
split -20  25 20  25
split -20  50 20  50
split -20 -50 20 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -20 25 -20 50 20 50 20 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -20 50 -20 225 20 225 20 50
```

```
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -20 -50 -20 -25 20 -25 20 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -20 -225 -20 -50 20 -50 20 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ---------------------
*  inner problem domain
* ---------------------
jregion -20 -25 -20 25 20 25 20 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
*
* --------------------------------
*  detailed jointing around tunnel
* --------------------------------
*
jregion -20 -10.0 -20 10.0 20 10.0 20 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
*
tunnel 0 0 2.5 24
jd
del area 1.0e-2
*
* ****************************
*  auto generation of zones
* ****************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -20.0 -10.0 -20.0 10.0 20.0 10.0 20.0 -10.0 edge 2.5
gen region -20.0 -25.0 -20.0 25.0 20.0 25.0 20.0 -25.0 edge 4.5
gen region -20.0 -50.0 -20.0 50.0 20.0 50.0 20.0 -50.0 quad 5.5
gen region -20.0 -225.0 -20.0 225.0 20.0 225.0 20.0 -225.0 quad 10.5
*
pr max
*
damp auto
*
****************************************************
```

```
* apply mechanical boundary conditions (units, MPa)
****************************************************
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -20.5 20.5 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 bound -20.5 20.5 -226 -224
yvel=0.0
bound -20.5 -19.5 -226 226 xvel=0.0
bound 19.5 20.5 -226 226 xvel=0.0
*
************************************************************************ ***** * define
mechanical and thermal material properties for joints/intact blocks
********************************************************************************* *
* material 1 = rock
*
change -21 21 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 & kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
******************************
* initial cycling equilibrium
******************************
cycle 4000
save 20b_ini.sav
*
************************
* remove tunnel blocks
************************
```

```
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 20b_exc.sav
*
*************************************
* set thermal boundary and histories
*************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100     thist tem 0 150 tem 0 200
tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 12.5 0 tem 15 0 tem 17.5 0 tem 20.0 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.4 2.54 flux 10.1633 -3.2197e-10
*
*
* run initial thermal time by explicit scheme for 100 steps
*
run age=3600 step=1000000 tol=0.05
reset damp
```

```
cycle 4000
pr max
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
```

```
save 20b_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 20b_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=4.32e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_40y.sav
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20b_50y.sav
*
* run thermal time to 100 years
```

```
*
run age=3.1536e9 delt=4.32e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 9000
pr max
sav 20b_100.sav
return
```

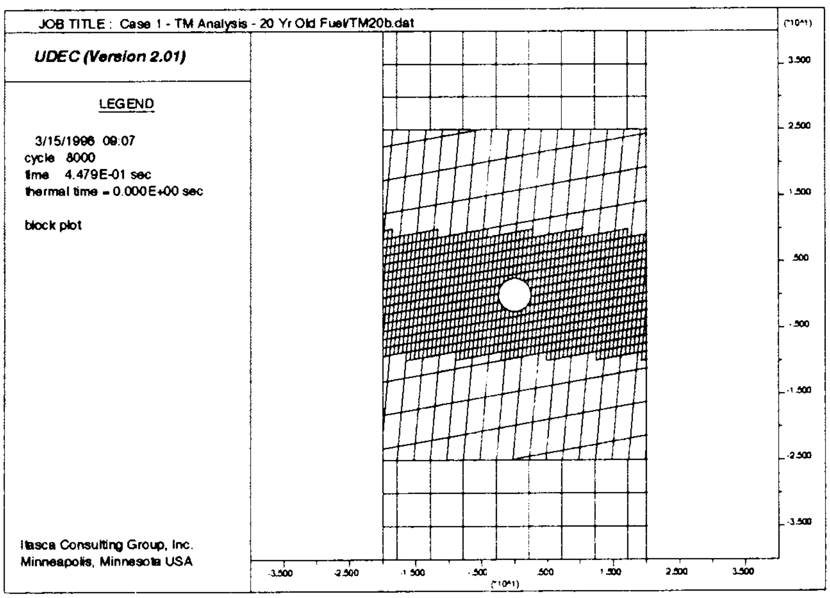

Figure I-1. UDEC discrete element mesh plot - Case TM20B

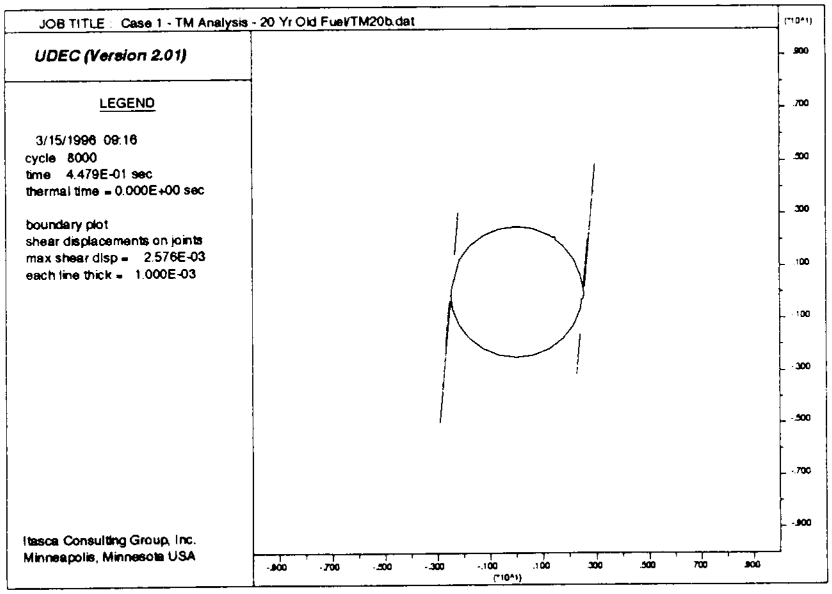

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Figure I-2. Joint shear displacements after excavation (maximum = ~~3.046~~ 2.576 mm) - Case TM20B

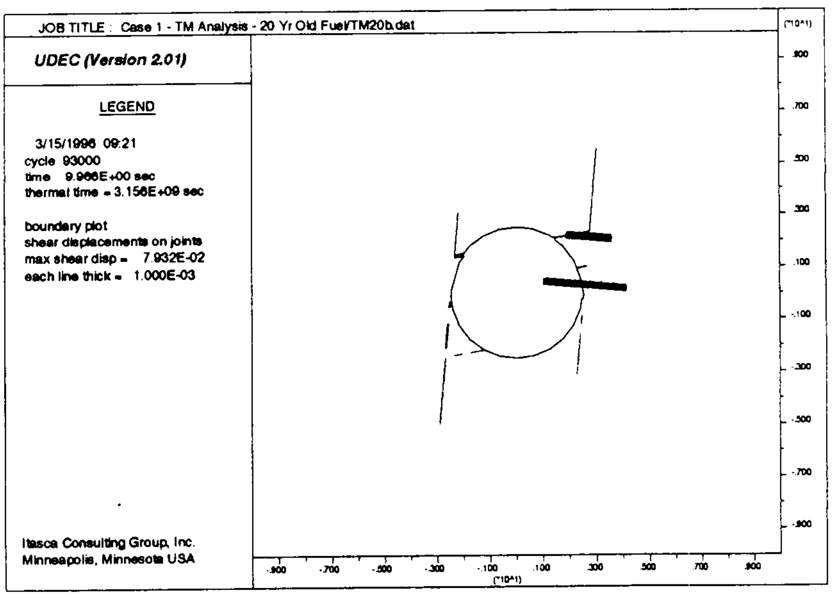

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Figure I-3. Joint shear displacements after 100 years (maximum = ~~1.706~~ 7.932 cm) - Case TM20B

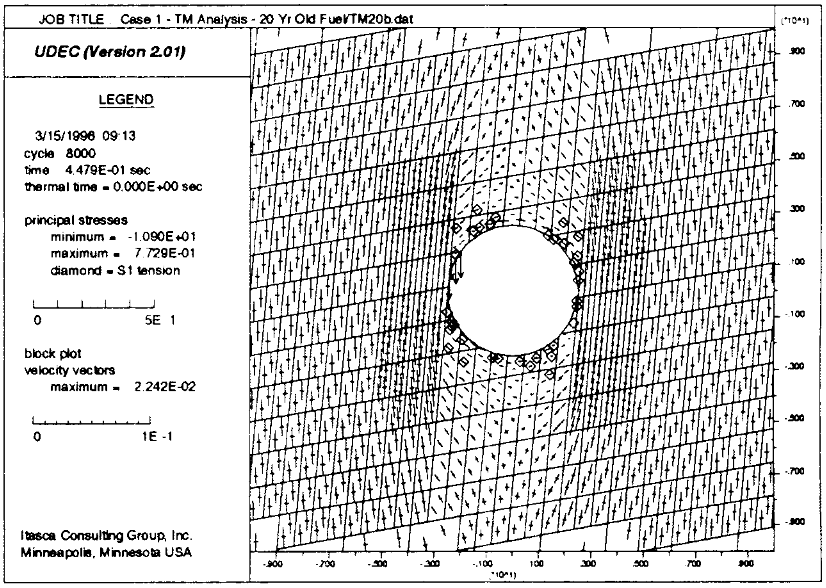

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Figure I-4. Principal stress distribution after excavation (maximum = ~~-13.02~~ 10.91 MPa) Case TM20B

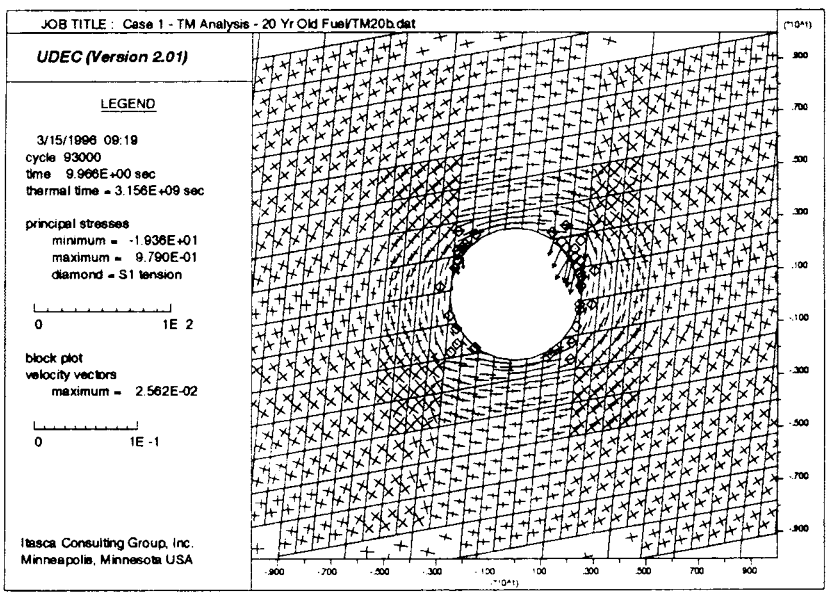

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Figure I-5. Principal stress and velocity vectors after 100 years (maximum stress = ~~56.24~~ 19.36 MPa) Case TM20B

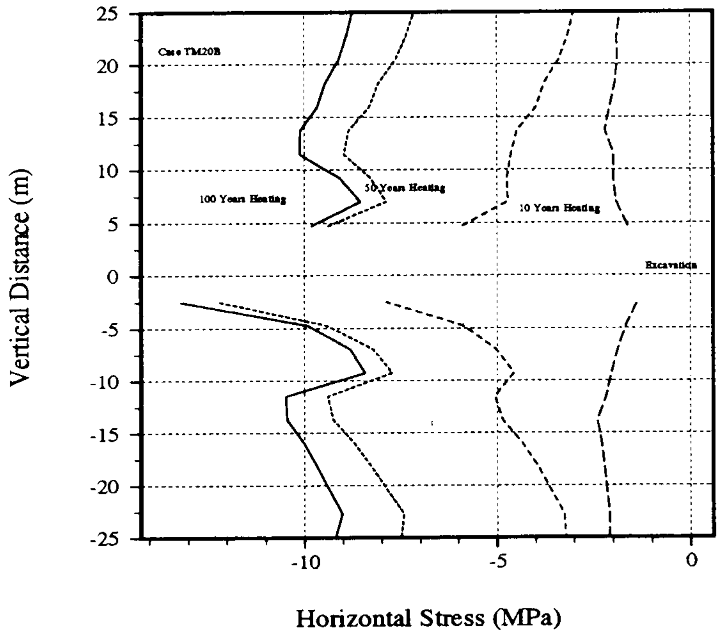

Figure I-6. Horizontal stress along a vertical section through center of tunnel - Case TM20B

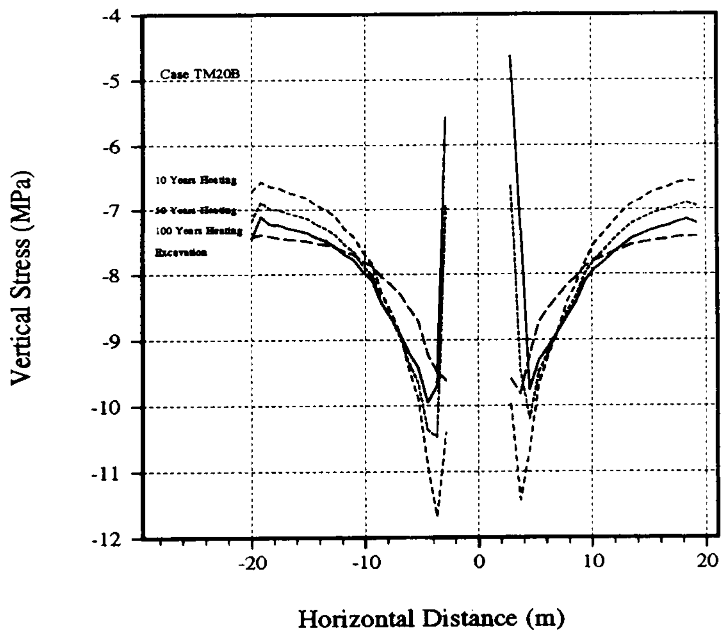

Figure I-7. Vertical stress along a vertical section through center of tunnel - Case TM20B

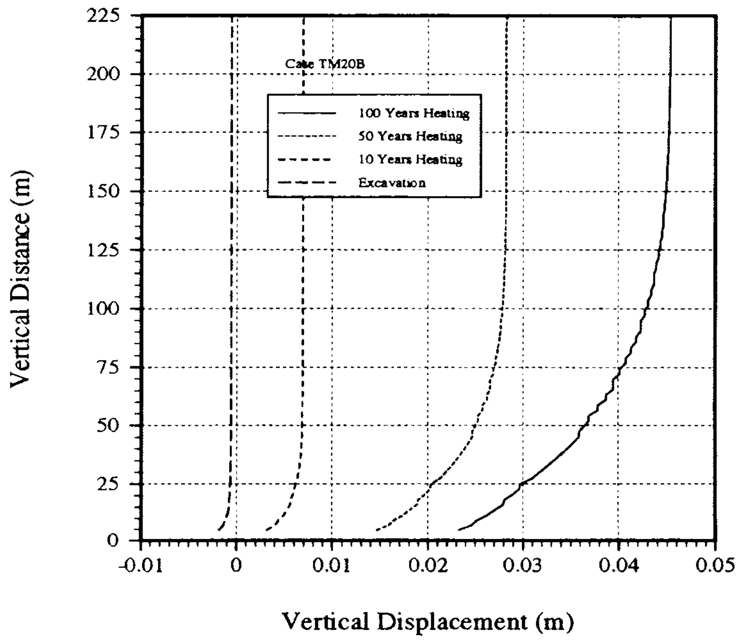

Figure I-8. Vertical expansion with distance at select time periods - Case TM20B

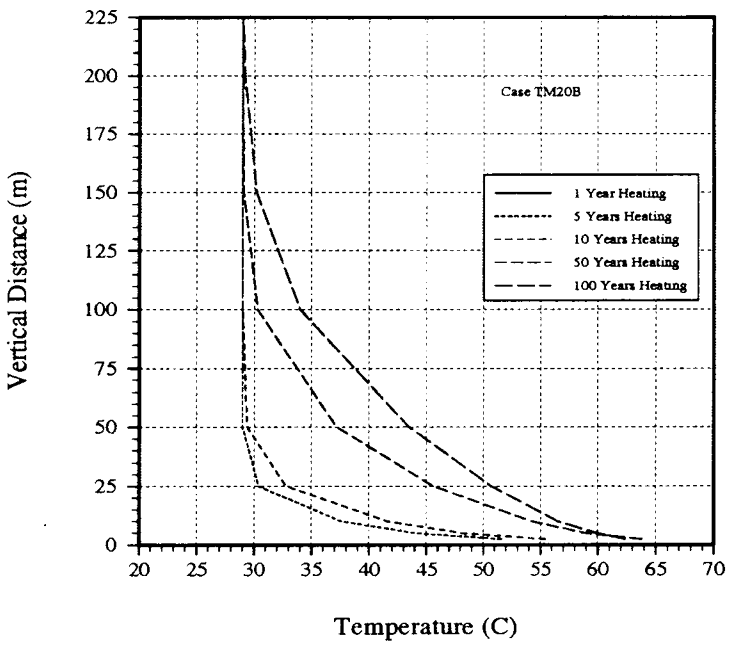

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Figure I-9. ~~Vertical displacement at tunnel roof with time~~ - Case TM20B Temperature with vertical distance above tunnel roof at select times

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Temperature along vertical line above tunnel (x=0.0)
Case TM20B: Time(years) vs y-coord (m)

y-coord	~~0yr~~	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	~~years~~ 100
1	2.5	29.0	44.3	47.4	49.2	50.5	51.6	55.4	63.8	62.4
2	5.0	29.0	36.8	39.8	41.6	43.0	44.1	48.2	58.9	59.9
3	10.0	29.0	31.4	33.6	35.2	36.5	37.6	41.6	54.2	56.5
4	25.0	29.0	29.0	29.2	29.5	29.9	30.4	32.8	45.6	50.7
5	50.0	29.0	29.0	29.0	29.0	29.0	29.0	29.4	37.2	43.5
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.3	34.0
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1	30.2
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.2
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Time (yrs)	TM20B.DAT Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3.0,0.0)
0	-0.2301	0.1784	-1.494	-9.585
1	-0.1245	0.2871	-4.117	-11.27
2	-0.08409	0.3167	-4.975	-11.39
3	-0.04316	0.3460	-5.601	-11.27
4	-0.003001	0.3750	-6.124	-11.08
5	0.03649	0.404	-6.578	-10.88
10	0.2255	0.5506	-8.277	-9.977
50	1.351	1.555	-13.79	-6.621
100	2.207	2.402	-15.43	-4.642

APPENDIX J - CASE TM20C.DAT

UDEC Input Deck - TMA20C. DAT MPA 3/25/96

```
set log tm20c.log
res 20c_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 40 years
*
run age=1.26144e9 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_50y.sav
*
* run thermal time to 100  years
*
run age=3.1536e9 delt=2.88e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
save 20c_100y.sav
```

```
return
set plot po
start
head
Case 1 - Thermal-Mechanical Analysis - 20 Yr Old Fuel/20 AML/TM20C.DAT config thermal
*
**************************TM20C.DAT************************
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees ccw from horizontal  - 1.25 m spacing
* 2nd joint set - 10 degrees - 1.25 m spacing
* 3rd jiont set-   70 degrees - 1.25 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4 *
* Size of problem domain is -20<x<20 -222<y<222
*  - Vertical boundaries are located along symmetry lines assuming 40 m drift spacings *  - Upper and lower horizontal boundaries set based on extent of thermal front at *    100 years of heating.
*
* input block, tunnel, and joint geometry
round 0.03
set ovtol 1.0
block -20 -225 -20 225 20 225 20 -225
split -21 -25 21 -25
split -21  25 21  25
split -21  50 21  50
split -21 -50 21 -50
*
* create jointing for 3 joint set (85 & .625m, 10 & 1.25m , and 70 & 1.25m) *
** outer problem domain
*
jregion -21 25 -21 50 21 50 21 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
jregion -21 50 -21 225 21 225 21 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -21 -50 -21 -25 21 -25 21 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset 0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -21 -225 -21 -50 21 -50 21 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
```

```
jset 0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
** inner problem domain
*
jregion -21 -25 -21 25 21 25 21 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
jset 70.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25
*
** detailed jointing around tunnel
*
jregion -20 -10.0 -20 10.0 20 10.0 20 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
jset 70.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -20 -10.0 -20 10.0 20 10.0 20 -10.0 edge 2.5
gen region -20 -25.0 -20 25.0 20 25.0 20 -25.0 edge 4.5
gen -20 20 -50.0 -25 quad 5.5
gen -20 20 -225.0 -50.0 quad 10.5
gen -20 20 25.0 50.0 quad 5.5
gen -20 20 50.0 225.0 quad 10.5
*
pr max
*
damp auto
*
* apply mechanical boundary conditions (units, MPa)
*
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -21 21 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225
bound -21 21 -226 -224 yvel=0.0
bound -21 -19 -226 226 xvel=0.0
bound 19 21 -226 226 xvel=0.0
*
* define mechanical and thermal material properties for joints/intact blocks *
*   material 1 = rock
```

```
*
change -21 21 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &  kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
cycle 4000
save tm20c_in.sav
win -20 20 -20 20
*pl bl st iw hold
*pl hi 5 6 hold
*
* remove tunnel blocks
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*pl bl st iw hold
*pl bl dis iw hold
*pl bou mohr hold
*pl hi 3 hold
*pl hi 5 hold
*pl hi 7 hold
*pl bou sh hold
```

```
*
sav 20c_exc.sav
*************************************************************************
*
* apply decaying heat flux to tunnel wall boundary
*
*************************************************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
reset time
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100
thist tem 0 150 tem 0 200 tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 12.5 0 tem 20.0 0
*
* apply heat flux to tunnel wall
*
thapp ann 0.0 0.0 2.40 2.54 flux 10.1633 -3.2197e-10
*
* run thermal time to 1 week
*
run age=6.048e5 temp=10000  step=1000000 tol=0.05
reset damp
*pl bl tem hold
*pl this 1 2 3 4 5 hold
cycle 4000
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 temp=10000 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*
```

```
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
save 20c_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_2y.sav
*
```

```
* run thermal time to 3 years
*
run age=9.4608e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 20c_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_5y.sav
*
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=1.44e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_10y.sav
*********************************
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
```

```
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 40 years
*
run age=1.26144e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20c_50y.sav
*
* run thermal time to 100  years
*
run age=3.1536e9 delt=8.64e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
save 20c_100y.sav
return
```

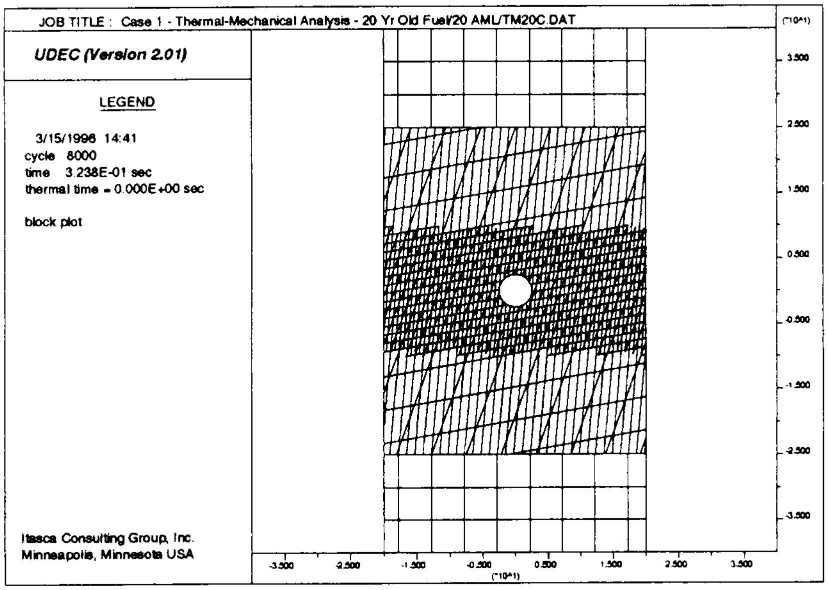

Figure J-1. UDEC discrete element mesh plot - Case TM20C

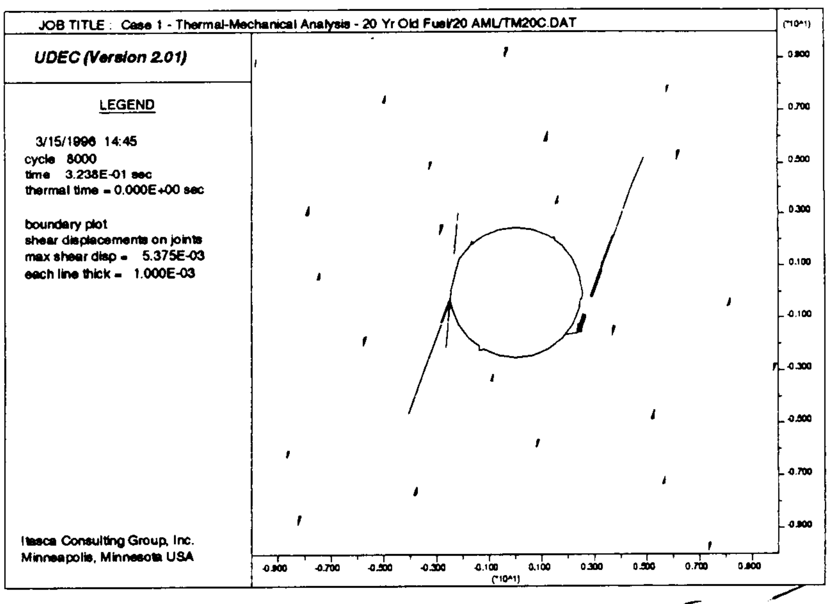

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Figure J-2. Joint shear displacements after excavation (maximum = ~~3.046~~ 5.375 mm) - Case TM20C

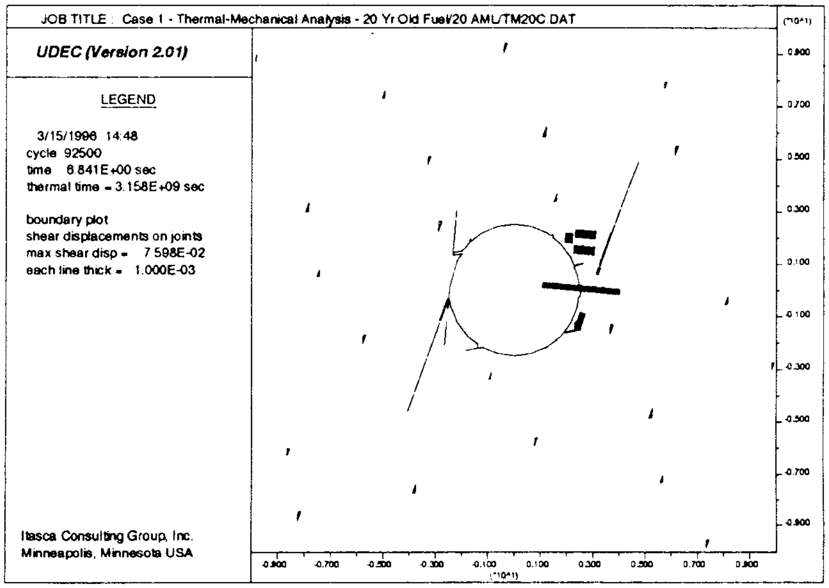

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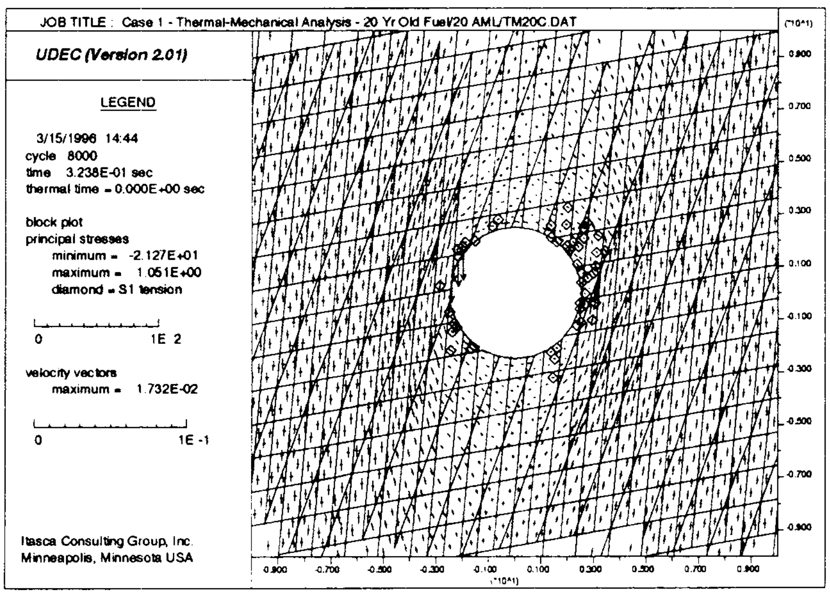
Figure J-3. Joint shear displacements after 100 years (maximum = ~~1.706~~ 7.598 cm) - Case TM20C



MPA 3/25/96

Figure J-4. Principal stress distribution after excavation (maximum = ~~13.02~~ 21.27 MPa) Case TM20C

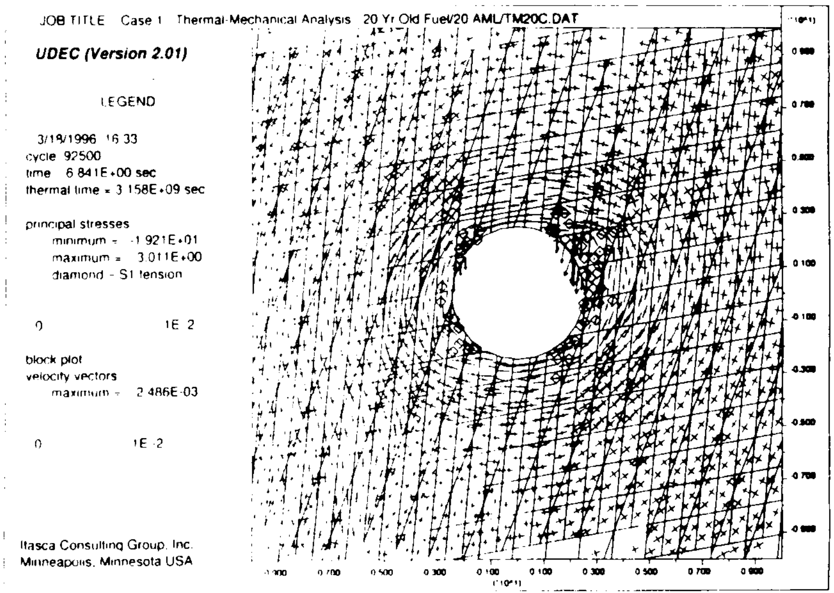


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Figure J-5 Principal stress and velocity vectors after 100 years (Maximum stress = ~~56.24~~ 19.21 MPa) Case TM20C

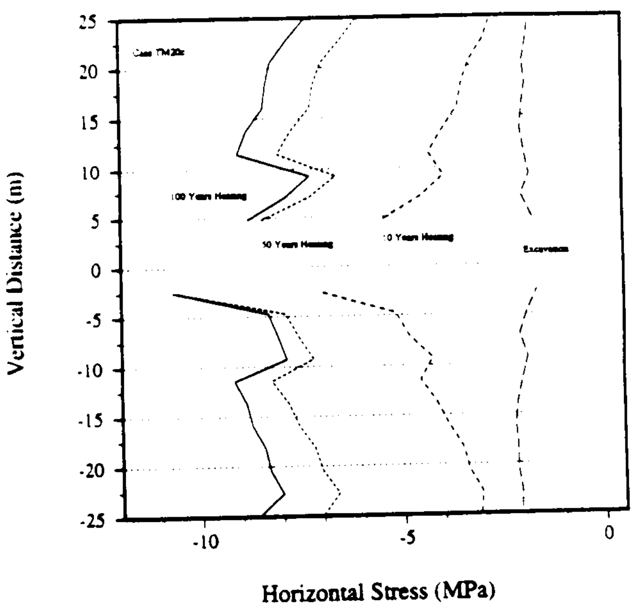


Figure J-6 Horizontal stress along a vertical section through center of tunnel - Case TM20C

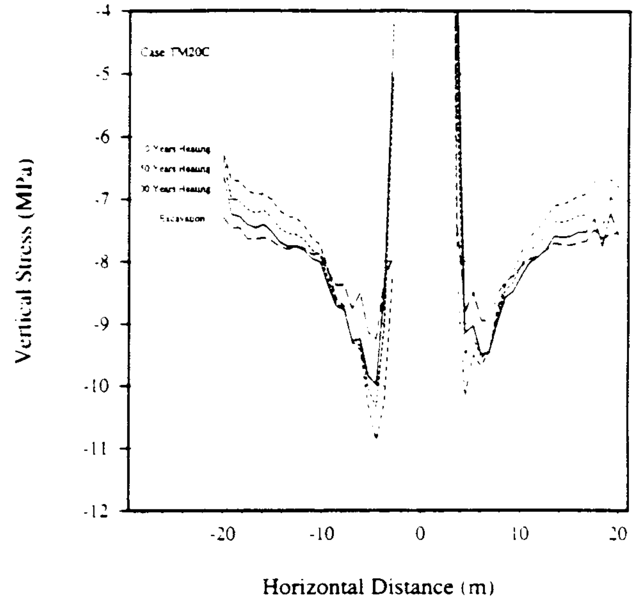


Figure J-7 Vertical stress along horizontal section through center of tunnel - Case TM20C

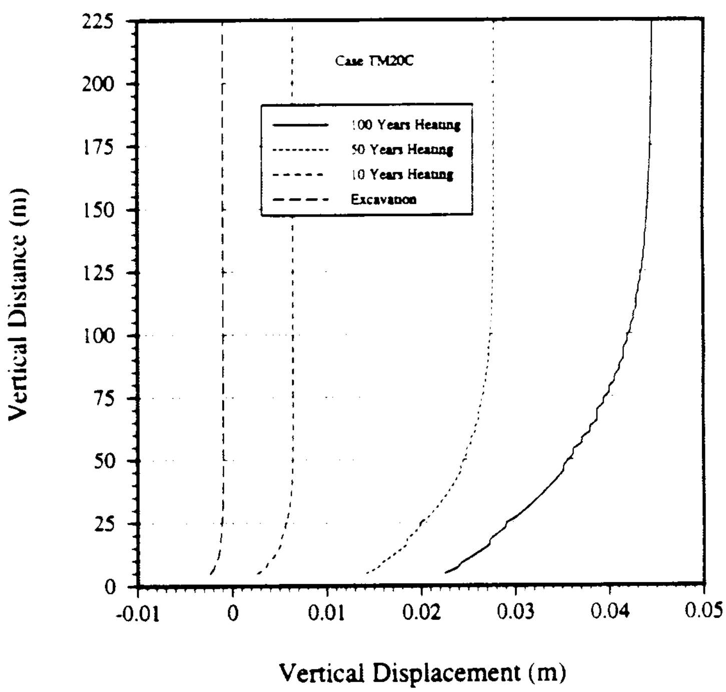
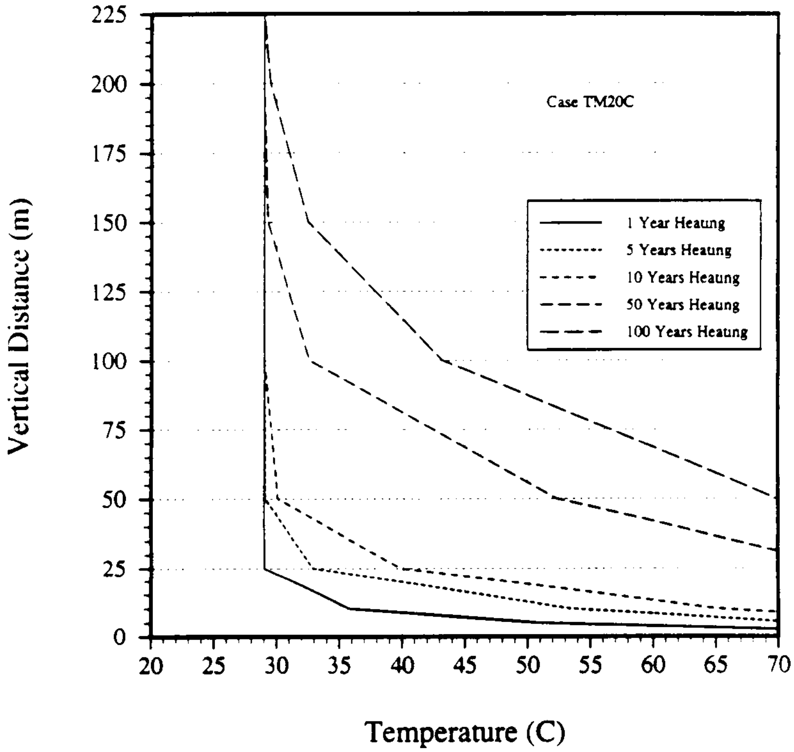


Figure J-8 Vertical expansion with distance at select time periods - Case TM20C



MPA 3/28/96

Figure J-9 ~~Vertical displacement at tunnel roof with time~~ - Case TM20C
Temperature with vertical distance above tunnel roof at select times

Temperature along vertical line above tunnel (x=0.0)
Case TM20C: Time(years) vs y-coord (m)

MPA 3/29/96

y-coord	~~0yr~~ y-coord	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	~~years~~ 100
	2.5	29.0	71.4	80.0	85.3	85.3	92.2	103	127	63.9
2	5.0	29.0	50.9	59.3	64.5	64.5	71.7	83.2	115	59.9
3	10.0	29.0	35.8	42.1	46.6	46.6	53.3	64.9	100	56.5
4	25.0	29.0	29.0	29.5	30.4	30.4	32.9	39.9	76.0	50.6
5	50.0	29.0	29.0	29.0	29.0	29.0	29.1	30.1	52.3	43.4
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	32.6	34.0
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.3	30.2
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.2
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Time (yrs)	TM20C.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3.0,0.0)
0	-0.2906	0.1952	-2.144	-14.46
1	-0.1831	0.3076	-4.370	-17.36
2	-0.1442	0.3373	-5.082	-17.88
3	-0.1034	0.3673	-5.613	-18.02
4	-0.06481	0.3952	-5.613	-18.02
5	-0.02634	0.4236	-6.473	-17.88
10	-0.1601	0.520	-7.976	-17.05
50	-01.291	1.581	-12.40	-12.63
100	-2.12	2.4	-13.82	-6.917

APPENDIX K - CASE TM20D.DAT

UDEC Input Deck - TM20D. DAT 9 HPA 3/29/96

```
set log tm20d.log
set plot po
start
*********************************************************************
* Title and block definition for AML20 with Lwp=50.6 m, Ldrift=40 m
*********************************************************************
head
Case 1 - TM Analysis - 20 Yr Old Fuel/TM20d.dat
config thermal
*
**** Coarse Model *****
*** Joint orientations ***
* 1st joint set -  85 degrees from horizontal - 1.25 m spacing
* 2nd joint set -  10 degrees - 5.0 m spacing
* 3rd joint set - 60 degrees - 5.0 m spacing
**
**  around tunnel orientations kept the same and spacings reduced by 1/4 *
* Size of problem domain is -11.25<x<11.25 -225<y<225
*  - Vertical boundaries are located along symmetry lines assuming 22.5 m drift spacings *  - Upper and lower horizontal boundaries set based on extent of thermal front at *    100 years of heating.
*
round 0.03
set ovtol 1.0
block -20 -225 -20 225 20 225 20 -225
split -20 -25 20 -25
split -20  25 20  25
split -20  50 20  50
split -20 -50 20 -50
*
************************
* create jointing
************************
* ----------------------
* outer problem domain
* ----------------------
jregion -20 25 -20 50 20 50 20 25
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 25.0
*
```

```
jregion -20 50 -20 225 20 225 20 50
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 50.0
*
jregion -20 -50 -20 -25 20 -25 20 -50
jset 90.0 0.0 300.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25.0
*
jregion -20 -225 -20 -50 20 -50 20 -225
jset 90.0 0.0 300.0 0.0 0.0 0.0 8.5 0.0 -12.8125 -50.0
jset  0.0 0.0 100.0 0.0 0.0 0.0 10.0 0.0 -12.8125 -50.0
*
* ---------------------
*  inner problem domain
* ---------------------
jregion -20 -25 -20 25 20 25 20 -25
jset 85.0 0.0 100.0 0.0 0.0 0.0 2.5 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 5.0 0.0 -12.8125 -25
*
* -------------------------------
*  detailed jointing around tunnel
* -------------------------------
*
jregion -20 -10.0 -20 10.0 20 10.0 20 -10.0
jset 85.0 0.0 100.0 0.0 0.0 0.0 0.625 0.0 -12.8125 -25
jset 10.0 0.0 50.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -22
jset 60.0 0.0 100.0 0.0 0.0 0.0 1.25 0.0 -12.8125 -25
*
tunnel 0 0 2.5 24
jd
del area 2.0e-2
*
* ***************************
*  auto generation of zones
* ***************************
gen region -5 -5 -5 5 5 5 5 -5 edge 1.0
gen region -20.0 -10.0 -20.0 10.0 20.0 10.0 20.0 -10.0 edge 2.5
gen region -20.0 -25.0 -20.0 25.0 20.0 25.0 20.0 -25.0 edge 4.3
gen region -20.0 -50.0 -20.0 50.0 20.0 50.0 20.0 -50.0 quad 5.5
gen region -20.0 -225.0 -20.0 225.0 20.0 225.0 20.0 -225.0 quad 10.5
*
pr max
*
```

```
damp auto
*
****************************************************
* apply mechanical boundary conditions (units, MPa)
****************************************************
grav 0.0 -9.81
insitu stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 szz -1.86 &
zgrad 0.0 0.00599
bound -20.5 20.5 224 226 stress -1.86 0.0 -7.0 ygrad 0.00599 0.0 0.0225 bound -20.5 20.5 -226 -224
yvel=0.0
bound -20.5 -19.5 -226 226 xvel=0.0
bound 19.5 20.5 -226 226 xvel=0.0
*
****************************************************************************** * define
mechanical and thermal material properties for joints/intact blocks
****************************************************************************** *
*  material 1 = rock
*
change -21 21 -226 226 jcons=5
**
prop mat=1 k=1.856e4 g=1.335e4 d=0.002297
prop mat=1 cond=2.1 thexp=8.8e-06 spec=9.32e08
prop jmat=1 jks=1.0e5 jkn=1.0e5 jdil=0 jc=0.08 jfric=38.0 jtens=0.04 &  kn=1.0e5 ks=1.0e5
*
set jcondf 5
*
* mohr-coulomb failure parameters
*
prop mat=1 coh=2.1 fric=49.0 tens=1.05
*
****************
* history records
****************
hist ncyc=10 unbal damp type 4
hist ydis 0 0 yvel 0 0 ydis 0 225 ydis 0 -225
hist ydis 0 15
hist sxx 0.0 0.0 syy 0.0 0.0
*
******************************
* initial cycling equilibrium
******************************
cycle 4000
save 20d_ini.sav
*
```

```
***********************
* remove tunnel blocks
***********************
*
del ann 0 0 0 2.5
*
* reset displacements after applying in situ loading conditions
*
reset damp time hist dis rot
hist unbal damp
hist ydis 0.0 2.5 ydis 0 -2.5 ydis 0.0 225.0
hist xdis 0.0 2.5
hist sxx 0.0 3.0 syy 0.0 3.0 syy 3.0 0.0
*
cycle 4000
*
sav 20d_exc.sav
*
*************************************
* set thermal boundary and histories
*************************************
*
* set up thermal boundaries (default thermal b.c. are adiabatic)
*
*  Initial temperature at repository horizon taken to be 29 C
*  - temperature gradient taken to be 0.02 deg C/m
*
tfix 33.0 -21 21 -226.0 -224.0
tfix 25.0 -21 21 224.0 226.0
*
print bound
*
initem 29.0 -21 21 -226 226
thist ntcyc=10 tem 0 2.5 tem 0 5 tem 0 10 tem 0 25 tem 0 50 tem 0 100     thist tem 0 150 tem 0 200
tem 0 220 tem 2.5 0 tem 5 0 tem 10 0
thist tem 12.5 0 tem 15 0 tem 17.5 0 tem 20 0
*
*********************************
* apply heat flux to tunnel wall
*********************************
thapp ann 0.0 0.0 2.4 2.56 flux 28.4701 -3.2197e-10
*
*
* run initial thermal time by explicit scheme for 100 steps
```

```
*
run age=3600 step=1000000 tol=0.05
reset damp
cycle 4000
pr max
*
* run thermal time to 1 week
*
run age=6.048e5 delt=100.0 temp=10000  step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 month
*
run age=2.592e6 delt=1000.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 3 months
*
run age=7.776e6 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 6 months
*
run age=1.5552e7 delt=3600.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 9 months
*
run age=2.3328e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 1 year
*
run age=3.1536e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
```

```
reset damp
cycle 4000
pr max
save 20d_1y.sav
*
* run thermal time to 18 months
*
run age=4.7304e7 delt=7200.0  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 2 years
*
run age=6.3072e7 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_2y.sav
*
* run thermal time to 3 years
*
run age=9.4608e7 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
sav 20d_3y.sav
pr max
*
* run thermal time to 4 years
*
run age=1.26144e8 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_4y.sav
*
* run thermal time to 5 years
*
run age=1.5768e8 delt=2.16e4  temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_5y.sav
*
```

```
* run thermal time to 7.5 years
*
run age=2.3652e8 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 10 years
*
run age=3.1536e8 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_10y.sav
*
* run thermal time to 20 years
*
run age=6.3072e8 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
*
* run thermal time to 30 years
*
run age=9.4608e8 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_30y.sav
*
* run thermal time to 40 years
*
run age=12.6144e8 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
sav 20d_40y.sav
*
* run thermal time to 50 years
*
run age=1.5768e9 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 4000
pr max
```

```
sav 20d_50y.sav
*
* run thermal time to 100 years
*
run age=3.1536e9 delt=2.16e4 temp=10000 step=1000000 tol=0.05 impl
reset damp
cycle 7500
pr max
sav 20d_100.sav
return
```

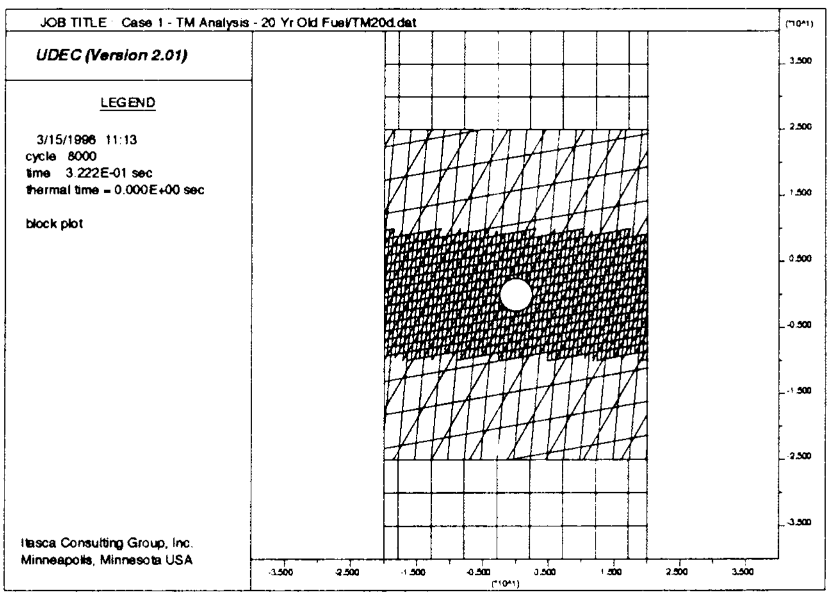
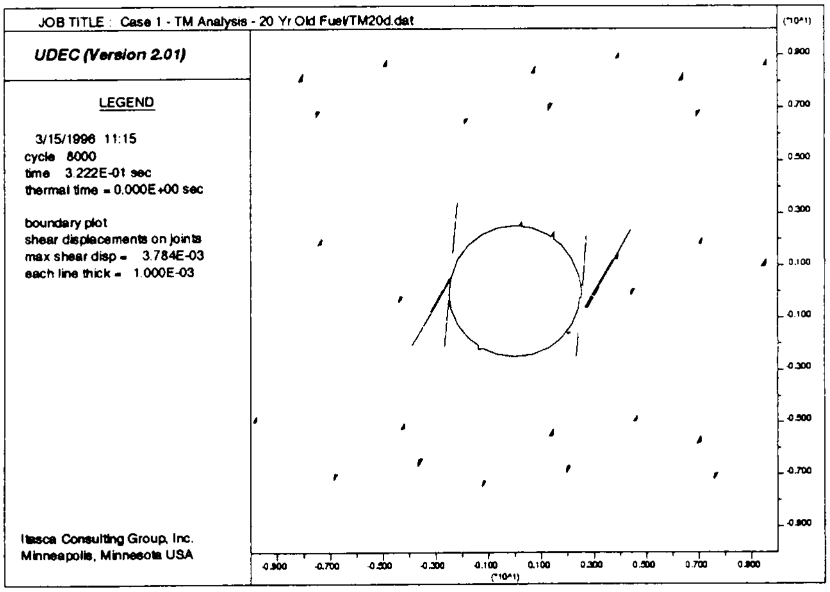
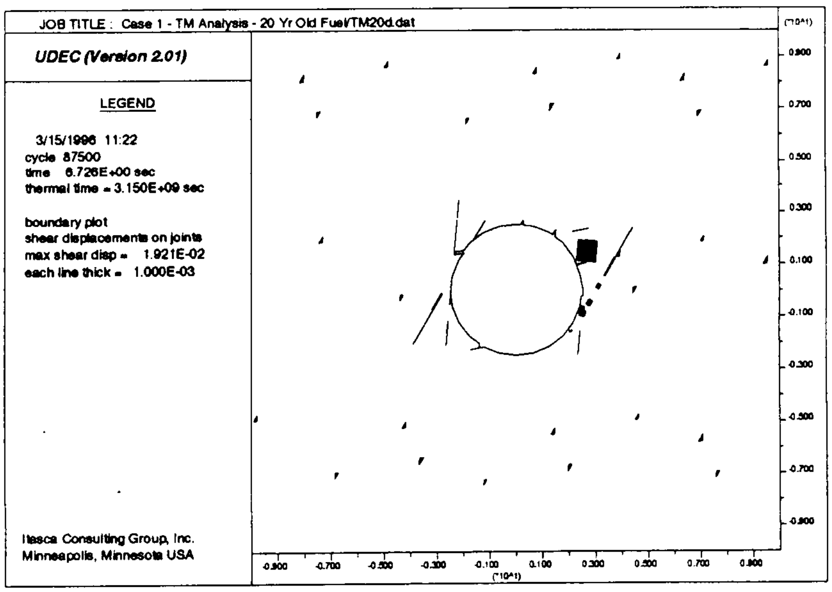


Figure K-1. UDEC discrete element mesh plot - Case TM20D



MPA 3/25/96

Figure K-2. Joint shear displacements after excavation (maximum = ~~3.046~~ 3.784 mm) - Case TM20D



MPA 3/25/96

Figure K-3. Joint shear displacements after 100 years (maximum = ~~1.706~~ 1.921 cm) - Case TM20D

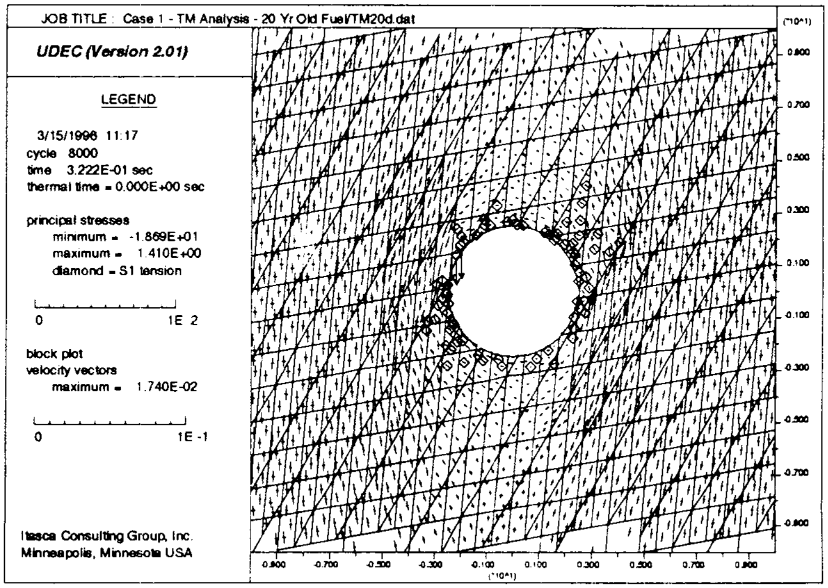
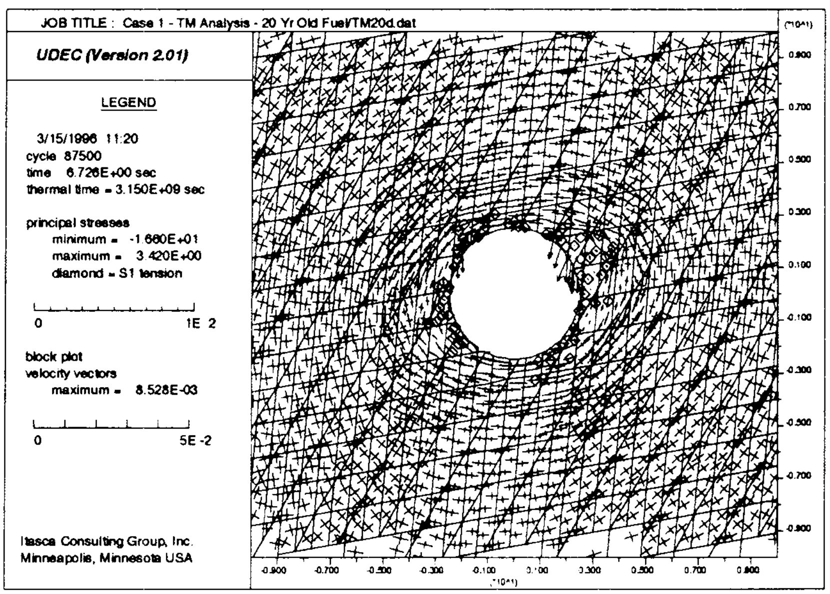


Figure K-4. Principal stress distribution after excavation (maximum = ~~13.02~~ 18.69 MPa) Case TM20D



16.60 MPA 3/25/96

Figure K-5. Principal stress and velocity vectors after 100 years (maximum stress = ~~56.24~~ MPa) Case TM20D

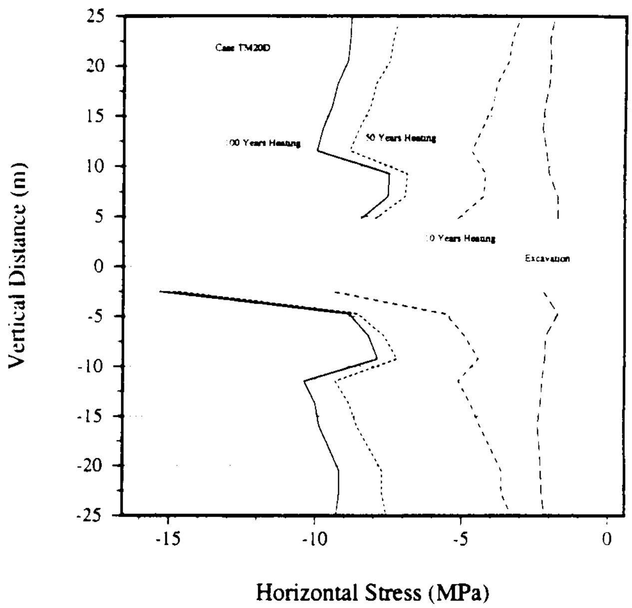


Figure K-6. Horizontal stress along a vertical section through center of tunnel - Case TM20D

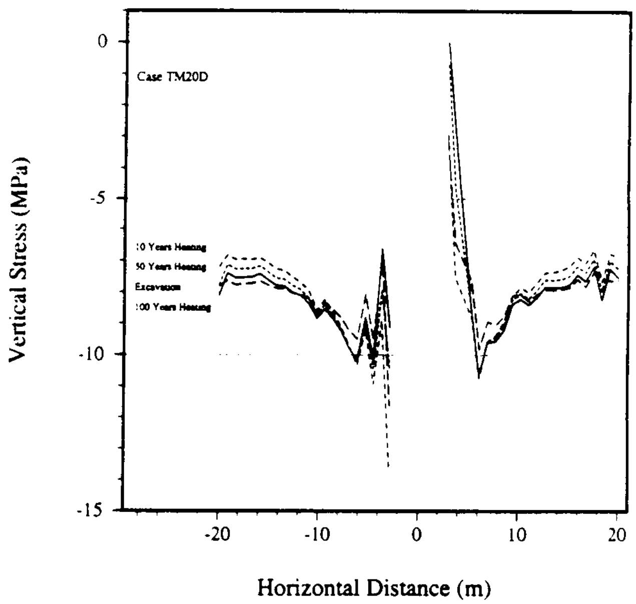


Figure K-7. Vertical stress along a vertical section through center of tunnel - Case TM20D

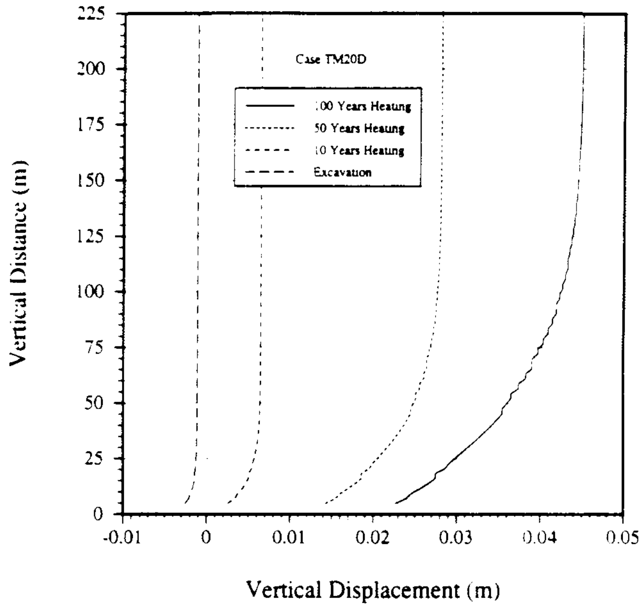


Figure K-8. Vertical expansion with distance at select time periods - Case TM20D

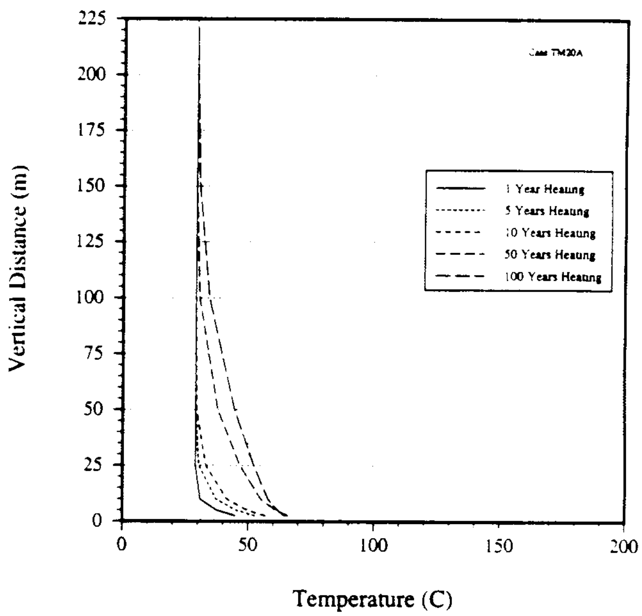


Figure K-9. V~~ertical displacement at tunnel roof with~~ time - Case TM20D

Temperature with vertical distance above tunnel roof at select times

Temperature along vertical line above tunnel (x=0.0)
Case TM20D: Time(years) vs y-coord (m)

y-coord	~~0yr~~	~~1~~ 0	~~2~~ 1	~~3~~ 2	~~4~~ 3	~~5~~ 4	~~10~~ 5	~~50~~ 10	~~100~~ 50	100 years
1	2.5	29.0	44.2	47.2	49.1	50.4	51.5	55.3	63.9	64.0
2	5.0	29.0	36.8	39.8	41.7	43.1	44.2	48.3	59.1	60.1
3	10.0	29.0	31.4	33.7	35.3	36.6	37.7	41.8	54.4	56.8
4	25.0	29.0	29.0	29.2	29.5	29.9	30.4	32.9	45.7	50.8
5	50.0	29.0	29.0	29.0	29.0	29.0	29.0	29.4	37.7	43.6
6	100.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	30.3	34.1
7	150.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.1	30.3
8	200.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.2
9	225.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Time (yrs)	TM20D.DAT			
	Roof Uy (cm)	Floor Uy (cm)	σ_{xx} (MPa) (0.0,3.0)	σ_{yy} (MPa) (3,0,0.0)
0	-0.3041	0.1938	-1.903	-17.52
1	-0.1937	0.3087	-3.516	-20.51
2	-0.1537	0.3394	-4.043	-20.96
3	-0.1119	0.3704	-4.389	-21.09
4	-0.07227	0.3990	-4.767	-21.15
5	-0.03303	0.4280	-5.089	-21.17
10	0.1579	0.5779	-6.091	-21.35
50	1.301	1.605	-9.499	-20.85
100	2.128	2.437	-10.37	-10.42

Appendix L -

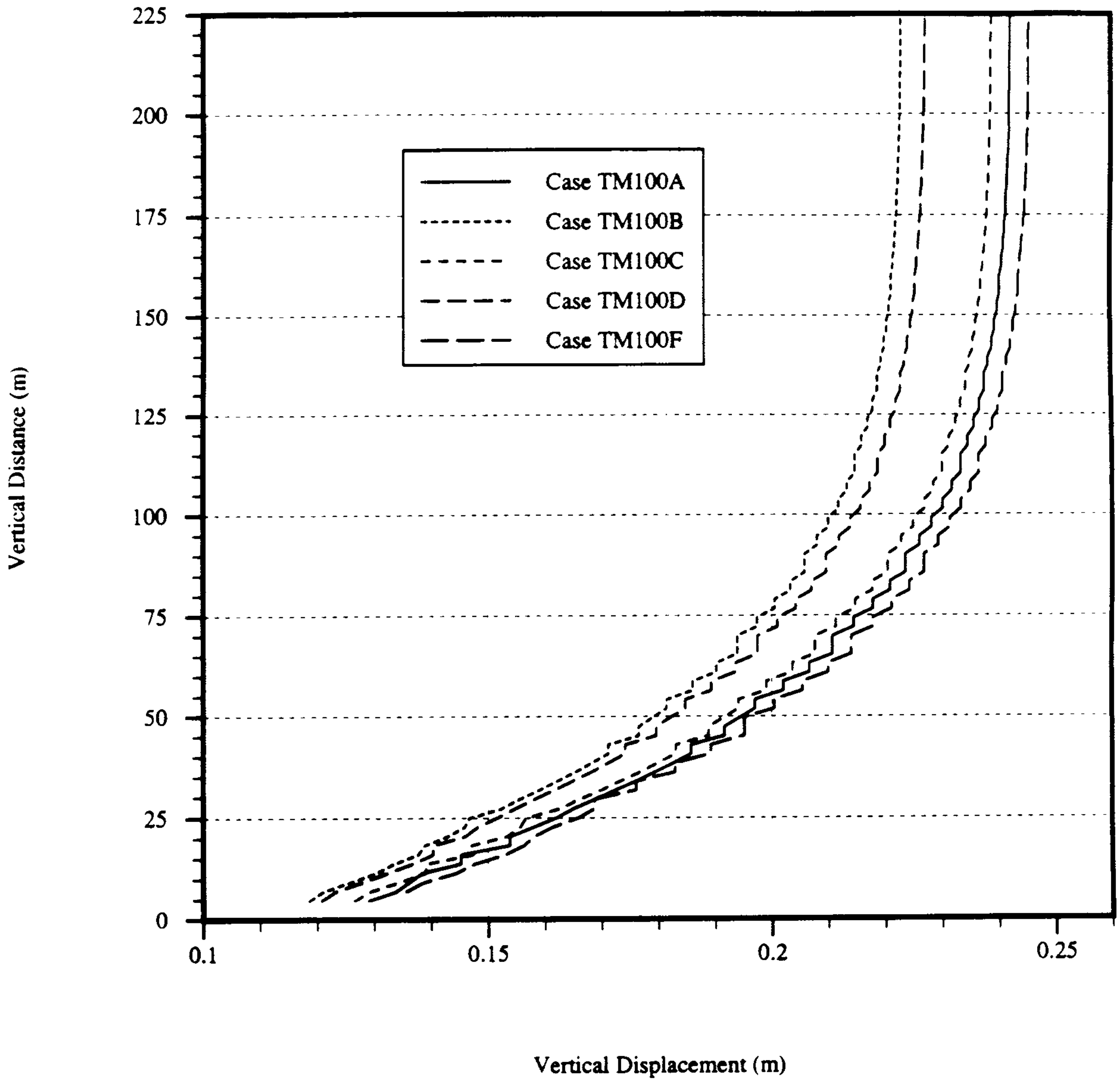


Figure L-1 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for different joint patterns for 100 MTU/Acre thermal load

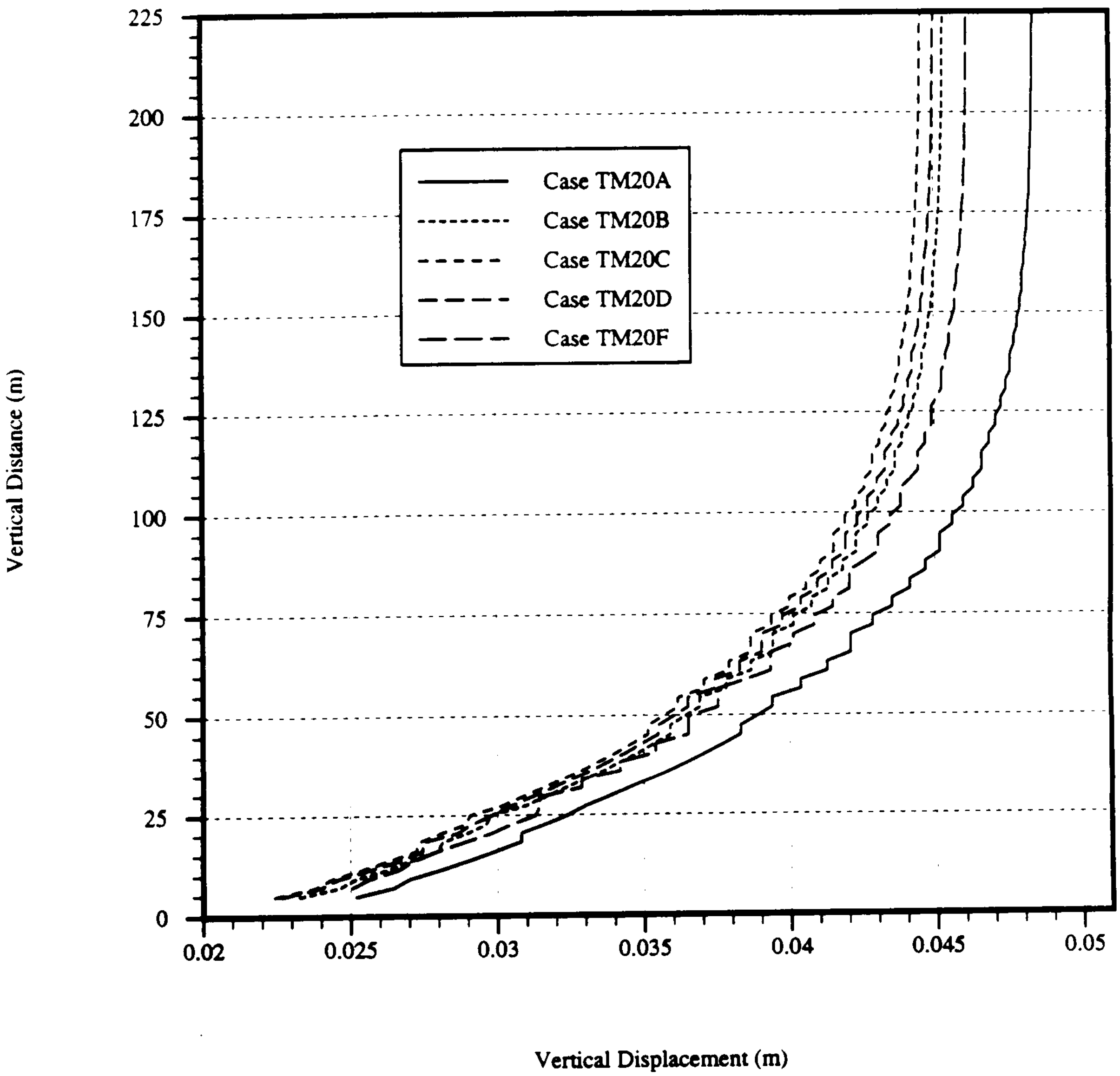


Figure L-2 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for different joint patterns for 20 MTU/Acre thermal load

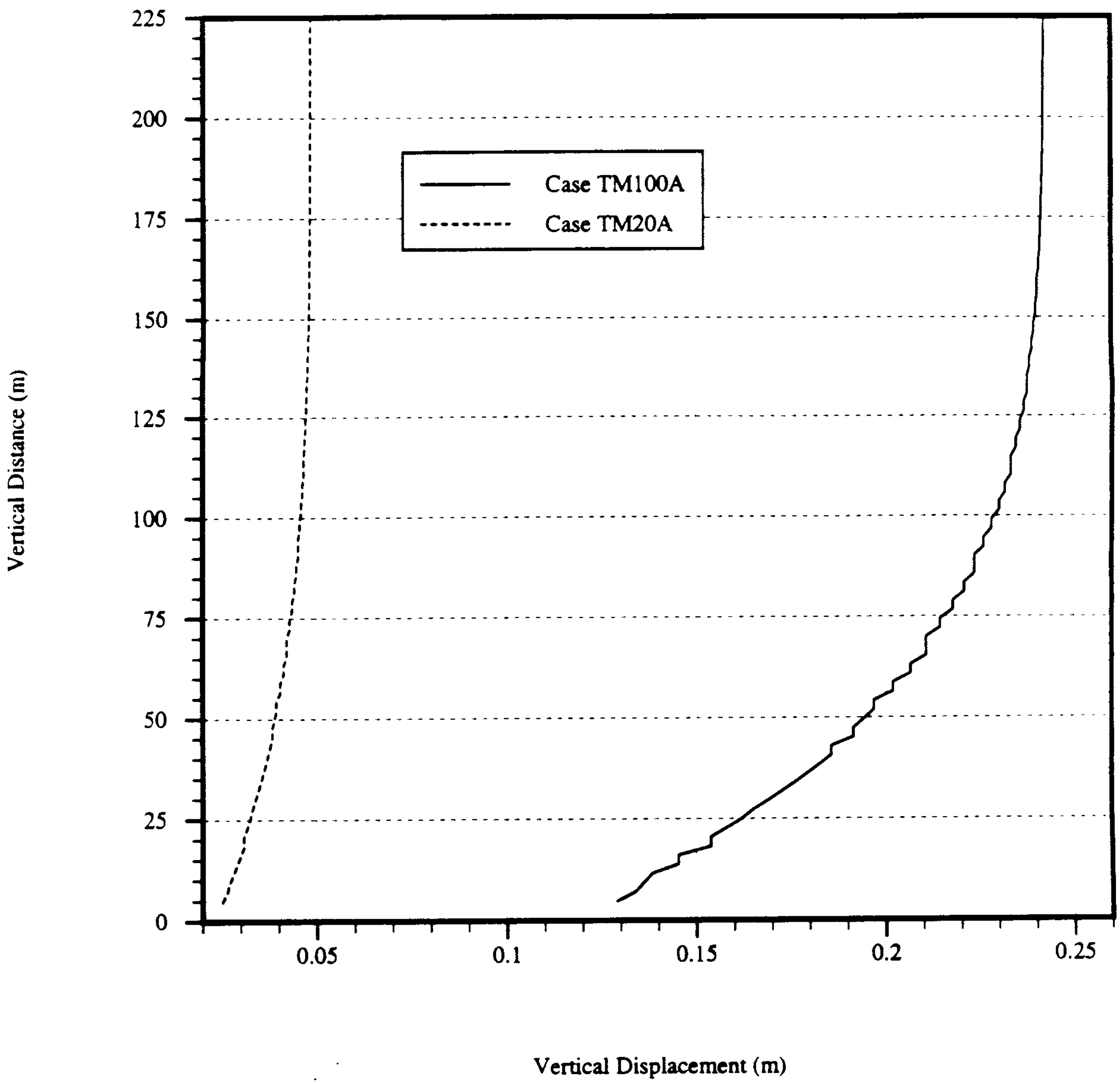


Figure L-3 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for joint pattern A (Case A)

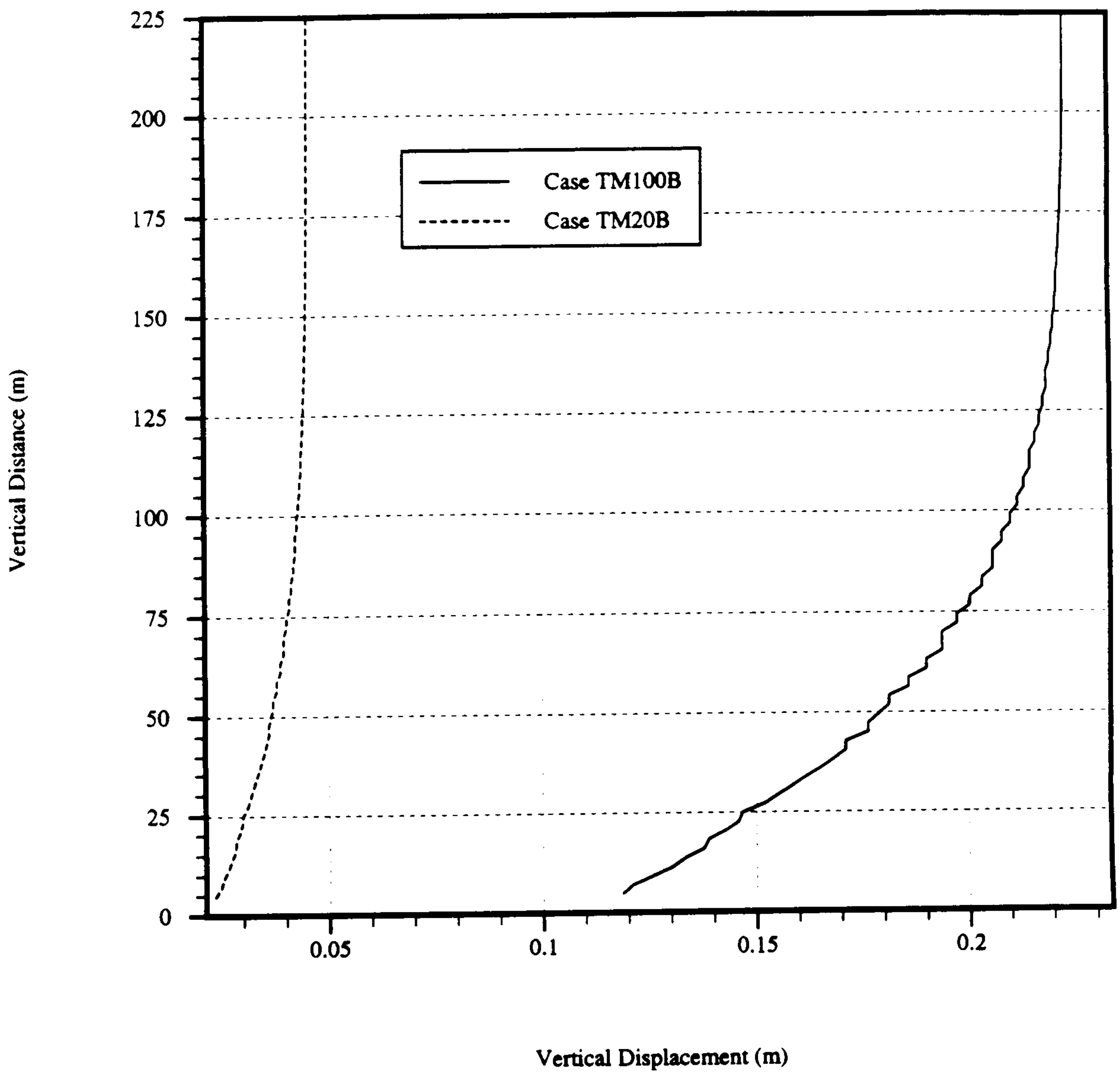


Figure L-4 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for joint pattern B (Case B)

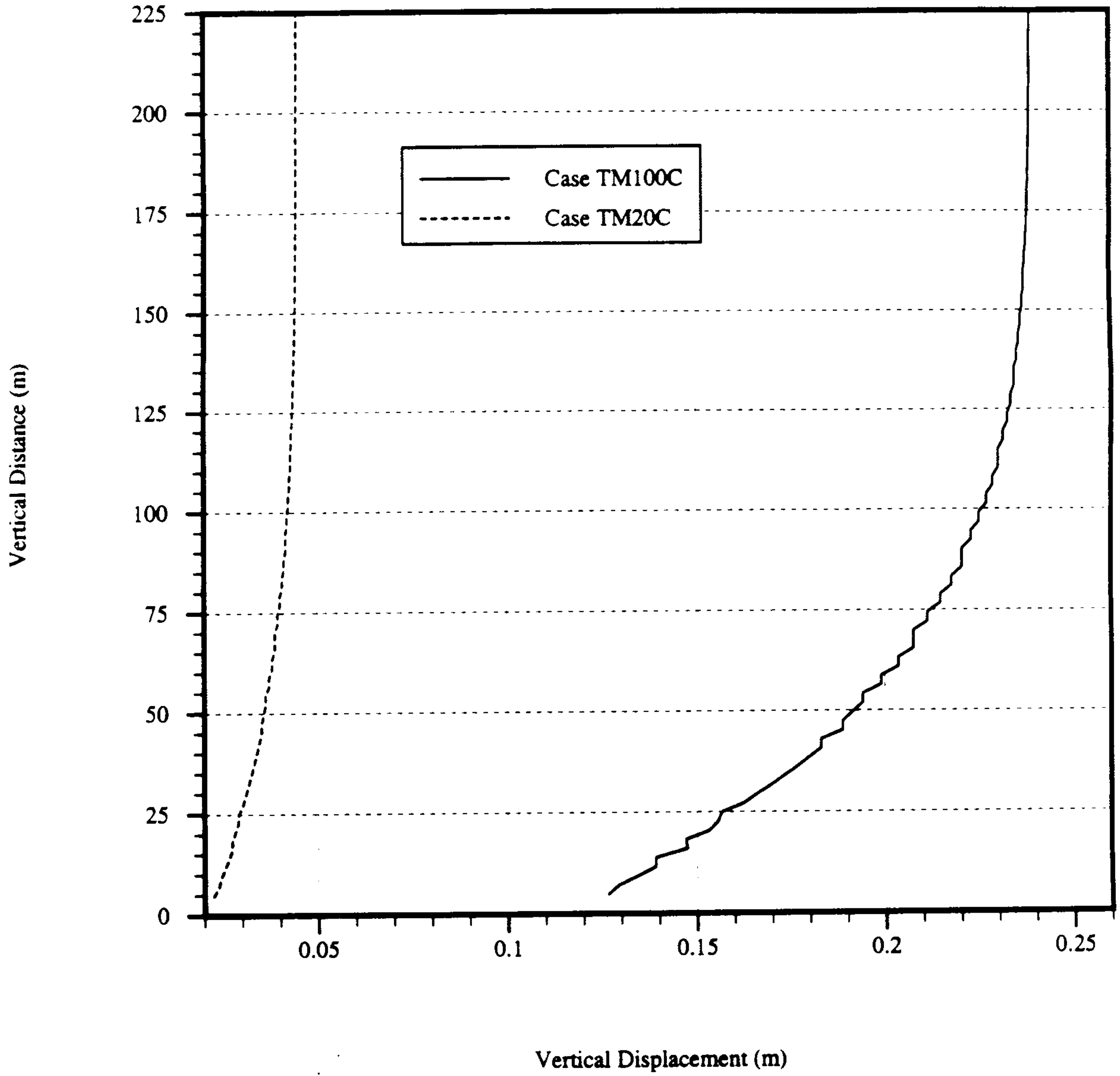


Figure L-5 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for joint pattern C (Case C)

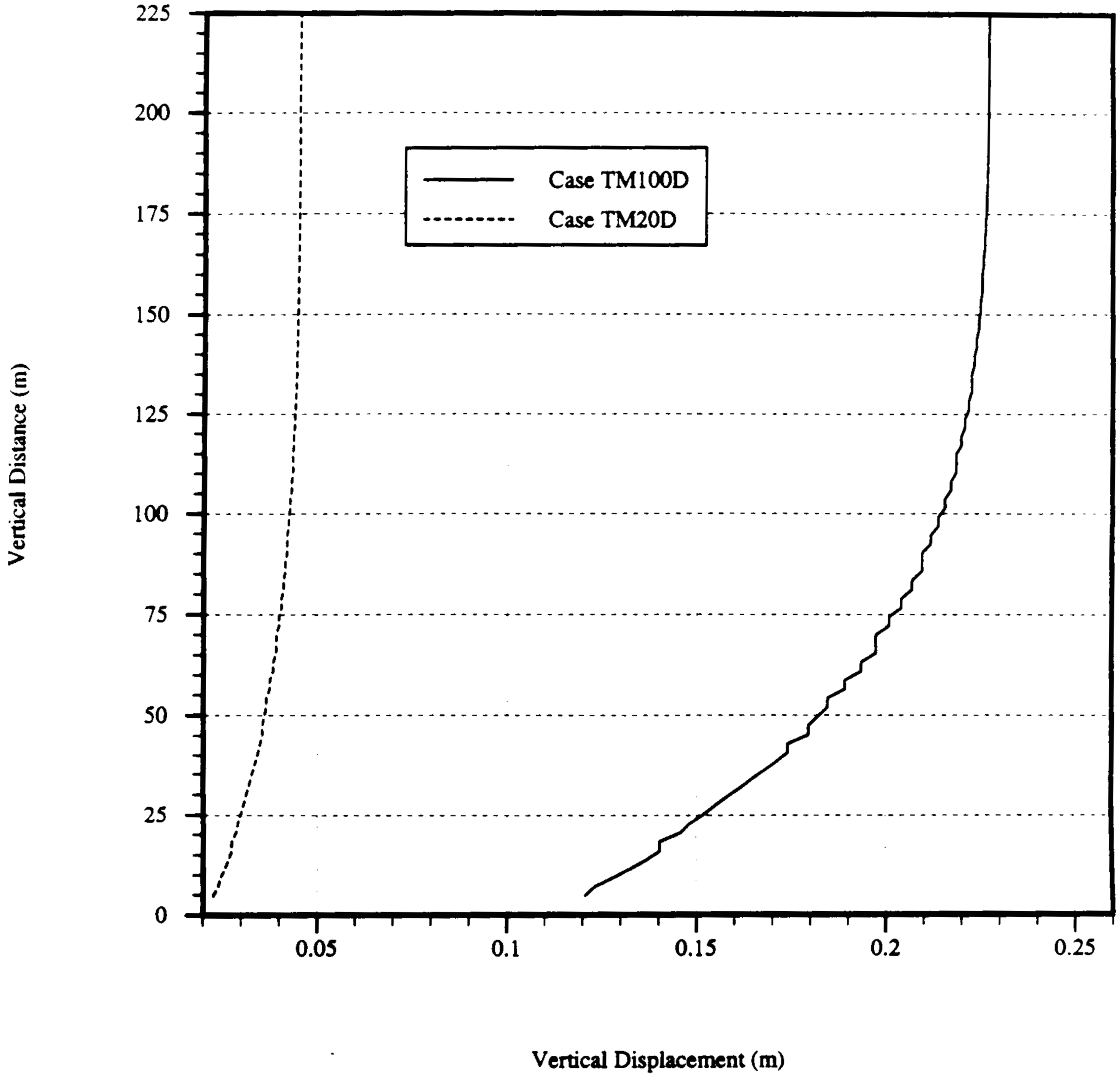


Figure L-6 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for joint pattern D (Case D)

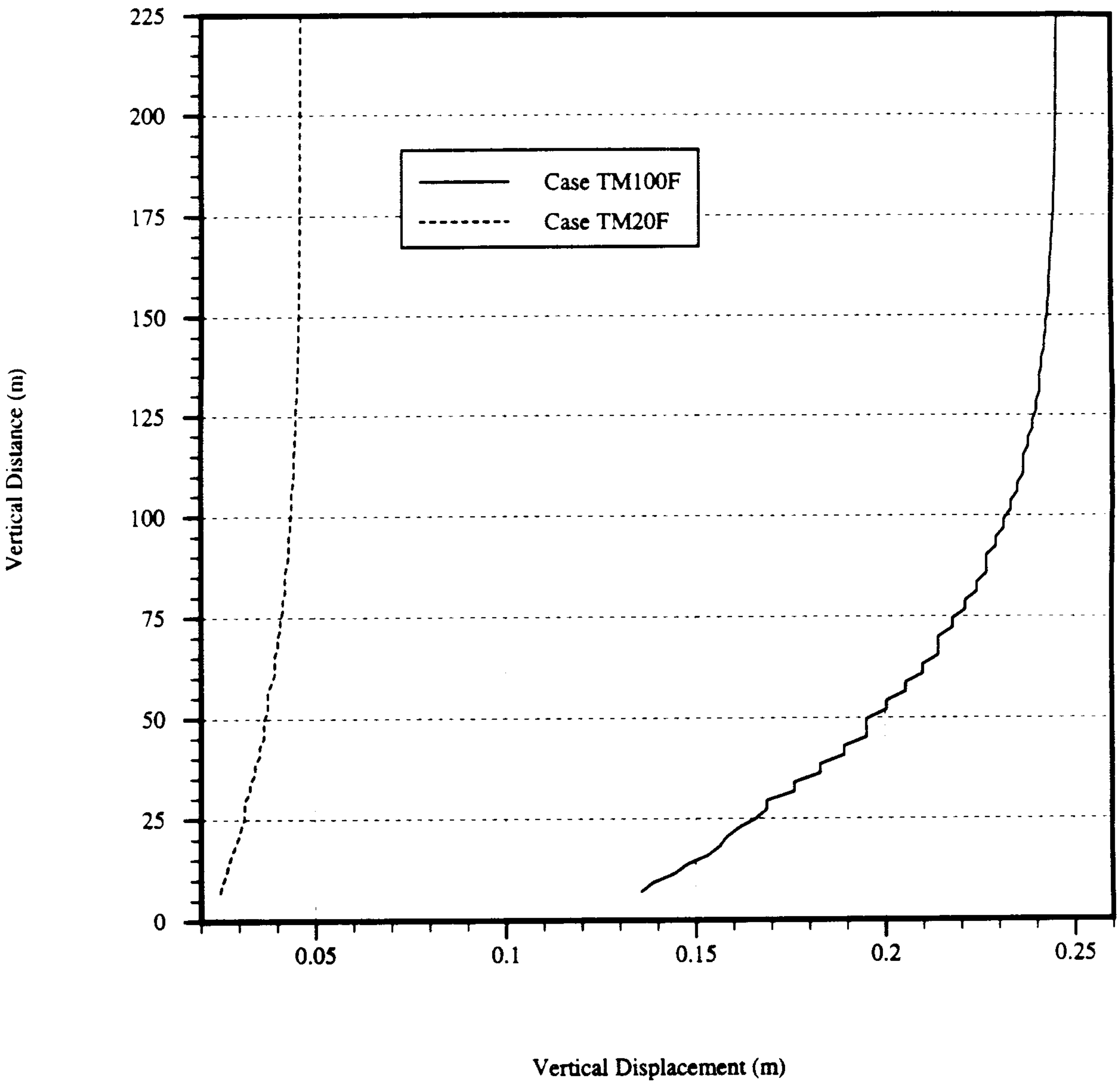


Figure L-7 Vertical displacement after 100 years of heating along a vertical section through model centerline above the tunnel for joint pattern F (Case F)

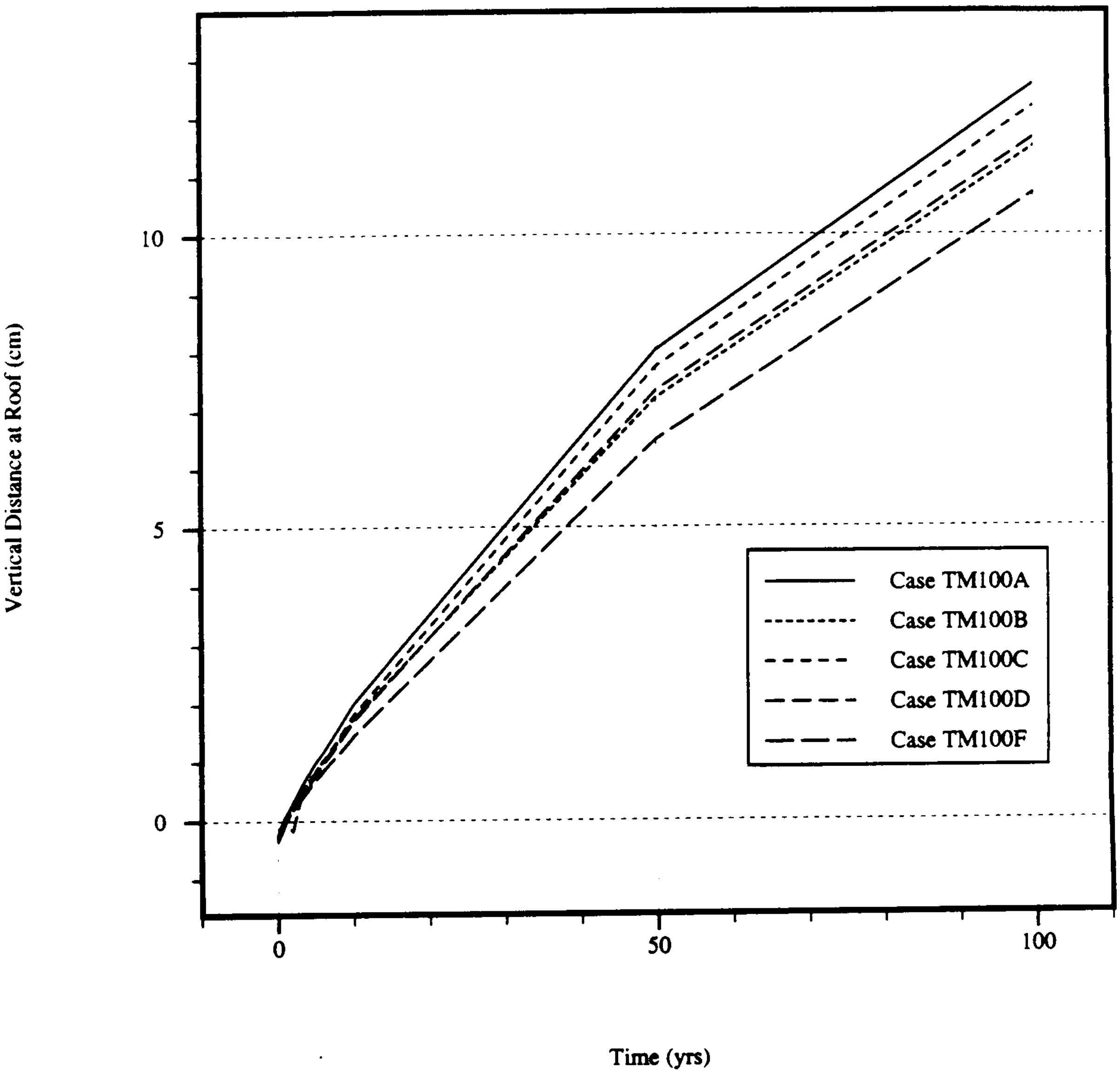


Figure L-8 Vertical displacement at roof as a function of time for different joint patterns for the thermal load of 100 MTU/Acre

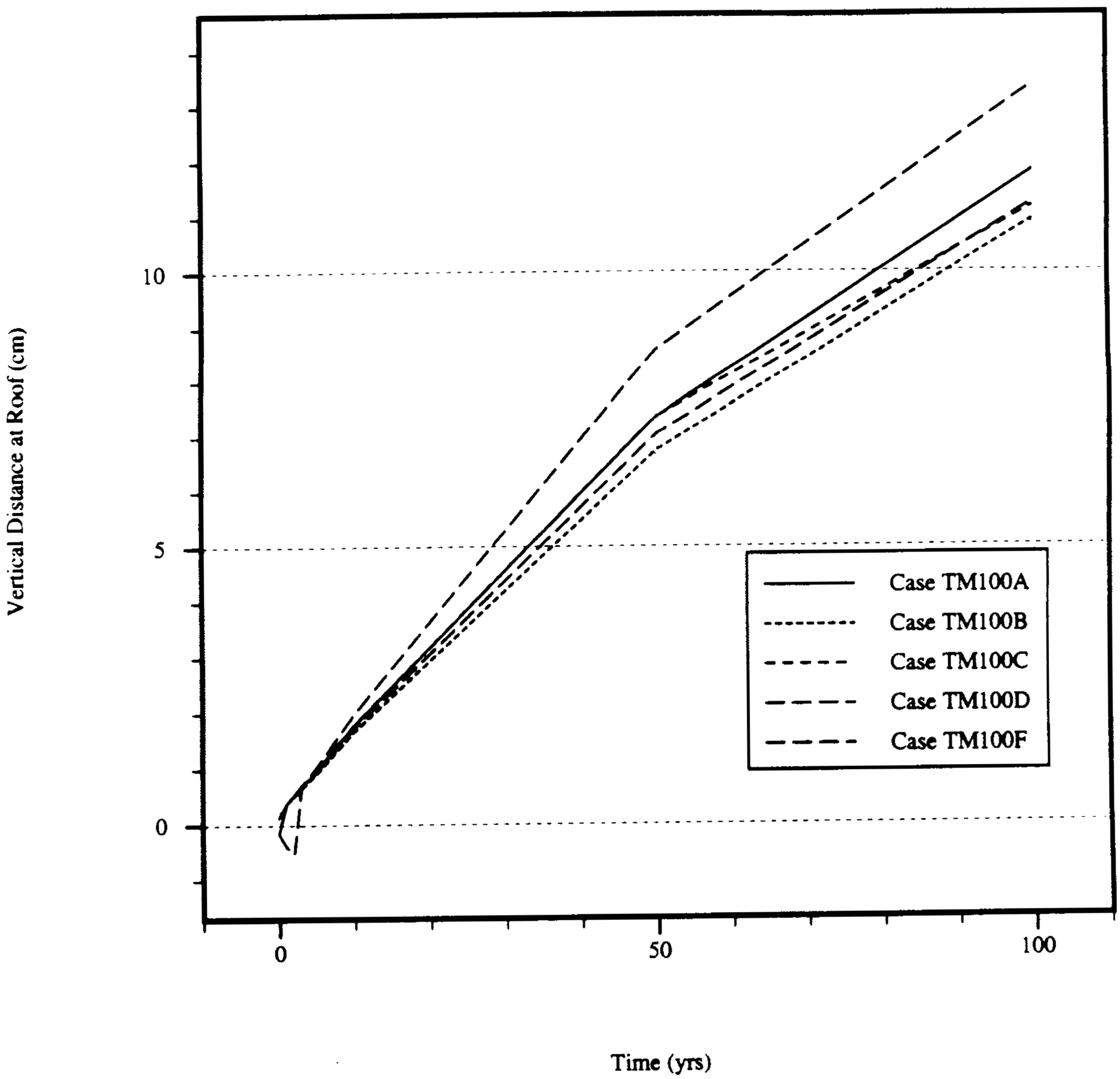


Figure L-9 Vertical displacement at floor as a function of time for different joint patterns for the thermal load of 100 MTU/Acre

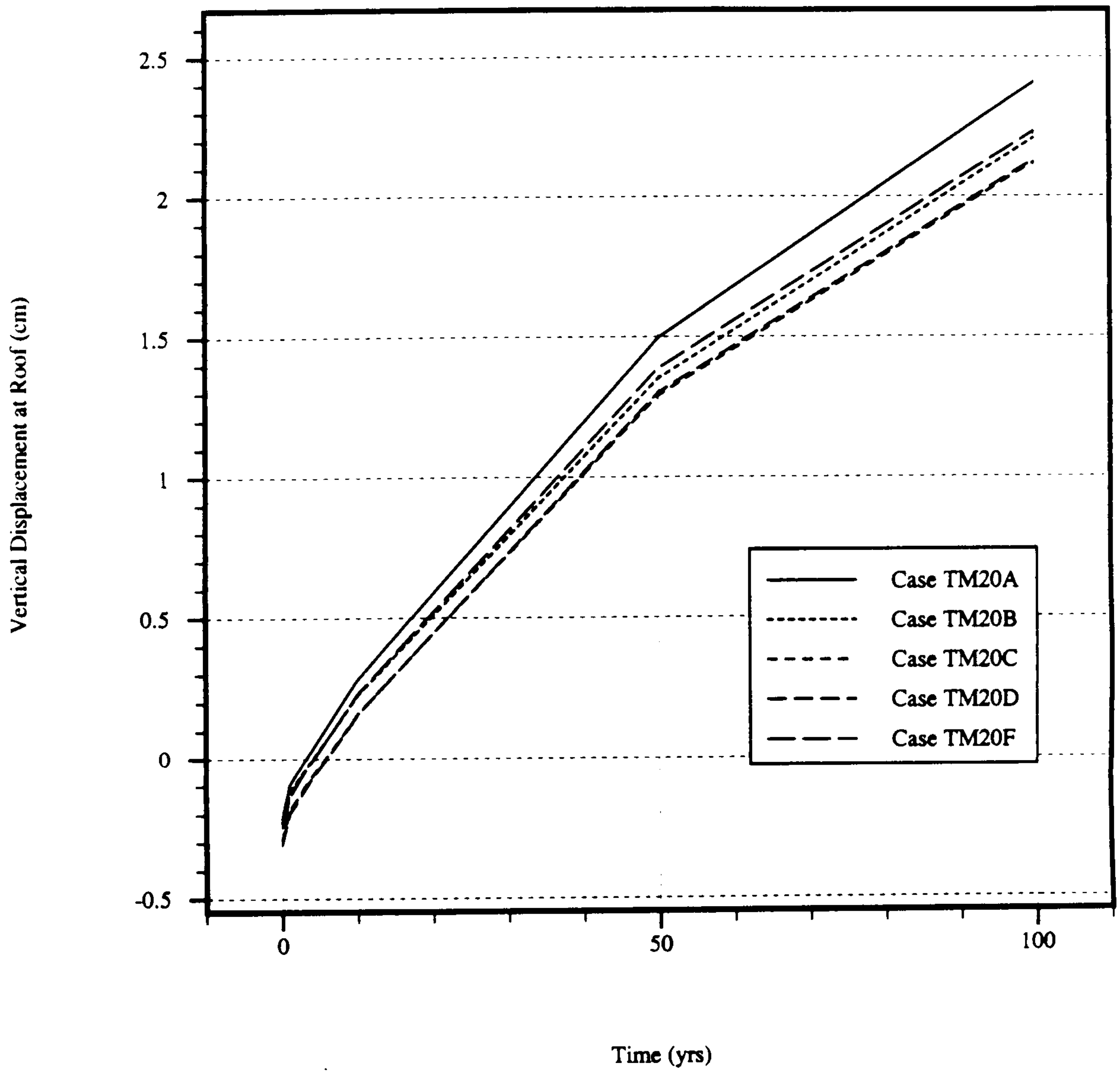


Figure L-10 Vertical displacement at roof as a function of time for different joint patterns for the thermal load of 20 MTU/Acre

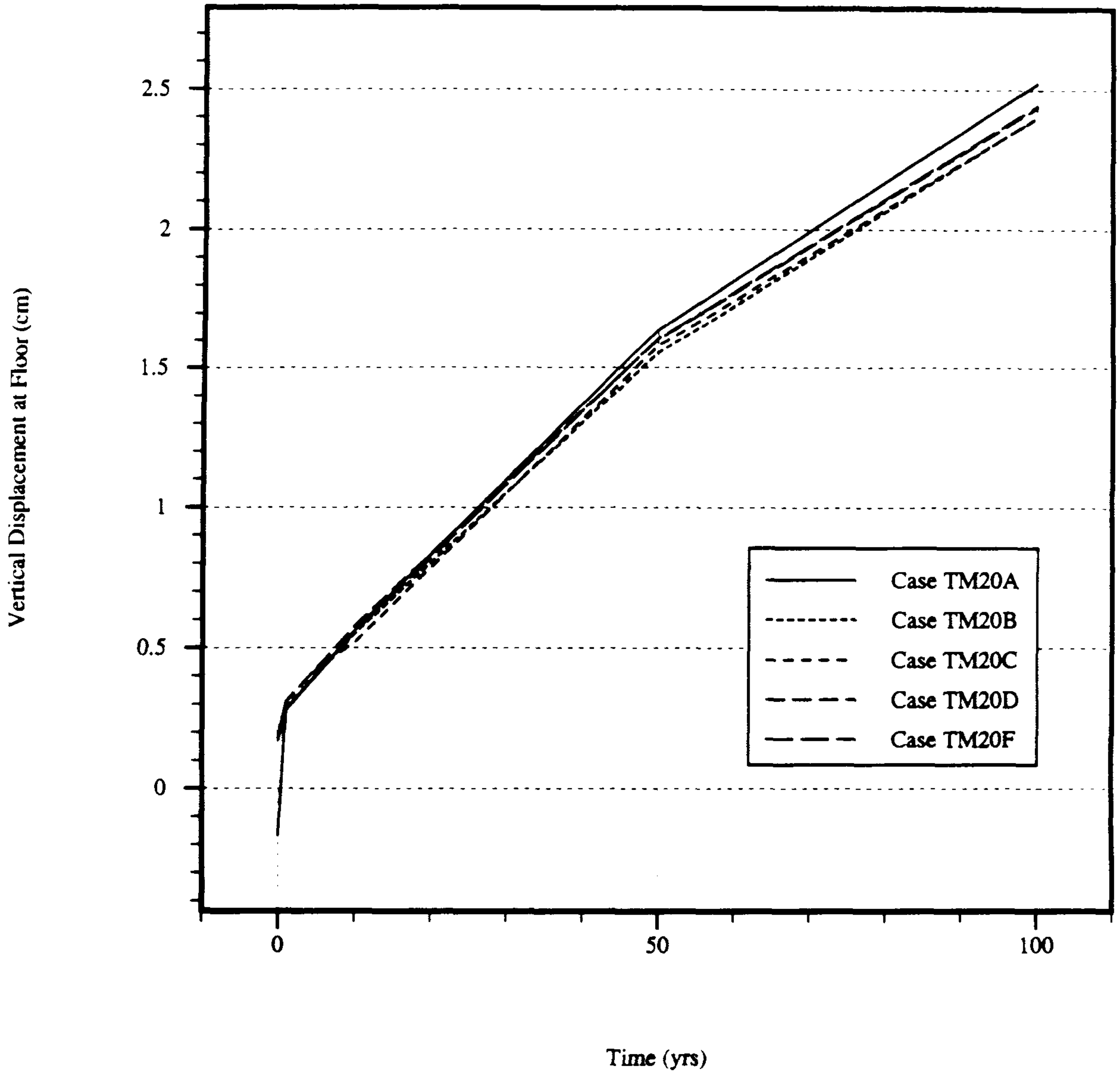


Figure L-11 Vertical displacement at floor as a function of time for different joint patterns for the thermal load of 20 MTU/Acre

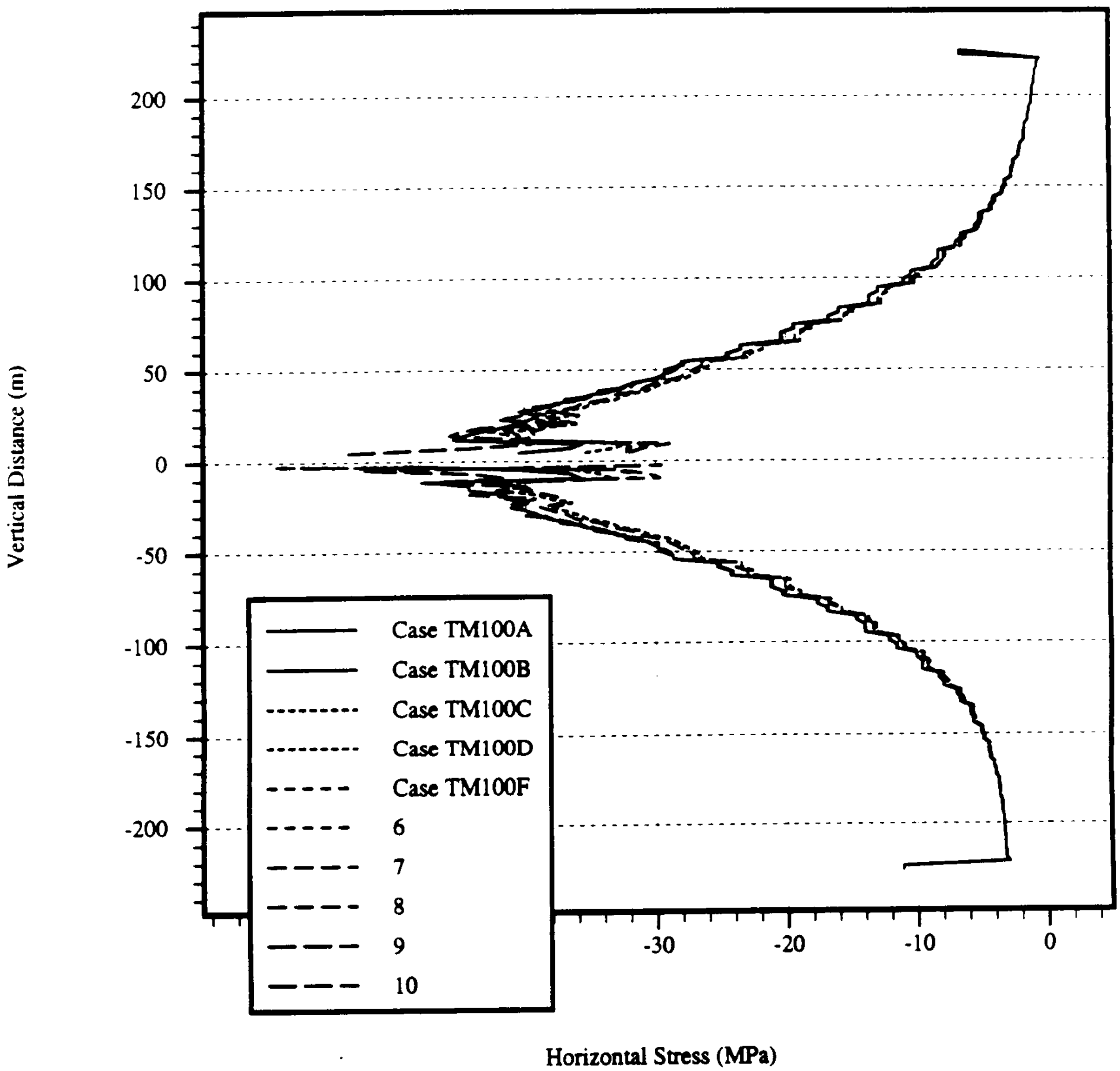


Figure L-12 Horizontal stress after 100 years of heating along a vertical section through the tunnel for the thermal loading of 100 MTU/Acre

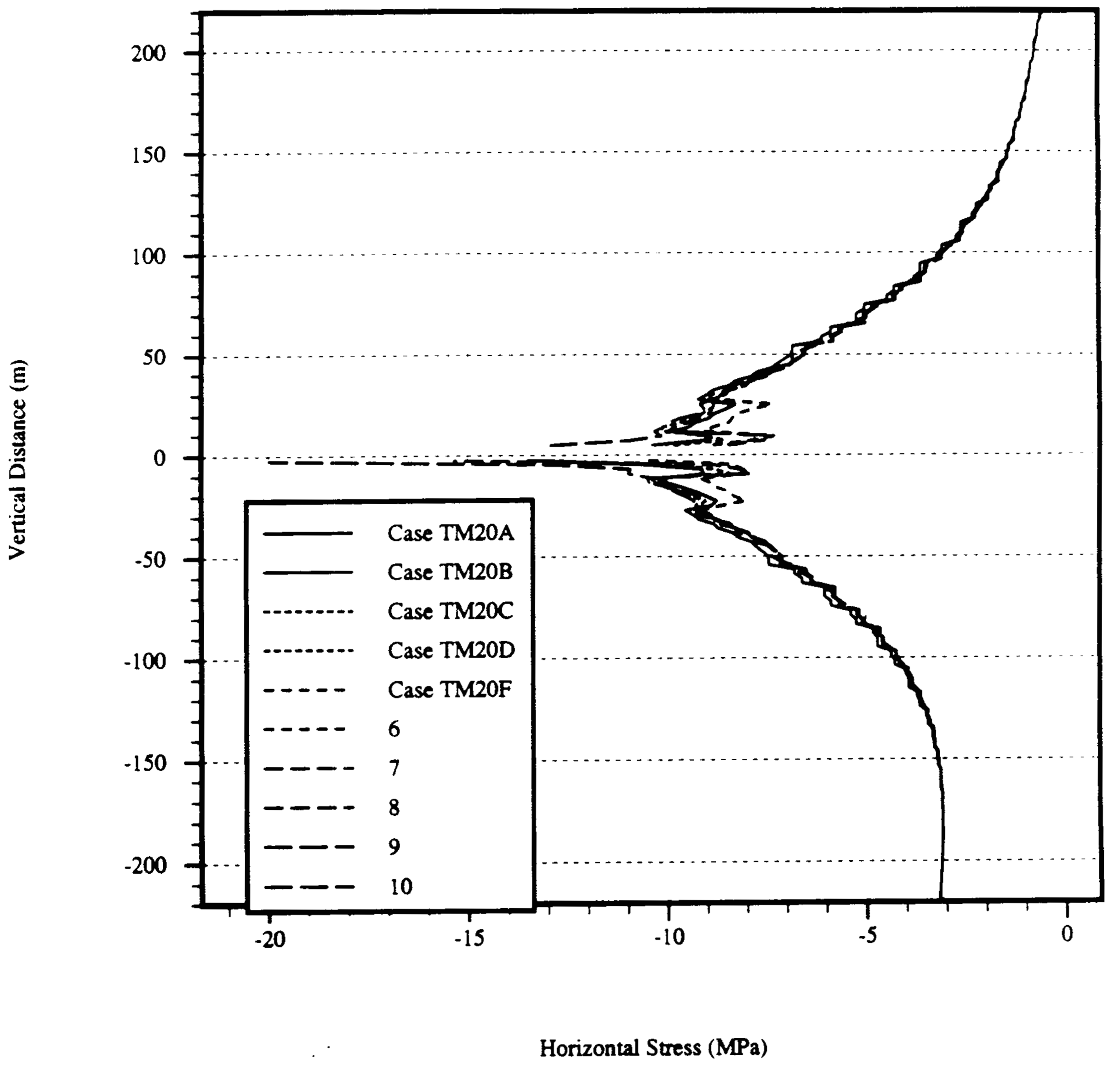


Figure L-13 Horizontal stress after 100 years of heating along a vertical section through the tunnel for the thermal loading of 20 MTU/Acre

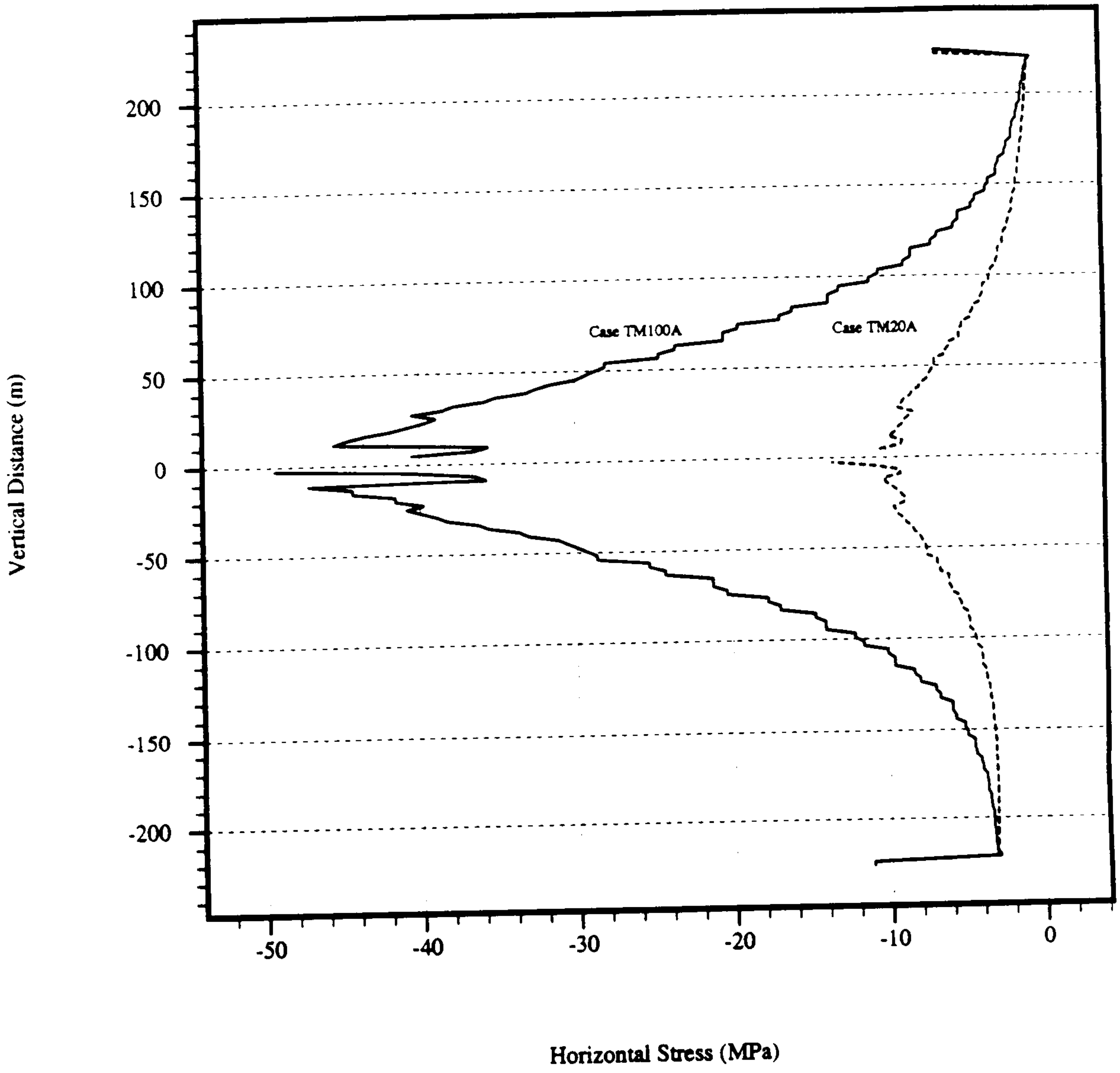


Figure L-14 Horizontal stress after 100 years of heating along a vertical section through the tunnel for joint pattern A (Case A)

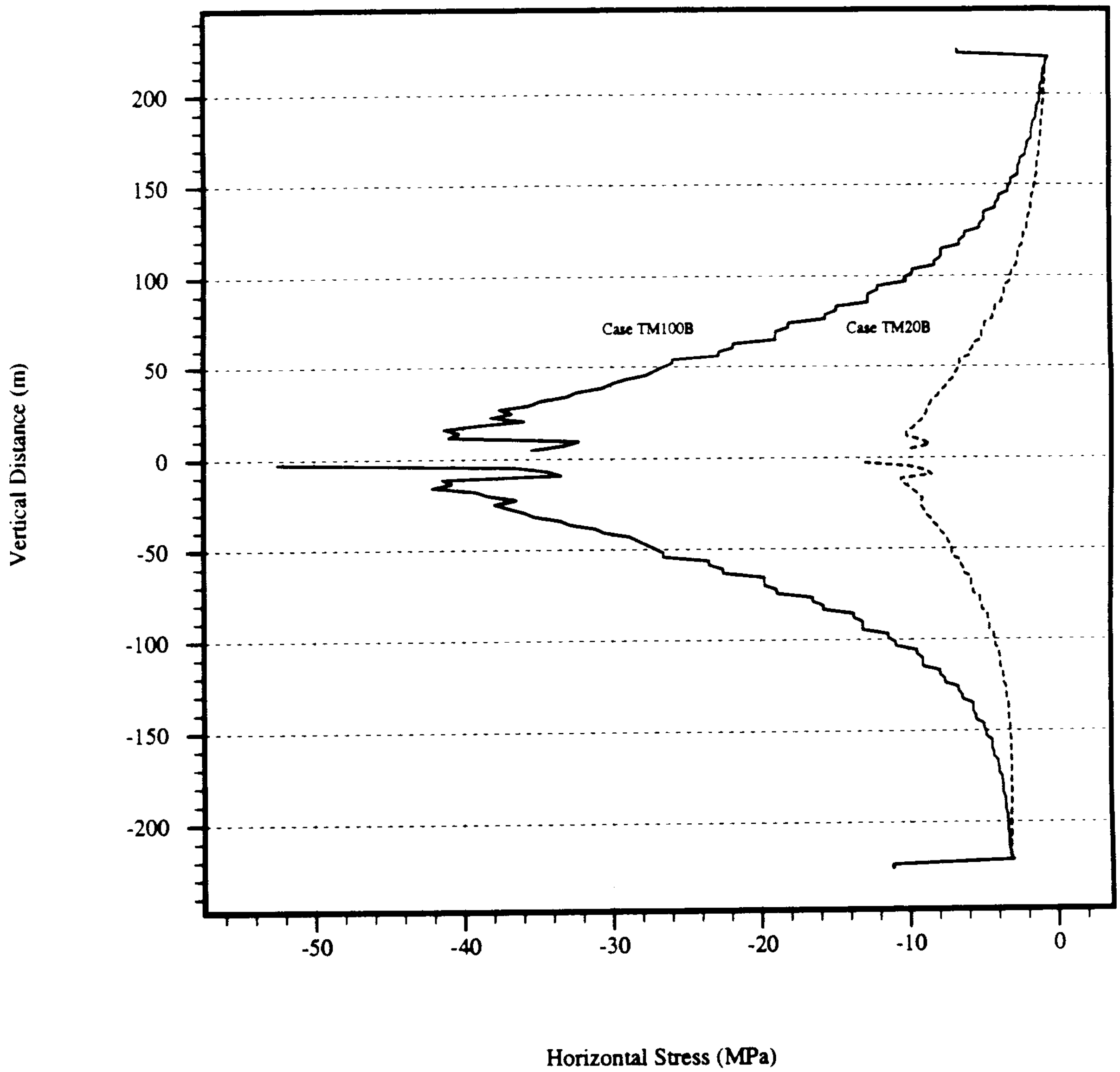


Figure L-15 Horizontal stress after 100 years of heating along a vertical section through the tunnel for joint pattern B (Case B)

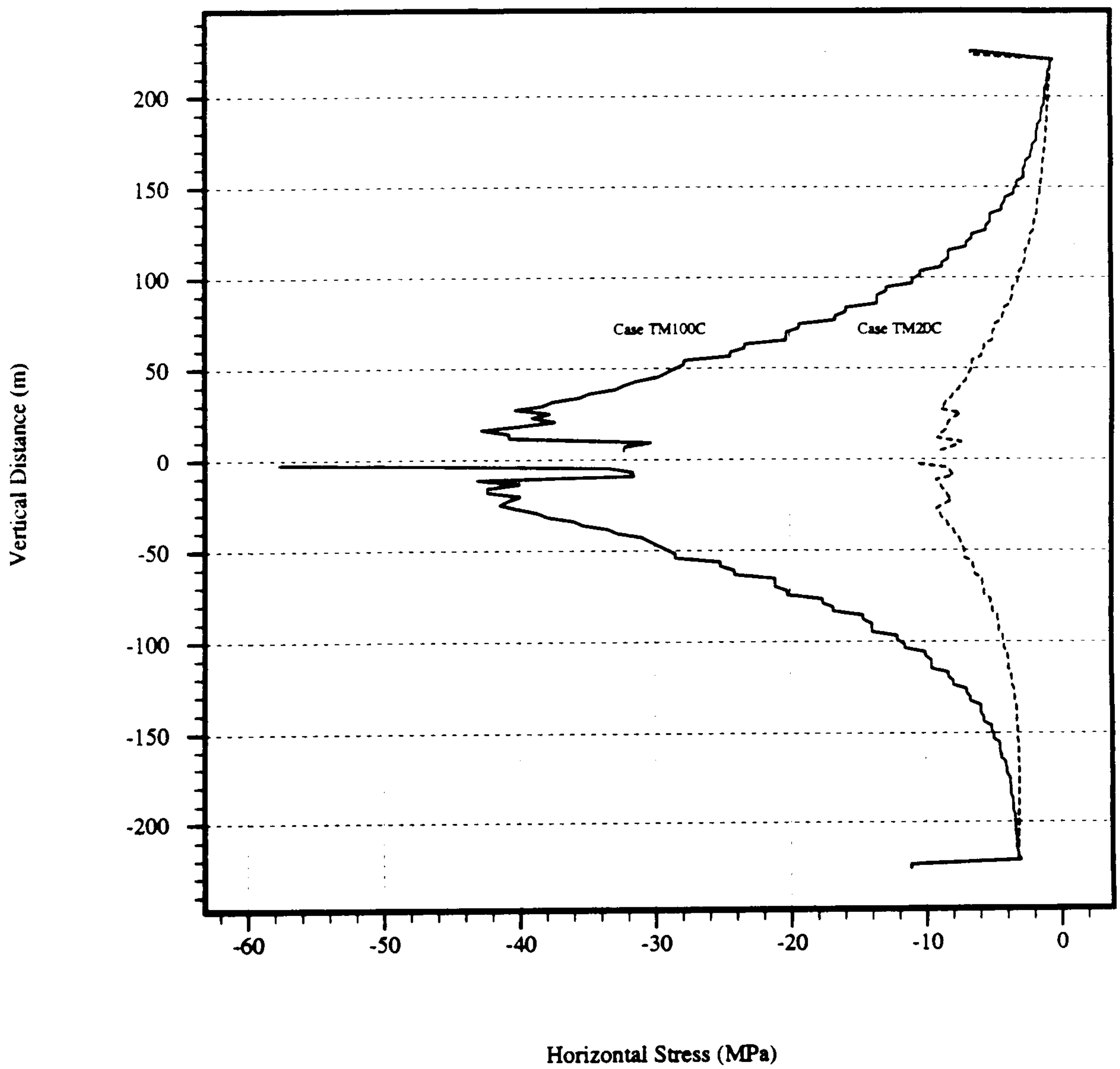


Figure L-16 Horizontal stress after 100 years of heating along a vertical section through the tunnel for joint pattern C (Case C)

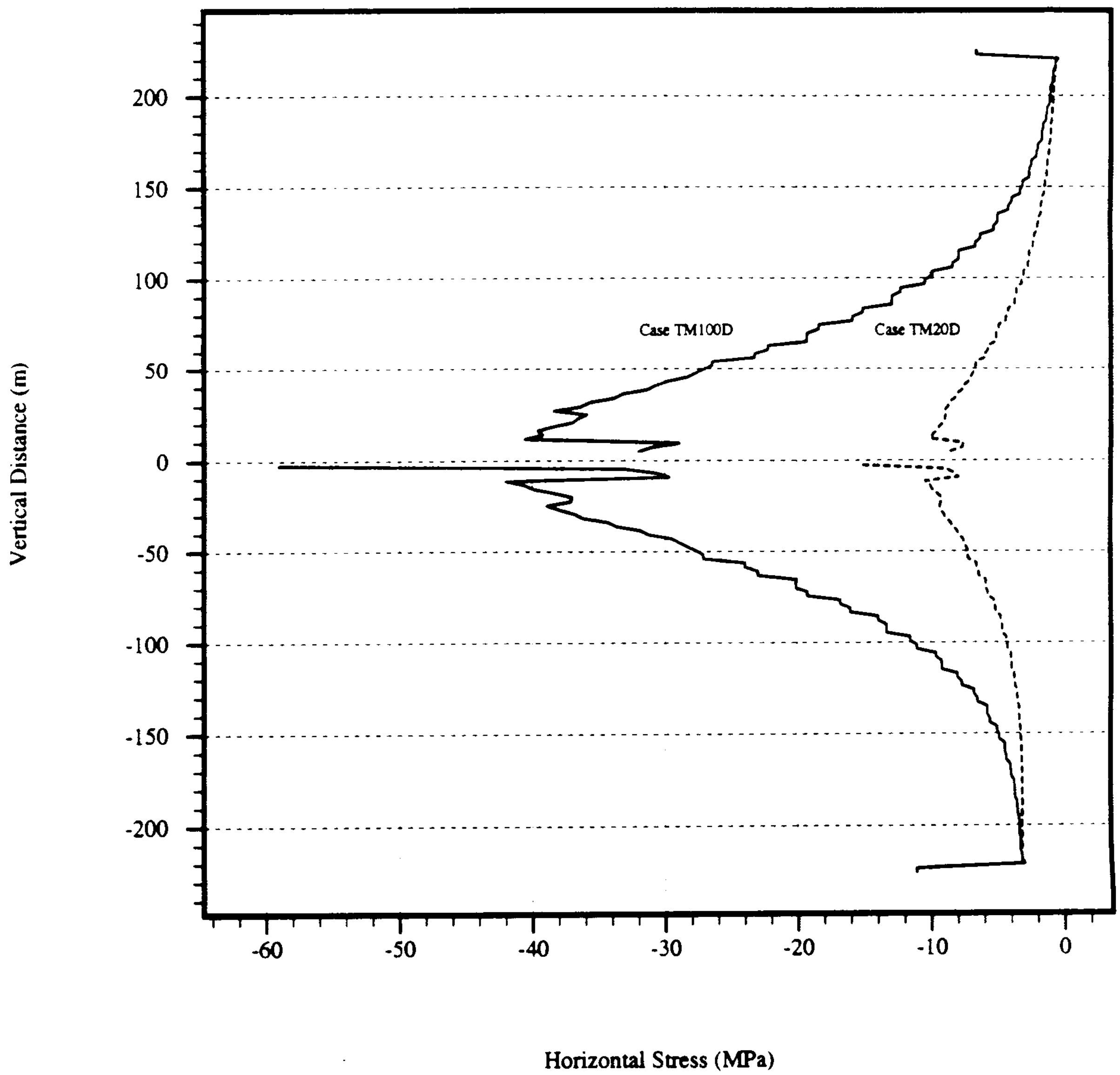


Figure L-17 Horizontal stress after 100 years of heating along a vertical section through the tunnel for joint pattern D (Case D)

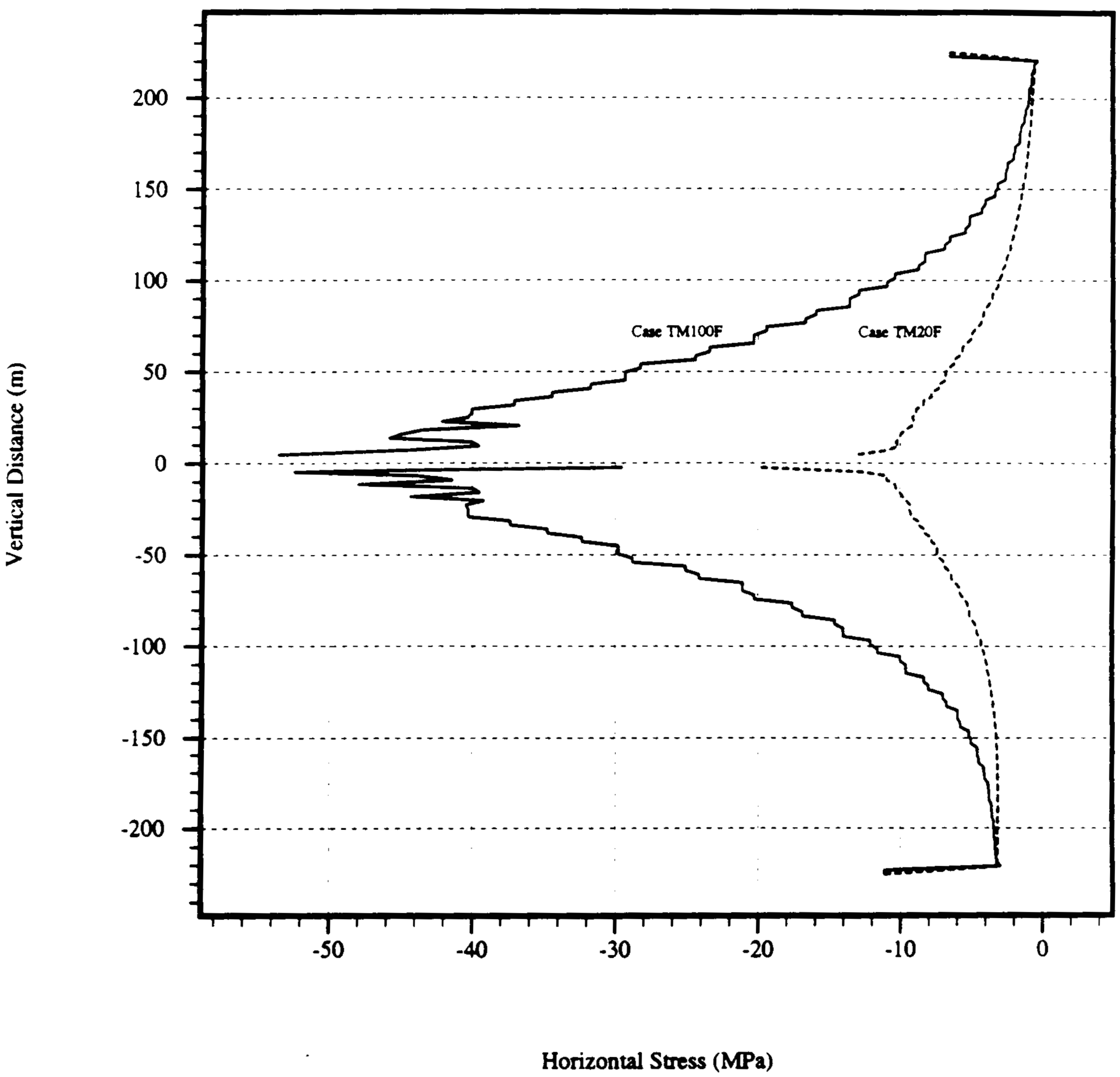


Figure L-18 Horizontal stress after 100 years of heating along a vertical section through the tunnel for joint pattern F (Case F)

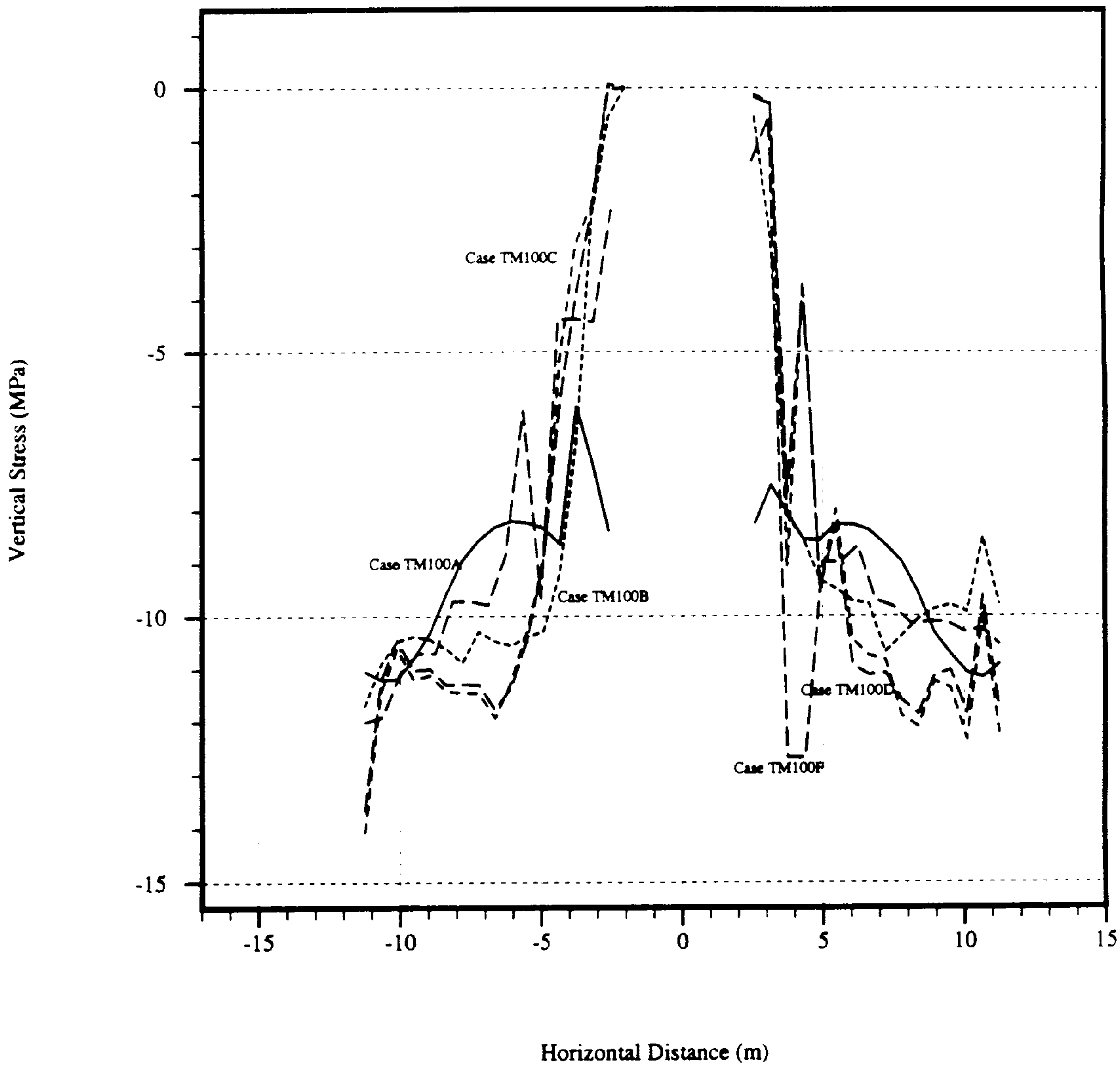


Figure L-19 Vertical stress after 100 years of heating along a horizontal section through the tunnel for the thermal loading of 100 MTU/Acre

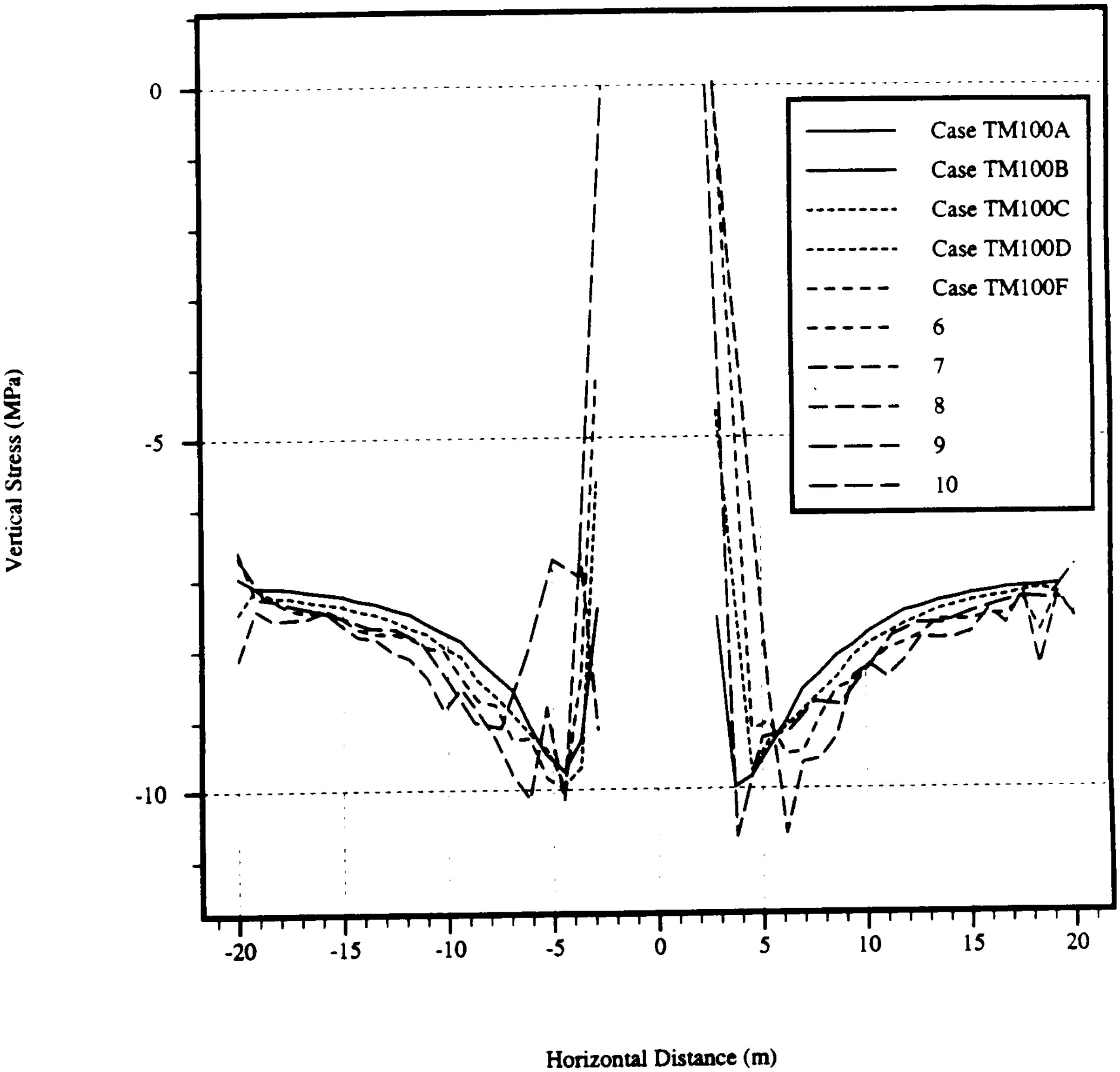


Figure L-20 Vertical stress after 100 years of heating along a horizontal section through the tunnel for the thermal loading of 20 MTU/Acre

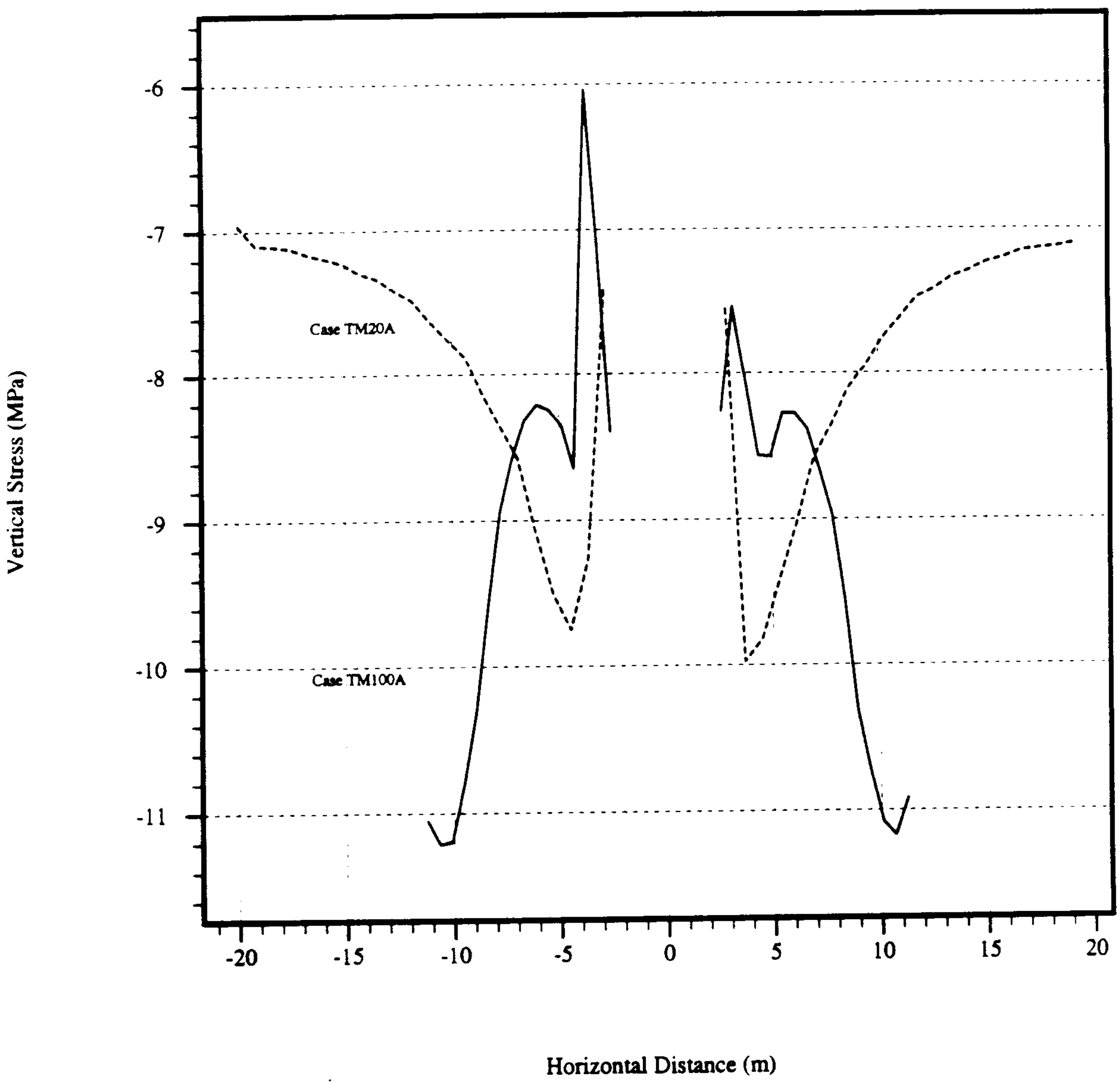


Figure L-21 Vertical stress after 100 years of heating along a horizontal section through the tunnel for joint pattern A (Case A)

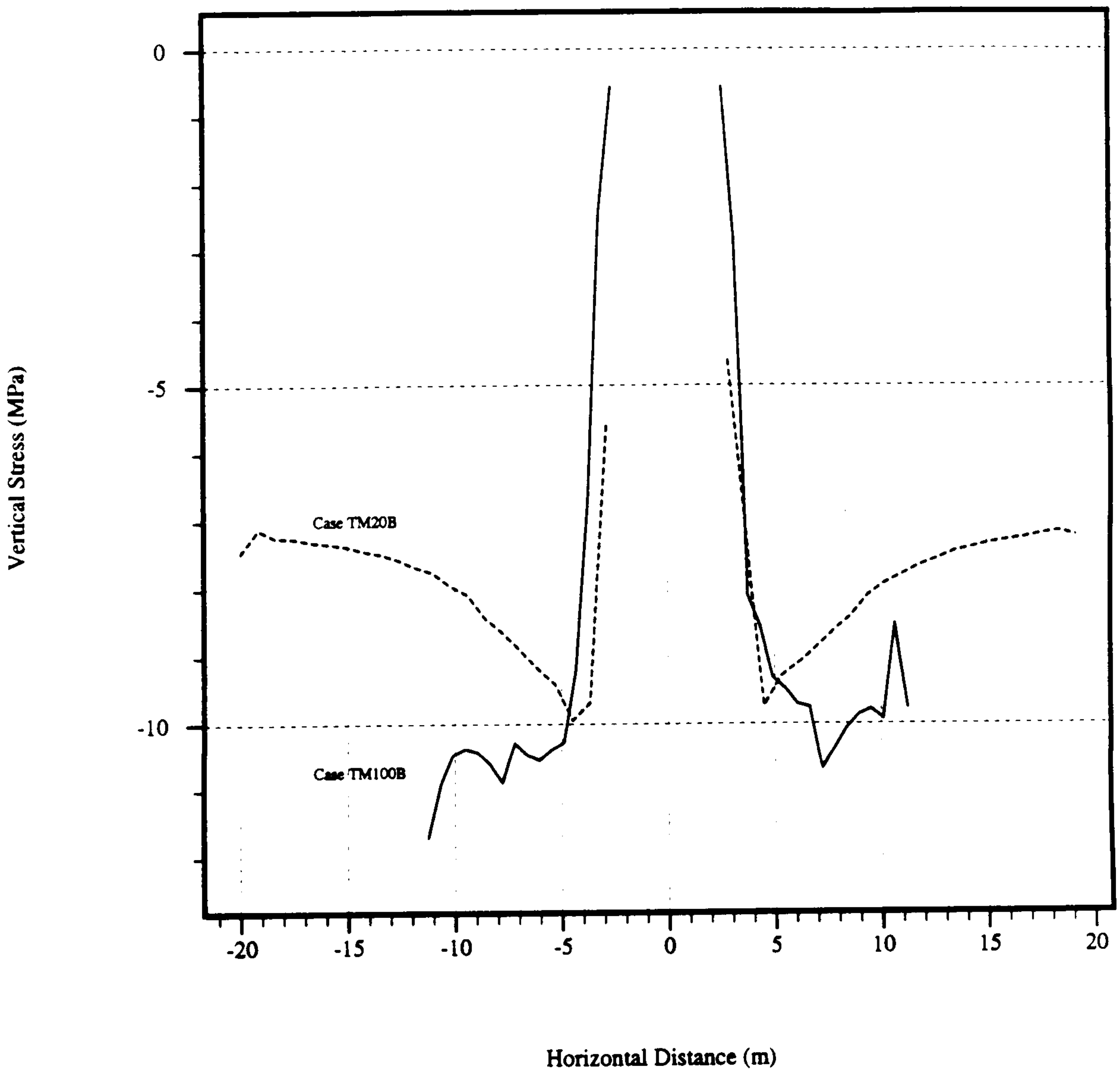


Figure L-22 Vertical stress after 100 years of heating along a horizontal section through the tunnel for joint pattern B (Case B)

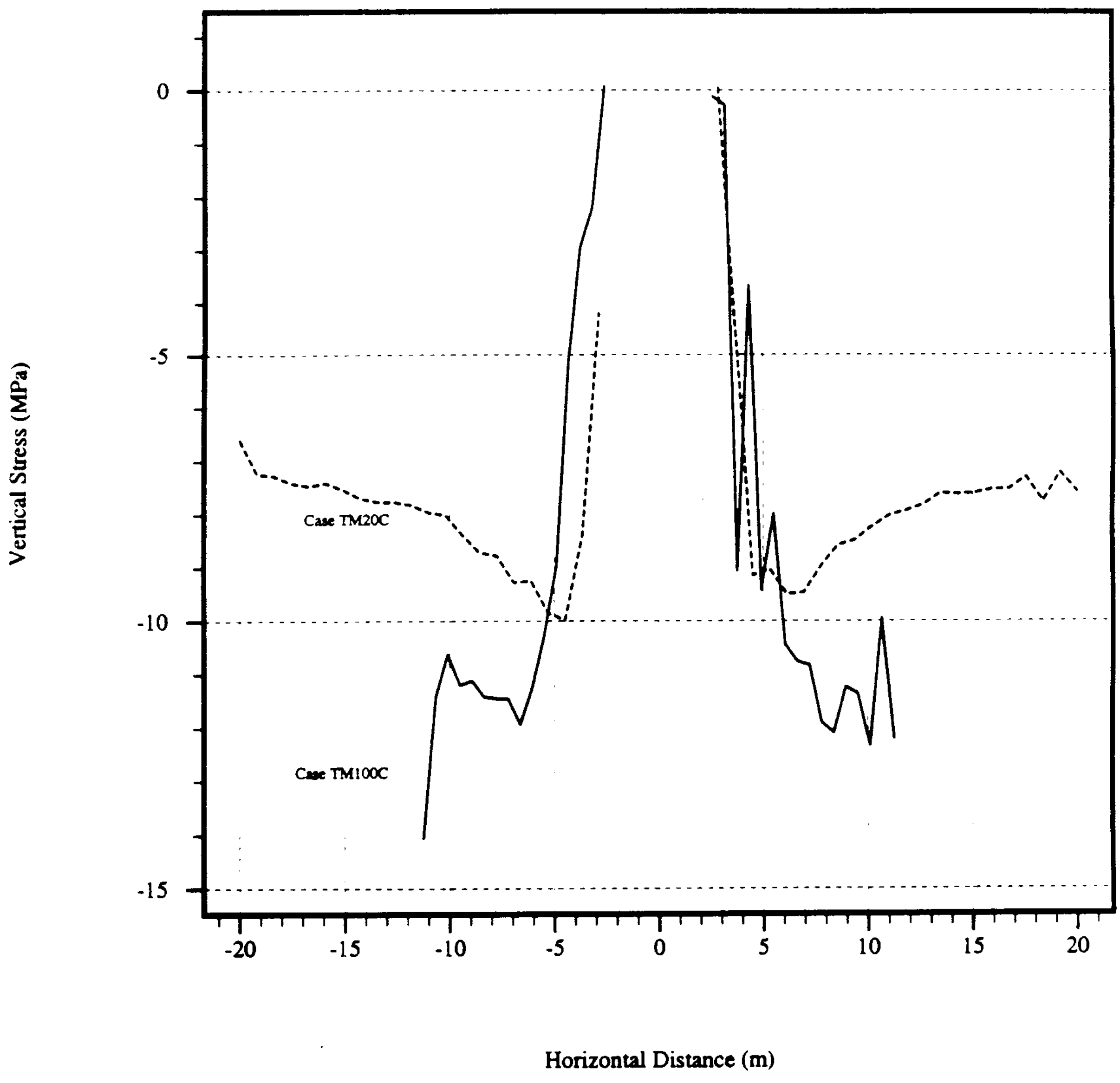


Figure L-23 Vertical stress after 100 years of heating along a horizontal section through the tunnel for joint pattern C (Case C)

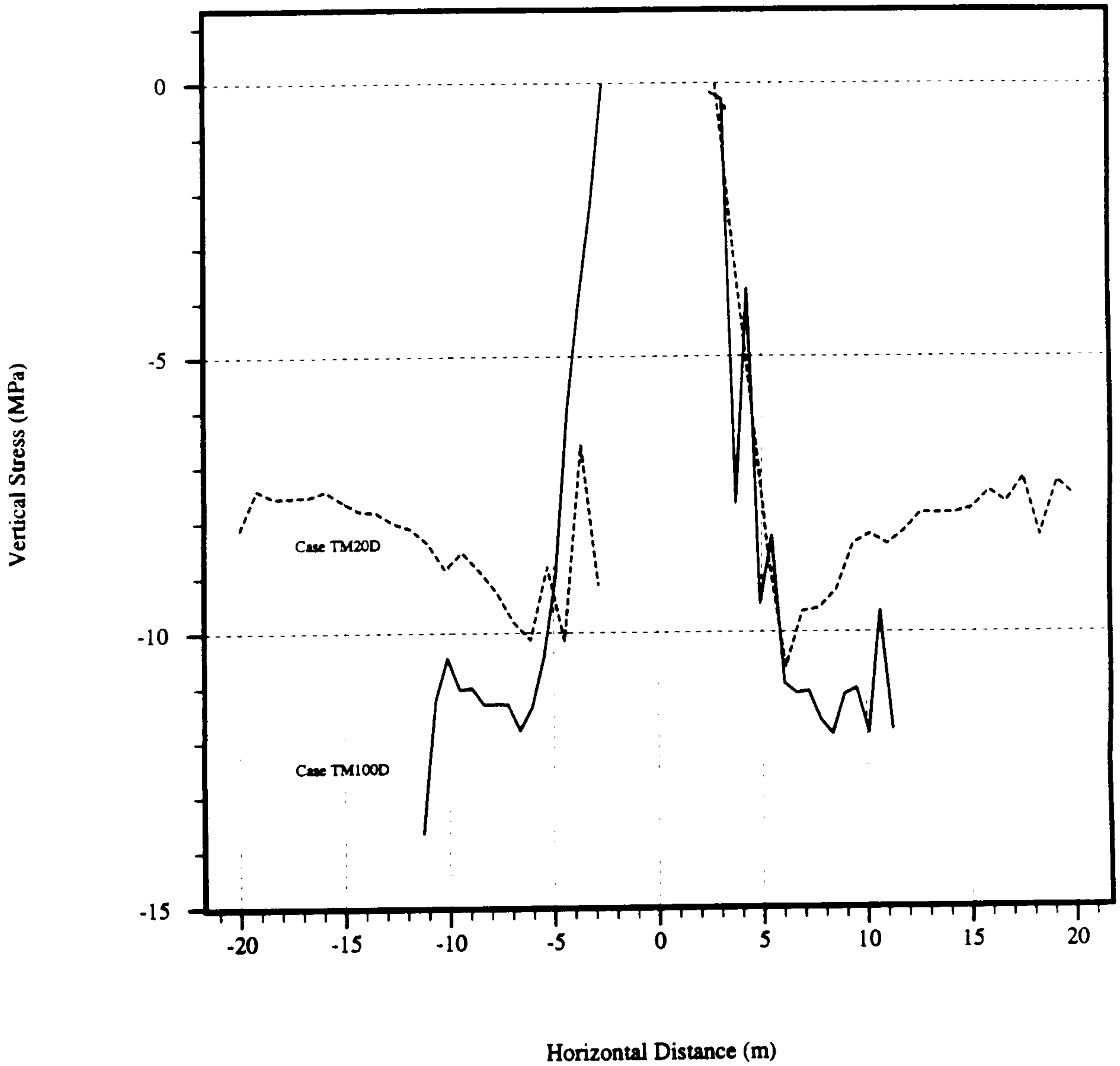


Figure L-24 Vertical stress after 100 years of heating along a horizontal section through the tunnel for joint pattern D (Case D)

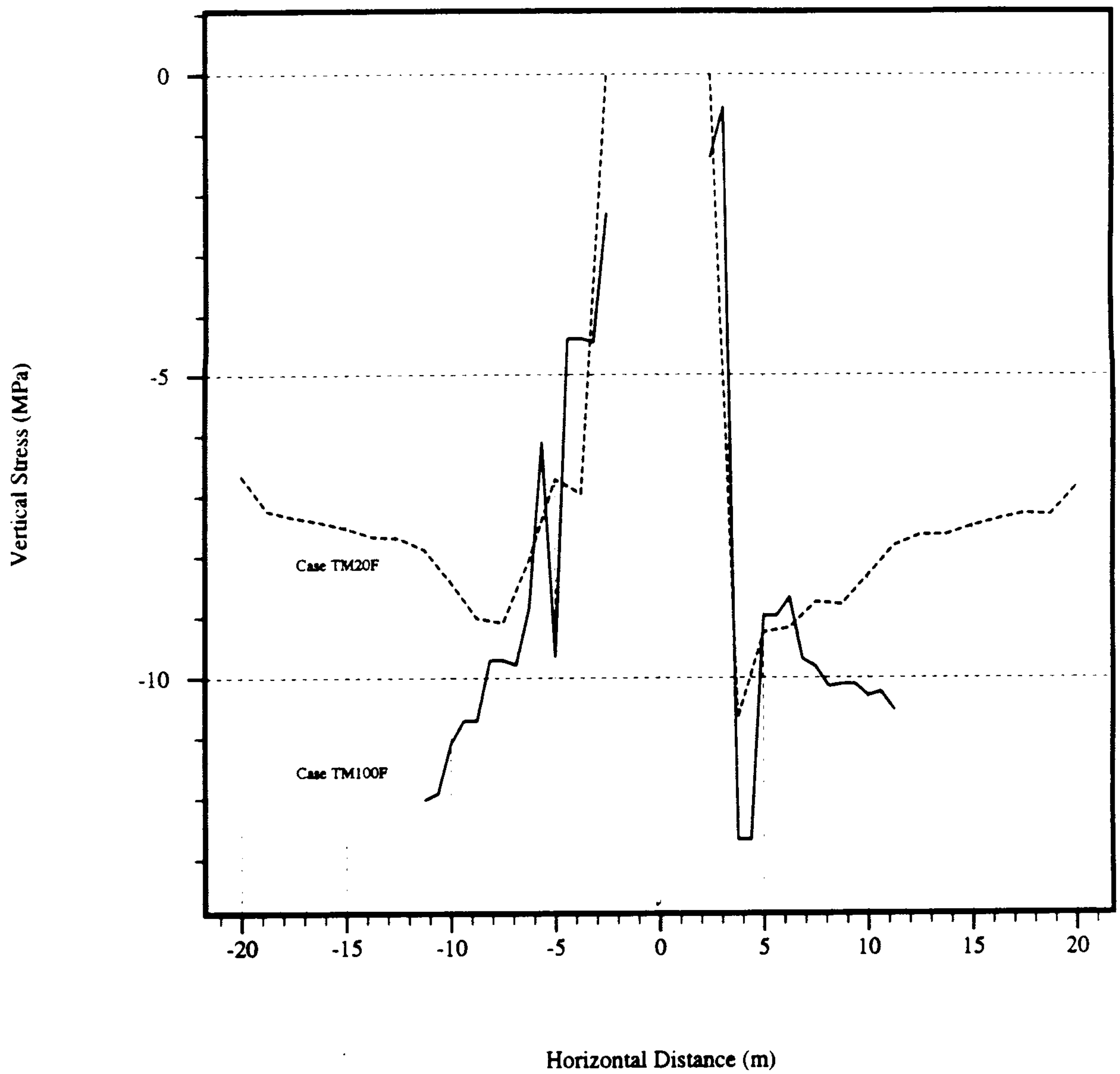


Figure L-25 Vertical stress after 100 years of heating along a horizontal section through the tunnel for joint pattern F (Case F)

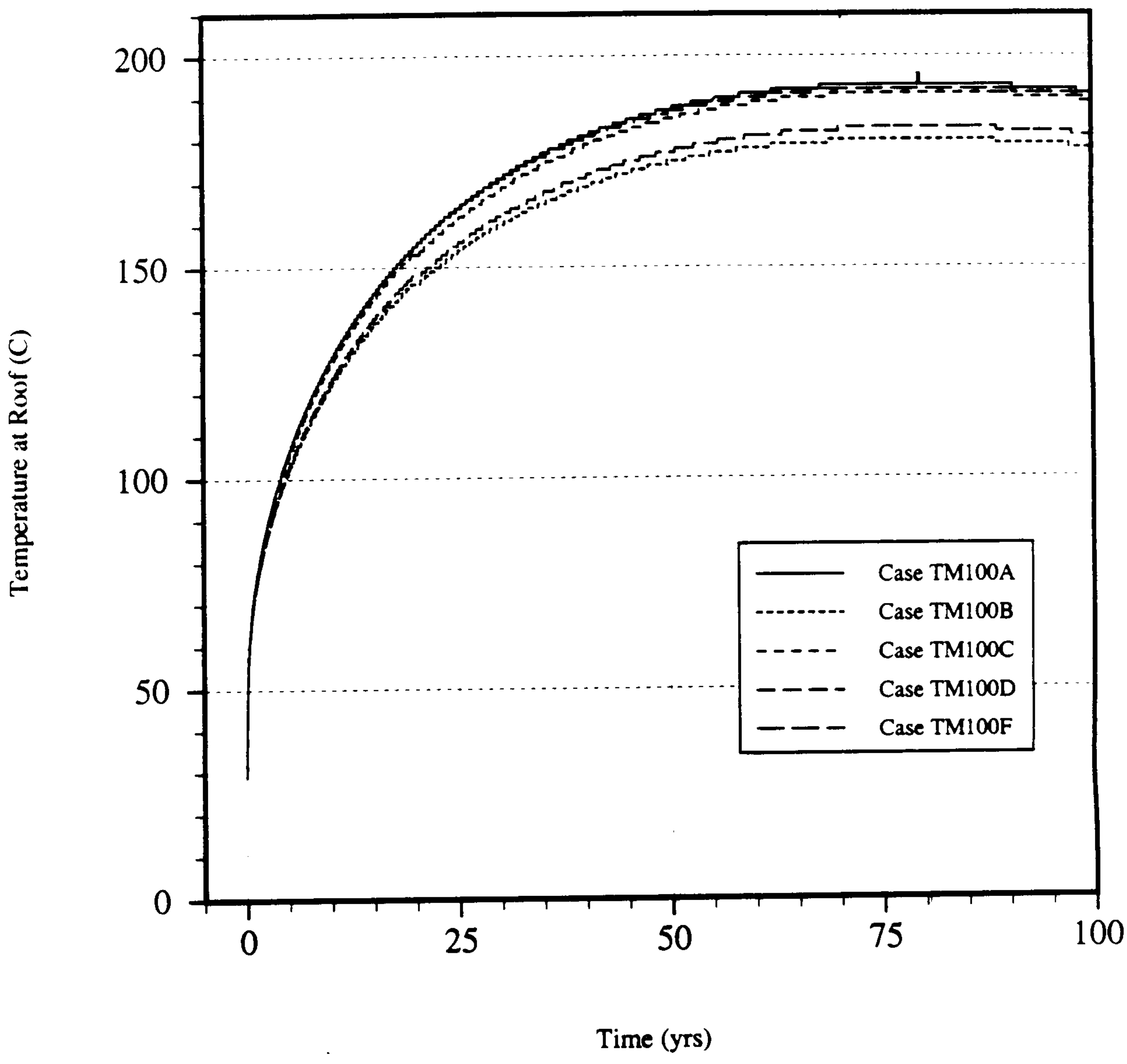


Figure L-26 Temperature histories on tunnel wall at roof for all of the joint patterns under the thermal loads of 100 MTU/Acre

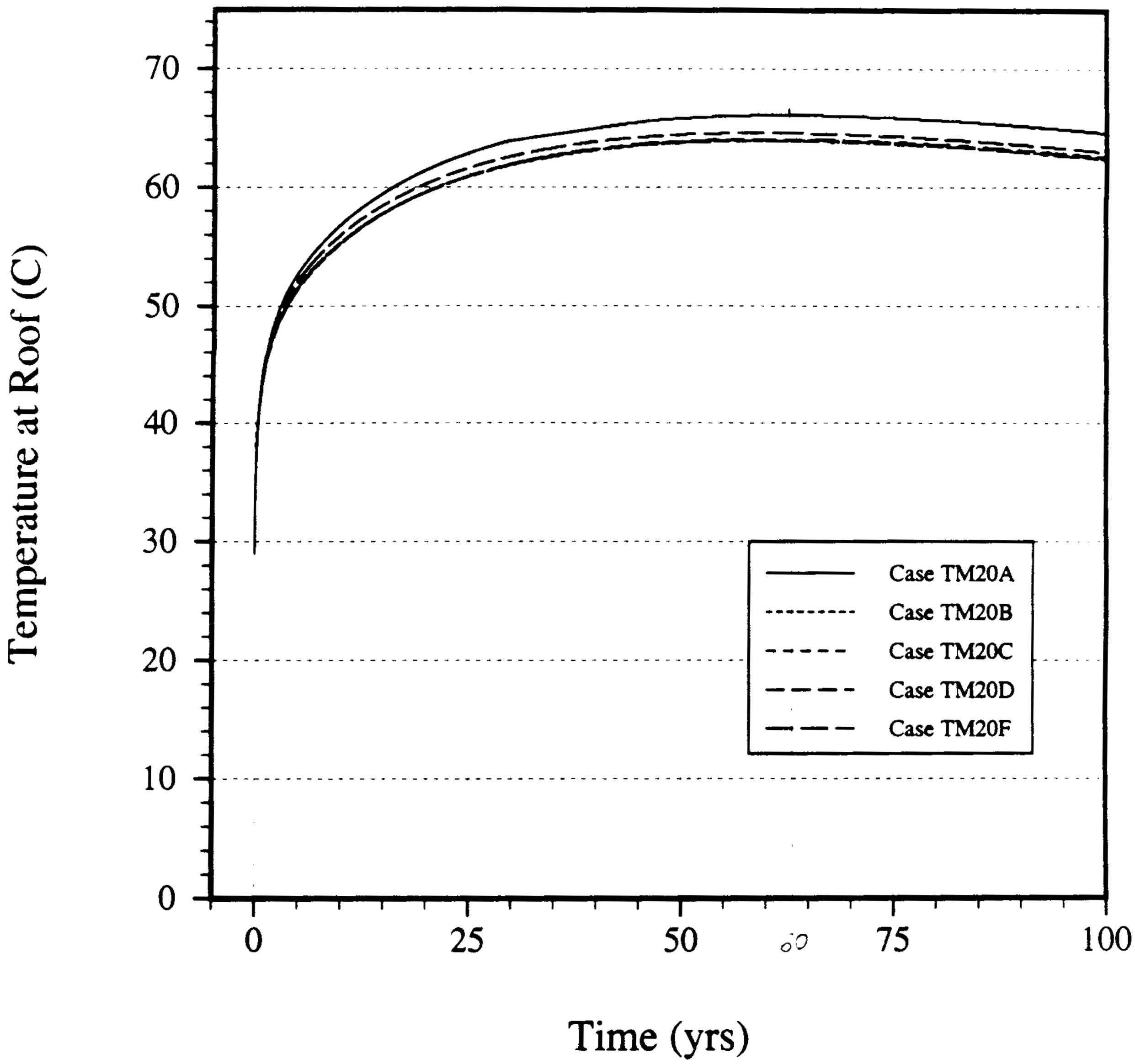


Figure L-27 Temperature histories on tunnel wall at roof for all of the joint patterns under the thermal loads of 20 MTU/Acre

Table L-1 Comparison of Roof, Floor, and Maximum Joint Shear Displacement

Case	Roof Disp (cm		Floor Disp (cm)		Joint Max Shear Disp (cm)	
	Excavation	100 yrs	Excavation	100 yrs	Excavation	100 yrs
TM100A	-0.23	12.55	0.16	11.82	0.80	1.06
B	-0.26	11.48	0.17	10.93	0.20	1.40
C	-0.34	12.17	0.16	11.17	0.37	1.47
D	-0.35	11.63	0.16	11.24	0.38	16.00
F	-0.29	10.69	0.14	13.36	0.30	1.70
TM20 A	-0.21	2.41	0.17	2.52	0.19	16.87
B	-0.23	2.21	0.18	2.40	0.26	7.93
C	-0.29	2.12	0.20	2.40	0.54	7.59
D	-0.30	2.13	0.19	2.44	0.38	1.92
F	-0.25	2.23	0.17	2.44	0.34	3.0

(08-22-96)

Table L-2 Maximum Compressive and Maximum Tensile Stresses

Case	Maximum Compressive Stresses (MPa)		Maximum Tensile Stress (MPa)	
	After Excavation	100 yrs	After Excavation	100 yrs
TM100A	15.0	86.0	0.7	1.5
B	11.5	75.0	0.7	4.0
C	20.0	63.0	1.6	6.4
D	20.0	61.0	1.5	5.0
F	13.0	56.2	0.0	0.0
TM20 A	14.9	21.7	0.8	0.8
B	10.9	19.4	0.8	1.0
C	21.3	19.2	1.1	3.0
D	18.7	16.6	1.4	3.4
F	13.7	22.3	0.0	0.0

Electronic Scientific Notebook No.165E:
Analyze the Stability of Emplacement Drifts
Excavated in a Jointed Rock Mass, Under In
Situ and Thermal Stress Fields to Develop an
Understanding of the Load that May Be
Generated by Rock Movement and Rock Fall

SCIENTIFIC NOTEBOOK #165
Second Quarter Status Report

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by

Mikko Ahola
Hengameh Karimi
Rui Chen

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Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

July 8, 1996

List of Tables

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4. IN-PROCESS ENTRIES

Scientific NoteBook: # 165

Issued to: Mikko Ahola

Issue Date: January 31, 1996

Printing Period: March 31, 1996 to June 30, 1996

Project Title: Thermal-Mechanical (TM) Modeling of Emplacement Drift Stability

Project Staff: Mikko Ahola
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By agreement with the CNWRA QA this notebook is to be printed at approximate quarterly intervals. This second volume of computerized scientific notebook is intended to address the criteria of CNWRA QAP-001.

4.1 Introduction

As indicated in the first quarter report dated March 19, 1996 the objective of this activity is to conduct a series of discrete element computer analyses using the UDEC computer code to independently assess DOE's repository thermal loading strategies and their impact on the near field thermal-mechanical response of the fractured rock surrounding the emplaced waste. A progress report documenting the details

of this activity will be submitted to the NRC to fulfill the intermediate milestone "Stability of Emplacement Drifts under Range of Thermal Loads - Phase I Report" (IM 5702-623-601). This work is conducted under the scope of RDCO Element Subtask 2.3 (Repository Design and TM Effects KTI).

The specific objectives for this second stage of the activity were to analyze selected case studies with specific parameters that where identified important based on our initial study reported in our first volume of scientific notebook. Again the UDEC code Version 2.01 was used to model 67 different scenarios.

4.2 Selection of Parameters and Input Information

The Yucca Mountain (YM) rock and thermal properties used in this study are based on information available from a number of sources including DOE's Reference Information Base (RIB), borehole drilling data from the Yucca Mountain region (Brechtel and Kessler, 1995), as well as from DOE's own thermal-mechanical studies (TRW, 1995). The thermal loads used in this study were selected to encompass DOE's "hot" and "cold" repository concepts.

It is recognized that the current information and level of understanding on the long term thermal degradation of the rock mass within the near-field repository environment is limited at best. As a result, this study only takes into account the ranges of mechanical and thermal parameters as measured in the laboratory or field, and does not take into account how they may change or degrade with temperature, time, stress, and moisture content. Currently, degradation in the model takes place in the form of plastic yield when stress conditions are such that a predefined yield function is met. However, the strength properties defining this yield surface are independent of other parameters such as temperature, etc. Further experimental and field studies are necessary to how such parameters may degrade in a repository environment, and how important their inclusion into the models are. The Version 2.01 of UDEC used for this study also does not have the ability to model temperature dependent mechanical and thermal properties.

Due to the large number of variables (e.g., joint geometries and orientations, mechanical and thermal properties) for conducting a thermal-mechanical drift stability parametric study with UDEC, it was decided that a set of scoping calculations first be conducted looking only at variations in the joint patterns (e.g., spacings, orientations, and number of joint sets) while the mechanical properties of the rock matrix and joints as well as thermal properties remain fixed at their representative mean values. As a result, this set of scoping runs analyzed the near-field thermal mechanical response based on 5 distinct joint patterns under low and high thermal loadings (20 and 100 MTU's/acre, respectively). Each of the 5 joint patterns contained at least two joint sets, namely one subhorizontal and one subvertical joint set. Several cases contained an additional subvertical or ubiquitous joint set. The subhorizontal joint set orientation varied between 0-10° with a constant spacing of 1.25 m. For the cases with only one subvertical joint set, the orientation varied between 85-90° with a constant spacing of 0.625 m. For the cases with an additional subvertical joint set (i.e., 3 joint sets total) the orientations were 70° or 60° and spacing fixed at 1.25 m. This joint geometry data was extracted from Christianson and Brady (1989) as well as borehole mappings from the North Ramp geotechnical study. In essence, the published results show the primary jointing being near vertical with spacings on the order of a few tenths of a meter with some horizontal jointing due to bedding foliations within the tuff with spacings on the order of meters. As the orientations approach vertical, the published data shows the joint frequency also increases. However, there is a

practical limit to modeling such high joint frequencies, especially when considering 3 joint sets. The fixed mechanical and thermal parameters for the scoping calculations were as follows:

Intact Rock

Young's Modulus	32.0 GPa
Poisson's Ratio	0.21
Density	2297.0 kg/m^3
Uniaxial Compressive Strength	166.0 MPa
Cohesion	2.1 MPa
Tensile Strength	1.05 MPa
Angle of Internal Friction	49.0°
Thermal Conductivity	2.1 W/m-K
Coeff. of Thermal Expansion	8.8E-6 /K
Specific Heat	932.0 J/kg-K

Rock Joints

Joint Normal Stiffness	1.0E5 MPa/m
Joint Shear Stiffness	1.0E5 MPa/m
Joint Cohesion	0.08 MPa
Joint Tensile Strength	0.04 MPa
Joint Angle of Friction	38.0°

Based on the results of the scoping runs, it was determined that the joint patterns did not appear to have a large impact on either the magnitude or distribution of stresses. However, it was generally observed that the more complex the joint pattern, resulted in more fluctuation in the stress and a higher maximum stress magnitude. Based on these results and the fact that the simulation of three joint sets was much more computationally intensive, it was decided that for the final set of 67 UDEC thermal-mechanical runs only two joint sets would be simulated, namely one subvertical and one sub-horizontal set. Using only two joint sets would also allow incorporation of a higher joint frequency, which was more representative of the subvertical joints. It was decided that for the final set of UDEC thermal-mechanical runs that the two joint set orientations would be variable as well as the subvertical joint set spacing. The subhorizontal joint set spacings are much larger (on the order of meters in the field) and were thus chosen to remain constant at 1.25 m for all runs. Do to the long thermal-mechanical run times, it was necessary to take into account ranges of only those mechanical and thermal properties that were considered to have the most impact on the state of the emplacement drift under thermal-mechanical loading. As a result, based mostly on engineering judgement and past modeling experience, it was decided that the additional variable parameters besides the joint pattern and thermal loading for the final UDEC runs would include the joint friction angle, intact rock cohesion, intact rock friction angle, intact rock Young's modulus, and thermal expansion coefficient. To limit the number of runs, only the likely high and low extreme values

were chosen based on DOE's Reference Information Base (RIB) and other reports mentioned earlier. The variable parameters and their ranges for the final set of runs are presented in this table. The remaining fixed parameters were similar to those used for the scoping calculations and are given below for completeness:

Number of joint sets	2
Horizontal joint spacing	1.25 m
Poisson's ratio	0.21
Density	2297.0 kg/m^3
Uniaxial compressive strength	166.0 MPa
Uniaxial tensile strength	5.0 MPa
Thermal conductivity	2.1 W/m-K
Specific heat	932.0 J/kg-K
Joint normal stiffness	1.0x10^5 MPa/m
Joint shear stiffness	1.0x10^5 MPa/m
Joint cohesion	0.08 MPa
Joint tensile strength	0.04 MPa

Table 4-1. Range of parameters for final TM parametric study

Parameter	Units	Upper Limit	**Lower Limit**
Vertical Joint Orientation	degrees	85.0	70.0
Horizontal Joint Orientation	degrees	20.0	10.0
Vertical Joint Spacing	m	0.5	0.2
Joint Friction Angle	degrees	38.0	28.0
Thermal Loading	MTU/Acre	100	20
Intact Rock Cohesion	MPa	43.0	18.0
Intact Rock Friction Angle	degrees	50.0	20.0
Intact Rock Young's Modulus	GPa	32.0	16.0
Thermal Expansion Coefficient	C^{-1}	12.0x10^{-6}	6.0x10^{-6}

Also for the 2D UDEC analysis, it was decided to analyze only two thermal loading strategies to limit the number of computational runs and still vary other mechanical and thermal material properties. These two input thermal loadings included a high (100 MTU/acre) as well as a low (20 MTU/acre)

thermal loading. DOE's current baseline thermal loading is approximately 84 MTU/acre. The heat generation due to the decay of the spent fuel within the waste package in DOE's in-drift configuration, is modeled in the UDEC as a thermal flux applied directly to the wall of the circular emplacement drift. In reality, heat transfer from the waste package to the surrounding rock in an unbackfilled drift would consist of a combination of radiation heat transfer to the wall of the emplacement drift as well as conduction heat transfer to the tunnel floor through the waste package support system. Depending on whether the unbackfilled drifts are ventilated, heat transfer could also take place in the form of forced convection. Because Version 2.01 of UDEC is incapable of modeling cavity radiation (i.e., currently it is set up to handle only boundary radiation to an infinite domain), it was decided to neglect modeling of the waste package itself and apply the volumetric heat generation directly as a heat flux to the drift wall. In essence, the analysis neglects heat removal from ventilation. For this study, the age of the fuel within the MPC being was assumed to be 20 years old at the time of waste emplacement. The surface heat flux (in W/m^2) applied to the tunnel wall in the 2D UDEC models is calculated by dividing the total waste package heat output (W) by the circumferential perimeter of the drift and the waste package spacing. For the UDEC analyses, the emplacement drift diameter was taken to be 5 m.

4.3 Model setup

In order to maintain a reasonable number of blocks and finite difference zones, only a region approximately 1 tunnel diameter into the rock mass was modeled as having the specified joint spacings assigned for each case. Beyond this region, primarily because of the fairly small subvertical joint spacings (i.e., 0.2 and 0.5 m), it was necessary to scale up the size of the blocks. The very far-field region, needed to allow propagation of the heat over the 100 year heating period, consisted of even larger discrete element blocks. The zoning of the individual blocks was also scaled accordingly. Rock support around the emplacement drift was neglected for this study, and the study only considered the unbackfilled scenario (i.e., preclosure period up to 100 years of operation). As a conservative analysis, the emplacement drifts were assumed to be non-ventilated.

4.4 Solution Scheme

The analyses scheme consisted of first obtaining model equilibrium under the *in situ* applied stresses as discussed in volume one. Once this was accomplished, the tunnel blocks were excavated and a new equilibrium stage was reached. At this stage, the mechanical time was reset to zero for the thermal-mechanical analyses. In conducting a thermal-mechanical analyses, UDEC uses a sequential coupling approach. Such an analyses consists of running the thermal analyses for a period of time during which nodal or gridpoint temperatures are updated. The thermal time is then held fixed while mechanical cycling is conducted to update zone stresses, nodal displacements, block rotations, etc. in order to reach a new mechanical equilibrium with this thermal state. In such analyses, the thermal time is the actual simulation time while the mechanical time is more of a pseudo-time for the intermediate calculations. For the thermal-mechanical analyses conducted here, the thermal time increments between mechanical cycling starting out at 1 week gradually progressing up to a month and eventually up to 1 year for say the first 5 years of the analyses mainly because of the large gradient in the decay function as shown in the previously in the first volume. During later stages of the 100-year thermal-mechanical analyses, the thermal increments were increased up to 25 years, as a result of much smaller temperature gradients throughout the model. An implicit thermal solution scheme based on the Crank-Nicholson method

(Itasca, 1993) was chosen allowing the user to specify a thermal time-step, although not completely arbitrary since some stability criteria for the implicit must be satisfied. For the set of analyses conducted in this study, the maximum allowable thermal time-step varied greatly among the various runs. For the cases run with low thermal loadings, thermal time-steps on the order of days and possibly greater were allowed. However, for the high thermal loading cases the thermal time-steps had to be reduced to as low as 0.5 hours for the entire 100-year thermal-mechanical simulation. As a result, run times varied from an overnight job to several days depending on the thermal loading scheme and type of computer (i.e., Sun Sparstations or 486 IBM compatible).

The reason for the small thermal time-steps for the cases run with high thermal loadings was likely due to the increase in plastic yielding around the drift, especially those specified with high thermal expansion coefficients and low intact block strength properties. Also, it is recommended for UDEC plasticity calculations (Itasca, 1993) that the finite difference zones within a block be generated such that the zones all share a common central gridpoint for more accurate plasticity results. Meeting this criteria was not possible in this study for those blocks immediately surrounding the tunnel due to there irregular shapes. Consequently, some accuracy in the results for the plastic stress state were sacrificed, and it is not clear whether the inability to meet this zoning criteria for some blocks affected the thermal time step. Finally, it should be noted that the fact that in the near-field region of the emplacement drift, blocks were separating and in some cases falling into the tunnel which could have again affected the thermal time-step, since the thermal analysis scheme assumes the material to be a continuum. During the simulation, those blocks that were beginning to fall into the tunnel could have easily be deleted from the analysis, however, the thermal flux (applied over a thin annular region encompassing the nodes along the perimeter of the tunnel) would have been altered since the total required flux assumes that it is applied over all the circular tunnel segments. During the analysis, the mechanical cycling was done to reach equilibrium within the rock mass except for those few unstable tunnel blocks. As a result, those unstable blocks around the tunnel did not have a chance to move much even though they had a finite velocity and carried no mechanical stress. Thus, the thermal flux could still be applied to those blocks to generate the required areal thermal loading. There were some fluctuations in the wall temperatures on the order of 10-20 degrees indicating that some of the unstable blocks may have displaced outside the annular heat flux region resulting in a discontinuity in the flux applied around the circumference of the tunnel. The small variances in these temperatures was determined not to have a great effect on the overall thermal-mechanical response of the rock mass.

5. Results

A total of 74 UDEC runs were performed for this thermal-mechanical analyses. This total includes 10 scoping runs discussed in the first quarterly report of the scientific notebook and the present 64 final runs conducted during the second quarter. As discussed earlier the ten scoping runs were aimed at the effects of joint patterns on near field thermal mechanical responses. The final runs were based on a factorial design methodology to systematically probe into the effects of other thermal and mechanical parameters. Some output parameters from numerical modeling have been considered as "performance measures" for the factorial analyses based on the observation of general results and based on engineering judgement. Table 5a and b presents the values of these performance measures for all of the factorial run cases after 50 and 100 years of heating, respectively. All the results of our UDEC runs are saved on 8mm cartridge tapes and will be included in the next quarterly report.

INFORMATION FOR TABLE 5-1a and 5-1b

Table 5-1a - Study Results for 50 years
Table 5-1b - Study Results for 100 years

Nomenclatures

σ_{min}	=	maximum tensile principal stress
σ_{max}	=	maximum comparative principal stress
jc_{max}	=	maximum joint closure
jo_{max}	=	maximum joint opening
jd_{max}	=	maximum joint shear displacement

Input Parameters

* Upper case represents high value, lower case represents low value.

A-a	=	Vertical joint orientation (85-70)
B-b	=	Horizontal joint orientation (20-10)
C-c	=	Vertical joint spacing (0.5-0.2)
D-d	=	Joint friction angle (38-28)
E-e	=	Thermal loading (100-20)
F-f	=	Intact rock cohesion (43-18)
G-g	=	Intact rock friction angle (50-20)
H-h	=	Intact rock Young's modulus (32-16)
I-i	=	Thermal expansion coefficient ($12\times10^{-6} - 6\times10^{-6}$)

Fixed Input Parameters

Number of joint sets = 2
Horizontal joint spacing = 1.25 m
Porsson's ratio = 0.21
Density = 2297.0 kg/m^3
Uniaxial compressive strength = 166.0 MPa
Uniaxial tensile strength = 5 MPa
Thermal conductivity = 2.1 W/m-K
Specific heat = 932.0 J/Kg-K
Joint normal stiffness = 1.0 E5 MPa/m
Joint shear stiffness = 1.0 E5 MPa/m
Joint cohesion = 0.08 MPa
Joint tensile strength = 0.04 MPa
Joint angle of friction = 38°

Table 5-1a - 50 Years

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case1.dat	abcDEfghi	2.7	-20.1	1.94×10^{-2}	0.12	0.64	0	0.175
Case2.dat	ABcDEfghi	2.9	-23.6	2.15×10^{-2}	0.003	0.50	0	-0.032
Case3.dat	AbCdEFghi	3.0	-10.0	4.59×10^{-2}	9.3×10^{-2}	0.53	6.6×10^{-3}	0.305
Case4.dat	aBCdEFghi	2.8	-34.5	2.87×10^{-2}	19.1×10^{-2}	0.79	0	0.528
Case5.dat	AbcdEfGhi	2.6	-27.4	3.80×10^{-2}	20.5×10^{-2}	0.75	0	0.623
Case6.dat	aBcdEfGhi	3.2	-30.7	2.34×10^{-2}	90.3×10^{-2}	1.90	9.5×10^{-3}	0.650
Case7.dat	abCDEFGhi	2.9	-36.0	2.96×10^{-2}	3.1×10^{-2}	0.44	0	-0.166
Case8.dat	ABCDEFGhi	2.6	-37.1	3.54×10^{-2}	1.9×10^{-2}	0.41	0	-0.117
Case9.dat	AbCDEfgHi	3.7	-54.0	5.66×10^{-2}	11.8×10^{-2}	0.48	40.5×10^{-3}	-0.175
Case10.dat	aBCDEfgHi	3.9	-54.1	4.36×10^{-2}	95.9×10^{-2}	0.48	584.6×10^{-3}	-0.448
Case11.dat	abcdEFgHi	3.8	-33.3	4.92×10^{-2}	106.1×10^{-2}	3.40	1888.6×10^{-3}	1.178
Case12.dat	ABcdEFgHi	4.3	-35.9	4.59×10^{-2}	105.4×10^{-2}	1.18	240.2×10^{-3}	0.406
Case13.dat	abCdEfGHi	4.8	-56.6	4.64×10^{-2}	3.1×10^{-2}	0.44	95.7×10^{-3}	-0.377
Case14.dat	ABCdEfGHi	3.9	-49.1	4.51×10^{-2}	24.8×10^{-2}	0.42	189.7×10^{-3}	-0.382
Case15.dat	AbcDEFGHi	3.8	-33.7	4.02×10^{-2}	18.5×10^{-2}	0.42	215.7×10^{-3}	-0.117
Case16.dat	aBcDEFGHi	4.9	-35.5	3.14×10^{-2}	75.3×10^{-2}	4.31	248.4×10^{-3}	-0.337
Case17.dat	abCdEfghI	4.4	-63.8	5.34×10^{-2}	57.6×10^{-2}	1.61	689.7×10^{-3}	0.160
Case18.dat	ABCdEfghI	3.3	-44.6	5.58×10^{-2}	43.9×10^{-2}	1.29	340.5×10^{-3}	-0.270
Case19.dat	AbcDEFghI	4.0	-48.8	5.97×10^{-2}	25.4×10^{-2}	0.75	80.4×10^{-3}	-0.429
Case20.dat	aBcDEFghI	3.0	-27.7	2.40×10^{-2}	3.8×10^{-2}	0.54	13.1×10^{-3}	-0.072

Table 5-1b - 100 Years

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case1.dat	abcDEfghi	3.4	-20.4	1.83×10^{-2}	0.21	3.39	0	0.095
Case2.dat	ABcDEfghi	3.4	-24.9	2.27×10^{-2}	0.04	0.50	0	-0.025
Case3.dat	AbCdEFghi	3.3	-109.6	0.05×10^{-2}	0.09	0.44	6.6×10^{-3}	0.317
Case4.dat	aBCdEFghi	2.7	-35.7	3.00×10^{-2}	0.22	0.80	0	0.516
Case5.dat	AbcdEfGhi	2.9	-28.6	2.79×10^{-2}	0.21	0.78	0	0.574
Case6.dat	aBcdEfGhi	3.3	-32.1	2.43×10^{-2}	0.26	3.35	6.6×10^{-3}	0.632
Case7.dat	abCDEFGhi	3.2	-38.0	3.13×10^{-2}	0.04	0.45	0	-0.217
Case8.dat	ABCDEFGhi	2.9	-39.2	3.72×10^{-2}	0.02	0.44	0	-0.177
Case9.dat	AbCDEfgHi	4.2	-56.8	5.67×10^{-2}	0.12	0.53	40.5×10^{-3}	-0.290
Case10.dat	aBCDEfgHi	4.1	-56.1	4.55×10^{-2}	0.22	2.89	584.6×10^{-3}	-0.533
Case11.dat	abcdEFgHi	3.7	-35.0	6.99×10^{-2}	1.05	3.86	1900.0×10^{-3}	1.216
Case12.dat	ABcdEFgHi	4.6	-36.2	4.27×10^{-2}	0.93	0.99	240.2×10^{-3}	0.396
Case13.dat	abCdEfGHi	4.1	-58.3	4.89×10^{-2}	0.03	0.52	366.2×10^{-3}	-0.424
Case14.dat	ABCdEfGHi	4.1	-51.1	4.68×10^{-2}	0.28	0.50	189.7×10^{-3}	-0.439
Case15.dat	AbcDEFGHi	4.3	-34.7	4.00×10^{-2}	0.20	0.42	215.7×10^{-3}	-0.166
Case16.dat	aBcDEFGHi	4.7	-37.2	3.28×10^{-2}	0.85	4.34	248.4×10^{-3}	-0.403
Case17.dat	abCdEfghi	4.3	-66.2	5.36×10^{-2}	0.57	1.70	1000×10^{-3}	0.060
Case18.dat	ABCdEfghI	4.5	-52.3	6.08×10^{-2}	0.93	2.20	1600×10^{-3}	-0.410
Case19.dat	AbcDEFghI	3.8	-50.4	5.46×10^{-2}	0.44	0.69	145.1×10^{-3}	-0.520
Case20.dat	aBcDEFghI	3.4	-28.6	2.48×10^{-2}	0.06	0.54	13.1×10^{-3}	-0.135

Table 5-1a - 50 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case21.dat	AbCDEfGhI	4.44	-62.46	6.417×10^{-2}	0.204	1.287	0.134	-0.529
Case22.dat	aBCDEfGhI	4.81	-51.24	4.455×10^{-2}	1.002	3.017	0.255	0.08
Case23.dat	abcdEFGhI	4.72	-57.77	7.07×10^{-2}	0.822	2.881	2.273	0.954
Case24.dat	ABcdEFGhI	4.58	-123.9	8.272×10^{-2}	0.410	1.605	0.393	-0.29
Case25.dat	AbcdEfgHI	4.09	-77.10	7.652×10^{-2}	1.144	1.722	112.7	-0.626
Case26.dat	aBcdEfgHI	4.63	-64.08	7.351×10^{-2}	1.09	3.842	197.7	1.24
Case27.dat	abCDEFgHI	4.70	-123.1	0.105	0.142	1.934	1.64	-1.57
Case28.dat	ABCDEFgHI	4.27	-124.2	8.07×10^{-2}	0.961	1.83	8.25	-1.205
Case29.dat	abcDEfGHI	4.82	-98.57	9.342×10^{-2}	0.504	1.980	5.35	-1.73
Case30.dat	ABcDEfGHI	3.91	-103.3	7.573×10^{-2}	1.14	1.646	4.89	-1.414
Case31.dat	AbCdEFGHI	4.30	-98.21	9.641×10^{-2}	0.291	1.773	4.14	-1.062
Case32.dat	aBCdEFGHI	4.63	-64.57	8.514×10^{-2}	1.398	2.888	7.85	0.79

Table 5-1b - 100 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case21.dat	AbCDEfGhI	4.26	-64.99	6.57×10^{-2}	0.177	1.405	0.296	-0.62
Case22.dat	aBCDEfGhI	3.83	-51.31	4.92	1.228	2.487	0.493	-0.11
Case23.dat	abcdEFGhI	4.78	-59.87	6.69×10^{-2}	1.325	3.119	2.273	0.964
Case24.dat	ABcdEFGhI	4.65	-122.3	8.164×10^{-2}	0.436	1.691	0.362	-0.37
Case25.dat	AbcdEfgHI	4.44	-76.84	7.62×10^{-2}	1.357	2.078	178.0	-0.69
Case26.dat	aBcdEfgHI	4.80	-68.06	7.35×10^{-2}	1.365	4.82	255.3	2.31
Case27.dat	abCDEFgHI	3.88	-115.0	1.03×10^{-1}	0.22	2.149	3.16	-1.8
Case28.dat	ABCDEFgHI	4.46	-66.8	9.584×10^{-2}	0.926	2.285	12.75	-0.93
Case29.dat	abcDEfGHI	4.29	-99.93	9.501×10^{-2}	0.795	2.722	13.48	-1.97
Case30.dat	ABcDEfGHI	4.91	-70.75	9.263×10^{-2}	0.622	2.742	11.33	1.49
Case31.dat	AbCdEFGHI	4.66	-100.3	9.723×10^{-2}	0.526	2.009	4.19	-1.28
Case32.dat	aBCdEFGHI	4.384	-66.60	8.79×10^{-2}	1.28	3.614	9.33	0.76

Table 5-1a - 50 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case53.dat	AbCdefGhI	1.44	-16.88	2.046×10^{-2}	7.721×10^{-2}	0.586	0.0	0.658
Case54.dat	aBCdefGhI	3.03	-14.97	2.109×10^{-2}	1.164	2.545	0.051	1.023
Case55.dat	abcDeFGhI	2.0	-16.3	1.52×10^{-2}	1.3×10^{-2}	0.50	0	0.318
Case56.dat	ABcDeFGhI	2.31	-27.31	1.809×10^{-2}	3.588×10^{-2}	0.427	0	0.462
Case57.dat	AbcDefgHI	1.54	-22.22	2.843×10^{-2}	1.902×10^{-2}	0.273	0.0	0.108
Case58.dat	aBcDefgHI	3.45	-22.95	1.996×10^{-2}	0.462	0.333	0.102	0.188
Case59.dat	abCdeFgHI	2.28	-30.5	3.508×10^{-2}	0.118	0.550	0.0	0.351
Case60.dat	ABCdeFgHI	43.13	-67.29	15.98×10^{-2}	0.7657×10^{-2}	7.274	25.097	0.799
Case61.dat	abcdefGHI	2.4	-25.8	2.90×10^{-2}	11.1×10^{-2}	0.67	0	0.483
Case62.dat	ABcdefGHI	2.4	-48.57	4.36×10^{-2}	6.64×10^{-2}	0.35	0	0.354
Case63.dat	AbCDeFGHI	1.47	-24.88	2.471×10^{-2}	3.814×10^{-2}	0.266	0.0	0.096
Case64.dat	aBCDeFGHI	3.58	-38.46	2.265×10^{-2}	6.882×10^{-2}	0.270	0.0	0.106

Table 5-1b - 100 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case53.dat	AbCdefGhI	1.744	-17.59	2.053×10^{-2}	7.435×10^{-2}	0.575	0.0	0.621
Case54.dat	aBCdefGhI	3.195	-15.23	2.201×10^{-2}	1.214	2.648	0.051	1.039
Case55.dat	abcDeFGhI	2.5	-16.6	1.53×10^{-2}	0.02	0.49	0	0.278
Case56.dat	ABcDeFGhI	2.865	-28.57	1.863×10^{-2}	0.0476	0.4264	0	0.441
Case57.dat	AbcDefgHI	1.82	-22.79	2.631×10^{-2}	4.719×10^{-2}	0.271	0.0	0.071
Case58.dat	aBcDefgHI	3.34	-23.09	1.991×10^{-2}	0.530	0.394	0.165	0.179
Case59.dat	abCdeFgHI	2.41	-31.69	3.467×10^{-2}	0.115	0.568	0.0	0.321
Case60.dat	ABCdeFgHI	4.154	-65.40	15.75×10^{-2}	0.7669	0.1147	26.042	0.799
Case61.dat	abcdefGHI	2.4	-24.2	0.26×10^{-2}	0.15	0.78	0	0.467
Case62.dat	ABcdefGHI	2.8	-50.18	4.07×10^{-2}	7.54×10^{-2}	0.339	0	0.342
Case63.dat	AbCDeFGHI	1.95	-26.36	2.980×10^{-2}	3.889×10^{-2}	0.252	0.0	0.078
Case64.dat	aBCDeFGHI	3.22	-41.19	2.437×10^{-2}	7.424×10^{-2}	0.302	0.051	0.092

Table 5-1a - 50 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case33.dat	abcdefghi	1.450	-15.17	0.0266	0.08177	2.487	0	0.945
Case34.dat	ABcdefghi	1.498	-14.68	0.0248	0.03774	0.5510	0	0.843
Case35.dat	AbCDeFghi	1.715	-33.91	0.01074	0.02453	0.3185	0	0.457
Case36.dat	aBCDeFghi	1.647	-12.13	0.00738	0.02501	0.4368	0	0.384
Case37.dat	AbcDefGhi	0.855	-14.97	0.01531	0.02459	0.4153	0	0.521
Case38.dat	aBcDefGhi	2.104	-10.61	0.00681	0.03428	0.5050	0	0.480
Case39.dat	abCdeFGhi	1.057	-14.58	0.01718	0.12230	0.5652	0	0.748
Case40.dat	ABCdeFGhi	1.468	-26.39	0.01531	0.08868	0.4828	0	0.813
Case41.dat	AbCdefgHi	2.011	-29.40	0.01657	0.03770	0.2750	0	0.297
Case42.dat	aBCdefgHi	3.386	-14.09	0.01479	0.37250	0.6545	6.905×10^{-2}	0.416
Case43.dat	abcDeFgHi	2.079	-12.61	0.00939	0.02610	1.8700	0	0.153
Case44.dat	ABcDeFgHi	2.892	-14.78	0.01407	0.02649	2.3280	0	0.235
Case45.dat	abCDefGHi	2.458	-17.10	0.01200	0.64950	0.9747	0	0.106
Case46.dat	ABCDefGHi	1.513	-23.20	0.01606	0.02393	0.2297	0	0.131
Case47.dat	AbcdeFGHi	1.997	-14.34	-0.01236	0.03547	0.2905	0	0.308
Case48.dat	aBcdeFGHi	2.532	-13.25	0.01179	0.24980	0.5936	5.0409×10^{-2}	0.512
Case49.dat	abCDefghI	1.406	-14.39	0.00791	0.01008	0.3934	0	0.387
Case50.dat	ABCDefghI	1.760	-27.90	0.02037	0.04939	0.4181	0	0.217
Case51.dat	AbcdeFghI	3.524	-17.98	0.02511	0.4220	0.1270	2.055	0.814
Case52.dat	aBcdeFghI	2.964	-16.72	0.01532	0.4920	1.1020	5.238×10^{-2}	1.148

Table 5-1b - 100 Years (cont'd)

UDEC RUNS	Parameters	σ_{min} (MPa)	σ_{max} (MPa)	jc_{max} (cm)	jo_{max} (cm)	jd_{max} (cm)	Area of Yield Zone (m^2)	Roof/Floor Convergence (cm)
Case33.dat	abcdefghi	1.612	-15.17	0.02179	0.08797	2.4980	0	0.929
Case34.dat	ABcdefghi	1.686	-15.11	0.02018	0.03982	0.5463	0	0.860
Case35.dat	AbCDeFghi	1.692	-32.93	0.01086	0.02655	0.3182	0	0.433
Case36.dat	aBCDeFghi	1.692	-11.49	0.00758	0.02515	0.4320	0	0.366
Case37.dat	AbcDefGhi	0.939	-13.97	0.01455	0.02616	0.4153	0	0.502
Case38.dat	aBcDefGhi	2.247	-10.81	0.00663	0.03674	0.4898	0	0.461
Case39.dat	abCdeFGhi	1.025	-14.75	0.01730	0.11960	0.5874	0	0.731
Case40.dat	ABCdeFGhi	1.451	-25.61	0.01577	0.08470	0.4805	0	0.800
Case41.dat	AbCdefgHi	2.100	-27.25	0.01728	0.03860	0.2670	0	0.280
Case42.dat	aBCdefgHi	3.453	-14.66	0.01518	0.39680	0.6568	6.904×10^{-2}	0.417
Case43.dat	abcDeFgHi	2.221	-13.27	0.00995	0.02390	2.6280	0	0.136
Case44.dat	ABcDeFgHi	2.713	-15.55	0.01490	0.02841	3.4070	0	0.224
Case45.dat	abCDefGHi	2.767	-17.50	0.01271	0.01140	0.2195	0	0.088
Case46.dat	ABCDefGHi	1.657	-24.29	0.01732	0.02671	0.2273	0	0.015
Case47.dat	AbcdeFGHi	2.199	-14.55	0.01258	0.03959	0.2801	0	0.297
Case48.dat	aBcdeFGHi	2.443	-13.52	0.01201	0.33270	0.5955	5.0409×10^{-2}	0.511
Case49.dat	abCDefghI	1.461	-13.87	0.00808	0.01030	0.3931	0	0.368
Case50.dat	ABCDefghI	2.035	-29.24	0.02162	0.06000	0.4134	0	0.186
Case51.dat	AbcdeFghI	3.924	-18.36	0.01712	0.4898	1.3110	2.1200	0.584
Case52.dat	aBcdeFghI	3.392	-16.96	0.01547	0.5283	1.1130	5.2382×10^{-2}	0.959

6. References

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SCIENTIFIC NOTEBOOK #165
Third Quarter Status Report

by

Sui-Min (Simon) Hsiung

SCIENTIFIC NOTEBOOK #165
Third Quarter Status Report

by

Sui-Min (Simon) Hsiung

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

August 20, 1996

List of Tables **Page**

[handwritten initials] 8/21/96

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7. IN-PROGRESS ENTRIES

Scientific NoteBook:	**# 165**
Issued to:	Mikko Ahola
Issue Date:	January 31, 1996
Printing Period:	July 1 through August 30, 1996
Project Title:	Thermal-Mechanical (TM) Modeling of Emplacement Drift Stability
Project Staff:	Mikko Ahola Rui Chen Hengameh Karimi

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This third volume of computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001. [Sui-Min (Simon) Hsiung, August 20, 1996]

7.1. Objectives

As indicated in the first quarterly report dated March 19, 1996, the objective of this activity is to conduct a series of discrete element computer analyses using the UDEC computer code to independently assess DOE's repository thermal loading strategies and their impact on the near field thermal-mechanical response of the fractured rock mass surrounding the emplacement area. A progress report documenting the details of this activity will be submitted to the NRC to fulfill the intermediate milestone "Sensibility Study of Drift Stability in Jointed Rock Mass Phase I: Discrete Element Thermal-Mechanical Analysis of Unbackfilled Drifts" (IM 5708-671-640). This work is conducted under the scope of Repository Design and Thermal-Mechanical Effects Key Technical Issue. [Sui-Min (Simon) Hsiung, August 20, 1996]

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The specific objectives of this third volume of Scientific Notebook entry is to document (i) the factorial experimental approach used for development of plan for numerical modeling of emplacement drifts using the UDEC code Version 2.01 and (ii) approach used for performing statistical analysis on UDEC modeling results. [Sui-Min (Simon) Hsiung, August 20, 1996]

7.2. Technical Approaches

As discussed earlier, the purpose of this analysis was to perform a parametric study on and identify important parameters that may affect the stability of the emplacement drifts under heated conditions. To achieve this goal, a large number of parameters would need to be examined and their impacts assessed. As a result, the number of numerical runs could be exceedingly large and complex if all possible effects of these parameters and, to the extent reasonable, their potential interactions were to be evaluated adequately. These large numbers of runs were not practical given the constraints of resources and time. Therefore, it was necessary to use a systematic approach so that meaningful work could be completed within the constraints. Toward this end, the concept of a 2^k factorial experimental design was adopted to study the effect on a response of k parameters, each at two levels. Note that the response in the context of stability evaluation of an underground excavation could be the state of stresses, joint slip, extent of roof falls, etc. These two levels are often denoted as high and low for convenience. The complete factorial design requires that each level of every parameter occur with each level of every other factor, thus giving a total of 2^k treatment combinations (Walpole and Myers, 1993). The 2^k factorial design offers a distinct advantage in that any two treatment combinations are orthogonal and therefore the effect of each treatment combination can be assessed independently. [Sui-Min (Simon) Hsiung, August 20, 1996]

8. 2^k FACTORIAL EXPERIMENTAL DESIGN FOR THERMAL-MECHANICAL ANALYSIS

Nine parameters identified in table 4-1 of volume two of this scientific notebook were used in the factorial design to determine number of UDEC runs to investigate potential effects of these parameters on the behavior of underground excavations at the proposed repository site under heated conditions. These parameters were, subvertical and subhorizontal joint inclinations, subvertical joint spacing, joint friction angle, thermal load, intact rock cohesion, intact rock friction angle, intact rock Young's modulus, and thermal expansion coefficient. Horizontal joint spacing was not included because, based on the current understanding, spacing is a few meters. Consequently, it was our judgment that its impact might be relatively small compared to vertical joint spacing which is a fraction of a meter. Another consideration was that too many parameters might make this study unmanageable. Number of joint sets was not included in the development of a numerical modeling plan because it might substantially change the block size of UDEC models such that comparison between results from a UDEC run with a large number of joint sets and those with a small number of joint sets becomes difficult, if not impossible.

To facilitate the design and discussion, each parameter was assigned an alphabet letter:

Parameter	A	= vertical joint inclination (measured upward from horizontal axis)
	B	= horizontal joint inclination
	C	= vertical joint spacing

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D = joint friction angle
E = thermal load
F = intact rock cohesion
G = intact rock friction angle
H = intact rock Young's modulus
I = thermal expansion coefficient

Higher level values of the parameters (A, B, C,...) were denoted by letters a, b, c,... and lower level values by the notation (1). A treatment combination was expressed as a combination of letters and notations. Hence, a treatment combination in which all the parameters consisted of high level values was expressed as abcdefghi. In the presence of high level letters for some parameters, the low level symbols (1) were omitted for clarity. For example, the treatment combination abc indicates the values for parameters A, B, and C are at high level while the rest of the parameters have low level values.

With nine parameters chosen for the study (k = 9), a full 2^k factorial plan requires 512 UDEC runs. While it was desirable to adopt this modeling plan so that each interaction between parameters allows only a degree of freedom, it may not be necessary since certain interactions may not be of interest or may be negligible. Furthermore, the available resources and time did not warrant this level of effort. Therefore, it was decided to select 64 treatment combinations—(1/8) of the 512 possible combinations. The process of selecting an 1/8 fraction of the total UDEC runs was the same as the allocation of 2^9 factorial UDEC runs into eight blocks (2^3 blocks).

When eight blocks are to be used with a 2^k factorial, three defining contrasts need to be chosen. Note that a contrast of a parameter or parameter interaction is the sum of responses at low and high levels of the parameter or parameter interaction. These defining contrasts should be chosen in such a way that information regarding the combinations of interest can be obtained for analysis. In this study, interest was placed on the potential effects of the main parameters and their second-order interactions (two-parameter interactions). The higher-order interactions were assumed to be negligible. Given this objective, three defining contrasts were selected after some trial and error effort. These three defining contrasts were

ABCDEF, ABCGI, and CDEGH

Since each block has 2^3-1 = 7 degrees of freedom, there exist four additional effects confounded with the blocks. They can be determined as follows

$$(ABCDEF)(ABCGI) = A^2B^2C^2DEFGI = DEFGI$$
$$(ABCDEF)(CDEGH) = ABFGH$$
$$(ABCGI)(CDEGH) = ABDEHI$$
$$(ABCDEF)(ABCGI)(CDEGH) = CFHI$$

Note that the powers associated with each parameter were reduced to either zero or one using the approach of modulo 2 (i.e., to calculate the remainder of the powers when divided by two). By necessity, information regarding these seven contrasts was sacrificed in the analysis because these contrasts are not orthogonal to the blocks nor to other treatment combinations. Since these seven contrasts are high order interactions, the sacrifice is acceptable. For a 1/8 fractional factorial design, there exist seven aliases for

each treatment combination. The word alias is given to the effects of two treatment combinations that have the same contrast. Effect is defined as the difference between the mean response (contrast) at the low and high levels of a parameter (Walpole and Myers, 1993). For example, the alias structure for the effect of CF (interaction between vertical joint spacing and intact rock cohesion) is written as

$$cf \equiv abde \equiv abfgi \equiv defgh \equiv cdegi \equiv abcdefhi \equiv hi \equiv abcgh$$

The symbol ≡ implies aliased with. Without supplementary evidence, there is no way to determine which of the two aliased effects is actually providing the influence on the response. This is a notable disadvantage of fractional factorial experiments. However, its benefits seem to outweigh the disadvantages in the context of this study. Notice from the previous alias structure there is an aliasing between the two-parameter interactions CF and HI. In fact, with the three defining contrasts chosen, there exists three alias structures that are aliasing between two-parameter interactions,

$$CF \equiv HI$$
$$CH \equiv FI$$
$$CI \equiv FH$$

Some judgment needs to be applied to determine which of the two aliased effects are important.

The numerical modeling plan was constructed by evaluating the expressions

$$L_1 = \gamma_A + \gamma_B + \gamma_C + \gamma_D + \gamma_E + \gamma_F \tag{7-1}$$

$$L_2 = \gamma_A + \gamma_B + \gamma_C + \gamma_G + \gamma_I \tag{7-2}$$

$$L_3 = \gamma_C + \gamma_D + \gamma_E + \gamma_G + \gamma_H \tag{7-3}$$

where γ is equal to one if its subscript is found in the treatment combination of interest—in other words, the corresponding parameter in the treatment combination to the subscript has a high level value. Otherwise, it is equal to zero. Note that the subscripts in the right hand side of Eqs. (7-1) to (7-3) are related to the three defining contrasts. The treatment combinations were assigned into corresponding blocks using the following scheme:

Block 1: $L_1 = 0$, $L_2 = 0$, $L_3 = 0$
Block 2: $L_1 = 0$, $L_2 = 0$, $L_3 = 1$
Block 3: $L_1 = 0$, $L_2 = 0$, $L_3 = 0$
Block 4: $L_1 = 0$, $L_2 = 1$, $L_3 = 1$
Block 5: $L_1 = 1$, $L_2 = 0$, $L_3 = 0$
Block 6: $L_1 = 1$, $L_2 = 0$, $L_3 = 1$
Block 7: $L_1 = 1$, $L_2 = 1$, $L_3 = 0$
Block 8: $L_1 = 1$, $L_2 = 1$, $L_3 = 1$

For example, for the treatment combination ab, γ_A and γ_B in Eqs. (3-6) to (3-8) are equal to one due to the presence of the high level values for these two parameters in the combination while the rest of the γ in the equations are zero due to the presence of the low level values. The related L_1, L_2, L_3 can be calculated as

$$L_1 = 1 + 1 + 0 + 0 + 0 + 0 = 2 = 0 \text{ (modulo 2)}$$
$$L_2 = 1 + 1 + 0 + 0 + 0 = 2 = 0 \text{ (modulo 2)}$$
$$L_3 = 0 + 0 + 0 + 0 + 0 = 0$$

Consequently, this treatment combination should belong to Block 1.

Any of the blocks using this scheme is a suitable set for the experiment. In this study, the principal block was selected. The principal block is the block containing the treatment combination (1), in which all parameters are with low level values. The 64 treatment combinations contained in the principal block are listed in table 7-1.

Table 7-1. Treatment combinations selected for performing UDEC analysis

(1)	ach	cdi	adhi
ab	bch	abcdi	bdhi
de	acdeh	cei	aehi
abde	bcdeh	abcei	behi
acdf	dfh	afi	cfhi
bcdf	abdfh	bfi	abcfhi
acef	efh	adefi	cdefhi
bcef	abefh	bdefi	abcdefhi
adg	cdgh	acgi	ghi
bdg	abcdgh	bcgi	abghi
aeg	cegh	acdegi	deghi
beg	abcegh	bcdegi	abdeghi
cfg	afgh	dfgi	acdfghi
abcfg	bfgh	abdfgi	bcdfghi
cdefg	adefgh	efgi	acefghi
abcdefg	bdefgh	abefgi	bcefghi

[Sui-Min (Simon) Hsiung, August 20, 1996]

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9. APPROACH FOR UDEC RESULT ANALYSIS

Analysis of the behavior of an underground excavation in a jointed rock medium is a complex problem. Assessment of numerical modeling results is often not so straight forward and relies on some engineering judgment. This is especially true when discontinuities are included in the analysis. In this study, attempts were made to identify several performance measures (responses) that can be used to assess the effects of the nine main parameters and the two-parameter interactions on the performance of underground excavations. The responses identified and selected include maximum and minimum principal stresses around the excavation, maximum joint closure and opening (or separation), maximum joint shear displacement, roof-to-floor convergence, and area of yield zone around the excavation. Lists of these responses after 50 yr and 100 yr of heating are provided in table 5-1a and table 5-1b provided in the second volume of this scientific notebook, respectively.

As discussed in section 8, the main parameters and two-parameter interactions are of interest in this study. The high-order interactions are assumed to be negligible. Consequently, it is possible to pool the sum of squares associated with these high-order interactions and use it as an alternate measure for variance of error in the modeling results, allowing estimating or testing significance of the main and the two-parameter interaction effects. Since there are 64 nonreplicated treatment combinations in the analysis, they are 63 degrees of freedom. Also, there are 45 main and two-parameter interactions. This provides a total of 63 − 45 = 18 degrees of freedom for error estimation. An analysis of variance for each of the response types was performed. In the analysis, the variance of each parameter is compared with the variance of the error term to determine if there is sufficient evidence exists to reject the null hypothesis. All the main parameters and the two-parameter interactions are tested for significance at the α=0.05 level.

A small computer program was written to (i) generate F-statistic data for variance analysis of each main parameters and the two-parameter interactions, and (ii) calculate two-way table of means of significant interactions between two parameters. The formulas coded in the computer program are adopted from a book entitled "Probability and Statistics for Engineers and Scientists" by Walpole and Myers (1993). The input data of each performance measures used for analysis, outputs, and the source code of the program are provided in a separate floppy diskette.

The data file containing the source code of the small program is under the name of

design.f

The files for input data and the corresponding output are:

str_min.50y	str_min.ou5	Minimum principal stress for 50 yr
str_min.100	str_min.ou1	Minimum principal stress for 100 yr
str_max.50y	str_max.ou5	Maximum principal stress for 50 yr
str_max.100	str_max.ou1	Maximum principal stress for 100 yr
clo_max.50y	clo_max.ou5	Maximum opening closure for 50 yr
clo_max.100	clo_max.ou1	Maximum opening closure for 100 yr
sep_max.50y	sep_max.ou5	Maximum opening separation for 50 yr
sep_max.100	sep_max.ou1	Maximum opening separation for 100 yr
shr_max.50y	shr_max.ou5	Maximum joint shear displacement for 50 yr

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shr_max.100	shr_max.ou1	Maximum joint shear displacement for 100 yr
yield_20.50y	yield_20.ou5	Extent of yield zone for 50 yr
yield_20.100	yield_20.ou1	Extent of yield zone for 100 yr
rf&fl.50y	rf&fl.ou5	Roof-to-floor convergence for 50 yr
rf&fl.100	rf&fl.ou1	Roof-to-floor convergence for 100 yr

[Sui-Min (Simon) Hsiung, August 20, 1996]

10. INPUT AND CALCULATION VERIFICATION

The data input for UDEC runs were prepared by M. Ahola, R. Chen, and H. Karimi. The data iuput prepared by H. Karimi were checked by R. Chen and M. Ahola. The data input prepared by M. Ahola and R. Chen were checked by themselves. [Rui Chen, August 21, 1996]

Various parts of computer output results for statistical analysis were verified through hand calculation. The proof of this verification is provided in a separate hard copy. [Sui-Min (Simon) Hsiung, August 20, 1996]

11. VERIFICATION OF THEORY OF 2^k FRACTIONAL FACTORIAL DESIGN

The theory of 2k fractional factorial experimental design as used in this analysis was checked against the theory given in a reference book (Walpole and Myers, 1993). [Asadul H. Chowdhury, August 21, 1996]

12. REFERENCES

Walpole, R.E., and R.H. Myers. 1993. *Probability and Statistics for Engineers and Scientists*. 5th edition. New York, NY: Macmillan Publishing Company.

This third quarterly report was generated to support preparation of a report entitled "A parametric study of drift stability in jointed rock mass, phase I: Discrete Element Thermal-mechanical Analysis of Unbackfilled Drifts." The subject report was completed and submitted to NRC on Sept. 5. 1996. Therefore, this quarterly report serves to close the Phase I activity. The scientific notebook #165 will remain open for subsequent related TM work.

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APPENDIX A

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Analysis of 1/8 fractorial experiment results---maximum principal stress around opening
(100 y, stre_max.100)
Total number of factors = 9
Number of fractional blocks = 8

Defining contrasts and confounded effects

Date of printing 7/11/96

abcdef
abcgi
cdegh
defgi
abdehi
cfhi
abfgh

Defining contrasts and confounded effects in symbolic form

1	1	1	1	1	1	0	0	0
1	1	1	0	0	0	1	0	1
0	0	1	1	1	0	1	1	0
0	0	0	1	1	1	1	0	1
1	1	0	1	1	0	0	1	1
0	0	1	0	0	1	0	1	1
1	1	0	0	0	1	1	1	0

Total number of treatments in the principal block= 64

Treatment combinations in the principal block

(1)	ach	cdi	adhi
ab	bch	abcdi	bdhi
de	acdeh	cei	aehi
abde	bcdeh	abcei	behi
acdf	dfh	afi	cfhi
bcdf	abdfh	bfi	abcfhi
acef	efh	adefi	cdefhi
bcef	abefh	bdefi	abcdefhi

This is a computer printout. It is not numbered. Numbering is not necessary.
Sui Min Ho 9/9/96

8/13/96

adg	cdgh	acgi	ghi
bdg	abcdgh	bcgi	abghi
aeg	cegh	acdegi	deghi
beg	abcegh	bcdegi	abdeghi
cfg	afgh	dfgi	acdfghi
abcfg	bfgh	abdfgi	bcdfghi
cdefg	adefgh	efgi	acefghi
abcdefg	bdefgh	abefgi	bcefghi

Numerical represetation of treatments in the principal block

0	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0	0
1	1	0	1	1	0	0	0	0
1	0	1	1	0	1	0	0	0
0	1	1	1	0	1	0	0	0
1	0	1	0	1	1	0	0	0
0	1	1	0	1	1	0	0	0
1	0	0	1	0	0	1	0	0
0	1	0	1	0	0	1	0	0
1	0	0	0	1	0	1	0	0
0	1	0	0	1	0	1	0	0
0	0	1	0	0	1	1	0	0
1	1	1	0	0	1	1	0	0
0	0	1	1	1	1	1	0	0
1	1	1	1	1	1	1	0	0
1	0	1	0	0	0	0	1	0
0	1	1	0	0	0	0	1	0
1	0	1	1	1	0	0	1	0
0	1	1	1	1	0	0	1	0
0	0	0	1	0	1	0	1	0
1	1	0	1	0	1	0	1	0
0	0	0	0	1	1	0	1	0
1	1	0	0	1	1	0	1	0

0	0	1	1	0	0	1	1	0
1	1	1	1	0	0	1	1	0
0	0	1	0	1	0	1	1	0
1	1	1	0	1	0	1	1	0
1	0	0	0	0	1	1	1	0
0	1	0	0	0	1	1	1	0
1	0	0	1	1	1	1	1	0
0	1	0	1	1	1	1	1	0
0	0	1	1	0	0	0	0	1
1	1	1	1	0	0	0	0	1
0	0	1	0	1	0	0	0	1
1	1	1	0	1	0	0	0	1
1	0	0	0	0	1	0	0	1
0	1	0	0	0	1	0	0	1
1	0	0	1	1	1	0	0	1
0	1	0	1	1	1	0	0	1
1	0	1	0	0	0	1	0	1
0	1	1	0	0	0	1	0	1
1	0	1	1	1	0	1	0	1
0	1	1	1	1	0	1	0	1
0	0	0	1	0	1	1	0	1
1	1	0	1	0	1	1	0	1
0	0	0	0	1	1	1	0	1
1	1	0	0	1	1	1	0	1
1	0	0	1	0	0	0	1	1
0	1	0	1	0	0	0	1	1
1	0	0	0	1	0	0	1	1
0	1	0	0	1	0	0	1	1
0	0	1	0	0	1	0	1	1
1	1	1	0	0	1	0	1	1
0	0	1	1	1	1	0	1	1
1	1	1	1	1	1	0	1	1
0	0	0	0	0	0	1	1	1
1	1	0	0	0	0	1	1	1

0	0	0	1	1	0	1	1	1
1	1	0	1	1	0	1	1	1
1	0	1	1	0	1	1	1	1
0	1	1	1	0	1	1	1	1
1	0	1	0	1	1	1	1	1
0	1	1	0	1	1	1	1	1

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Aliases to the main effects and two-factor interactions

a	bcdef	bcgi	acdegh	adefgi	bdehi	acfhi	bfgh
ab	cdef	cgi	abcdegh	abdefgi	dehi	abcfhi	fgh
ac	bdef	bgi	adegh	acdefgi	bcdehi	afhi	bcfgh
ad	bcef	bcdgi	acegh	aefgi	behi	acdfhi	bdfgh
ae	bcdf	bcegi	acdgh	adfgi	bdhi	acefhi	befgh
af	bcde	bcfgi	acdefgh	adegi	bdefhi	achi	bgh
ag	bcdefg	bci	acdeh	adefi	bdeghi	acfghi	bfh
ah	bcdefh	bcghi	acdeg	adefghi	bdei	acfi	bfg
ai	bcdefi	bcg	acdeghi	adefg	bdeh	acfh	bfghi
b	acdef	acgi	bcdegh	bdefgi	adehi	bcfhi	afgh
bc	adef	agi	bdegh	bcdefgi	acdehi	bfhi	acfgh
bd	acef	acdgi	bcegh	befgi	aehi	bcdfhi	adfgh
be	acdf	acegi	bcdgh	bdfgi	adhi	bcefhi	aefgh
bf	acde	acfgi	bcdefgh	bdegi	adefhi	bchi	agh
bg	acdefg	aci	bcdeh	bdefi	adeghi	bcfghi	afh
bh	acdefh	acghi	bcdeg	bdefghi	adei	bcfi	afg
bi	acdefi	acg	bcdeghi	bdefg	adeh	bcfh	afghi
c	abdef	abgi	degh	cdefgi	abcdehi	fhi	abcfgh
cd	abef	abdgi	egh	cefgi	abcehi	dfhi	abcdfgh
ce	abdf	abegi	dgh	cdfgi	abcdhi	efhi	abcefgh
cf	abde	abfgi	defgh	cdegi	abcdefhi	hi	abcgh
cg	abdefg	abi	deh	cdefi	abcdeghi	fghi	abcfh
ch	abdefh	abghi	deg	cdefghi	abcdei	fi	abcfg
ci	abdefi	abg	deghi	cdefg	abcdeh	fh	abcfghi
d	abcef	abcdgi	cegh	efgi	abehi	cdfhi	abdfgh
de	abcf	abcdegi	cgh	fgi	abhi	cdefhi	abdefgh

df	abce	abcdfgi	cefgh	egi	abefhi	cdhi	abdgh
dg	abcefg	abcdi	ceh	efi	abeghi	cdfghi	abdfh
dh	abcefh	abcdghi	ceg	efghi	abei	cdfi	abdfg
di	abcefi	abcdg	ceghi	efg	abeh	cdfh	abdfghi
e	abcdf	abcegi	cdgh	dfgi	abdhi	cefhi	abefgh
ef	abcd	abcefgi	cdfgh	dgi	abdfhi	cehi	abegh
eg	abcdfg	abcei	cdh	dfi	abdghi	cefghi	abefh
eh	abcdfh	abceghi	cdg	dfghi	abdi	cefi	abefg
ei	abcdfi	abceg	cdghi	dfg	abdh	cefh	abefghi
f	abcde	abcfgi	cdefgh	degi	abdefhi	chi	abgh
fg	abcdeg	abcfi	cdefh	dei	abdefghi	cghi	abh
fh	abcdeh	abcfghi	cdefg	deghi	abdefi	ci	abg
fi	abcdei	abcfg	cdefghi	deg	abdefh	ch	abghi
g	abcdefg	abci	cdeh	defi	abdeghi	cfghi	abfh
gh	abcdefgh	abchi	cde	defhi	abdegi	cfgi	abf
gi	abcdefgi	abc	cdehi	def	abdegh	cfgh	abfhi
h	abcdefh	abcghi	cdeg	defghi	abdei	cfi	abfg
hi	abcdefhi	abcgh	cdegi	defgh	abde	cf	abfgi
i	abcdefi	abcg	cdeghi	defg	abdeh	cfh	abfghi

Main and two-factor interaction effects aliases in the principal block

a	bfgh
a	bcgi
ab	abcfhi
ad	bcef
ad	behi
ae	bcdf
ae	bdhi
ag	acdeh
ag	adefi
b	afgh
b	acgi
bd	acef
bd	aehi

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be	acdf
be	adhi
bg	bcdeh
bg	bdefi
cf	abde
cf	abcdefhi
ch	abcfg
ch	abghi
ci	cdefg
ci	deghi
d	cegh
d	efgi
de	cdefhi
dg	abdfh
dg	abcdi
e	cdgh
e	dfgi
eg	abefh
eg	abcei
fh	cdefg
fh	deghi
fi	abcfg
fi	abghi
g	abcdefg
g	abdeghi
hi	abde
hi	abcdefhi

Main and two-factor interaction effects and their symbolic representations

a	1	0	0	0	0	0	0	0	0
b	0	1	0	0	0	0	0	0	0
c	0	0	1	0	0	0	0	0	0
d	0	0	0	1	0	0	0	0	0
e	0	0	0	0	1	0	0	0	0

f	0	0	0	0	0	1	0	0	0
g	0	0	0	0	0	0	1	0	0
h	0	0	0	0	0	0	0	1	0
i	0	0	0	0	0	0	0	0	1
ab	1	1	0	0	0	0	0	0	0
ac	1	0	1	0	0	0	0	0	0
ad	1	0	0	1	0	0	0	0	0
ae	1	0	0	0	1	0	0	0	0
af	1	0	0	0	0	1	0	0	0
ag	1	0	0	0	0	0	1	0	0
ah	1	0	0	0	0	0	0	1	0
ai	1	0	0	0	0	0	0	0	1
bc	0	1	1	0	0	0	0	0	0
bd	0	1	0	1	0	0	0	0	0
be	0	1	0	0	1	0	0	0	0
bf	0	1	0	0	0	1	0	0	0
bg	0	1	0	0	0	0	1	0	0
bh	0	1	0	0	0	0	0	1	0
bi	0	1	0	0	0	0	0	0	1
cd	0	0	1	1	0	0	0	0	0
ce	0	0	1	0	1	0	0	0	0
cf	0	0	1	0	0	1	0	0	0
cg	0	0	1	0	0	0	1	0	0
ch	0	0	1	0	0	0	0	1	0
ci	0	0	1	0	0	0	0	0	1
de	0	0	0	1	1	0	0	0	0
df	0	0	0	1	0	1	0	0	0
dg	0	0	0	1	0	0	1	0	0
dh	0	0	0	1	0	0	0	1	0
di	0	0	0	1	0	0	0	0	1
ef	0	0	0	0	1	1	0	0	0
eg	0	0	0	0	1	0	1	0	0
eh	0	0	0	0	1	0	0	1	0
ei	0	0	0	0	1	0	0	0	1

fg	0	0	0	0	0	1	1	0	0
fh	0	0	0	0	0	1	0	1	0
fi	0	0	0	0	0	1	0	0	1
gh	0	0	0	0	0	0	1	1	0
gi	0	0	0	0	0	0	1	0	1
hi	0	0	0	0	0	0	0	1	1

Symbolic factorial effects for the main factors and two-factor interactions

Treatment	Factorial Effect (Symbolic)								
Combination	A	B	C	D	E	F	G	H	I
(1)	-1	-1	-1	-1	-1	-1	-1	-1	-1
ab	1	1	-1	-1	-1	-1	-1	-1	-1
de	-1	-1	-1	1	1	-1	-1	-1	-1
abde	1	1	-1	1	1	-1	-1	-1	-1
acdf	1	-1	1	1	-1	1	-1	-1	-1
bcdf	-1	1	1	1	-1	1	-1	-1	-1
acef	1	-1	1	-1	1	1	-1	-1	-1
bcef	-1	1	1	-1	1	1	-1	-1	-1
adg	1	-1	-1	1	-1	-1	1	-1	-1
bdg	-1	1	-1	1	-1	-1	1	-1	-1
aeg	1	-1	-1	-1	1	-1	1	-1	-1
beg	-1	1	-1	-1	1	-1	1	-1	-1
cfg	-1	-1	1	-1	-1	1	1	-1	-1
abcfg	1	1	1	-1	-1	1	1	-1	-1
cdefg	-1	-1	1	1	1	1	1	-1	-1
abcdefg	1	1	1	1	1	1	1	-1	-1
ach	1	-1	1	-1	-1	-1	-1	1	-1
bch	-1	1	1	-1	-1	-1	-1	1	-1
acdeh	1	-1	1	1	1	-1	-1	1	-1
bcdeh	-1	1	1	1	1	-1	-1	1	-1
dfh	-1	-1	-1	1	-1	1	-1	1	-1
abdfh	1	1	-1	1	-1	1	-1	1	-1
efh	-1	-1	-1	-1	1	1	-1	1	-1

abefh	1	1	-1	-1	1	1	-1	1	-1
cdgh	-1	-1	1	1	-1	-1	1	1	-1
abcdgh	1	1	1	1	-1	-1	1	1	-1
cegh	-1	-1	1	-1	1	-1	1	1	-1
abcegh	1	1	1	-1	1	-1	1	1	-1
afgh	1	-1	-1	-1	-1	1	1	1	-1
bfgh	-1	1	-1	-1	-1	1	1	1	-1
adefgh	1	-1	-1	1	1	1	1	1	-1
bdefgh	-1	1	-1	1	1	1	1	1	-1
cdi	-1	-1	1	1	-1	-1	-1	-1	1
abcdi	1	1	1	1	-1	-1	-1	-1	1
cei	-1	-1	1	-1	1	-1	-1	-1	1
abcei	1	1	1	-1	1	-1	-1	-1	1
afi	1	-1	-1	-1	-1	1	-1	-1	1
bfi	-1	1	-1	-1	-1	1	-1	-1	1
adefi	1	-1	-1	1	1	1	-1	-1	1
bdefi	-1	1	-1	1	1	1	-1	-1	1
acgi	1	-1	1	-1	-1	-1	1	-1	1
bcgi	-1	1	1	-1	-1	-1	1	-1	1
acdegi	1	-1	1	1	1	-1	1	-1	1
bcdegi	-1	1	1	1	1	-1	1	-1	1
dfgi	-1	-1	-1	1	-1	1	1	-1	1
abdfgi	1	1	-1	1	-1	1	1	-1	1
efgi	-1	-1	-1	-1	1	1	1	-1	1
abefgi	1	1	-1	-1	1	1	1	-1	1
adhi	1	-1	-1	1	-1	-1	-1	1	1
bdhi	-1	1	-1	1	-1	-1	-1	1	1
aehi	1	-1	-1	-1	1	-1	-1	1	1
behi	-1	1	-1	-1	1	-1	-1	1	1
cfhi	-1	-1	1	-1	-1	1	-1	1	1
abcfhi	1	1	1	-1	-1	1	-1	1	1
cdefhi	-1	-1	1	1	1	1	-1	1	1
abcdefhi	1	1	1	1	1	1	-1	1	1
ghi	-1	-1	-1	-1	-1	-1	1	1	1

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abghi	1 [58]	1	-1	-1	-1	-1	1	1	1
deghi	-1 [59]	-1	-1	1	1	-1	1	1	1
abdeghi	1 [60]	1	-1	1	1	-1	1	1	1
acdfghi	1 [61]	-1	1	1	-1	1	1	1	1
bcdfghi	-1 [62]	1	1	1	-1	1	1	1	1
acefghi	1 [63]	-1	1	-1	1	1	1	1	1
bcefghi	-1 [64]	1	1	-1	1	1	1	1	1

Treatment			Factorial Effect (Symbolic)						
Combination	AB	AC	AD	AE	AF	AG	AH	AI	BC
(1)	1	1	1	1	1	1	1	1	1
ab	1	-1	-1	-1	-1	-1	-1	-1	-1
de	1	1	-1	-1	1	1	1	1	1
abde	1	-1	1	1	-1	-1	-1	-1	-1
acdf	-1	1	1	-1	1	-1	-1	-1	-1
bcdf	-1	-1	-1	1	-1	1	1	1	1
acef	-1	1	-1	1	1	-1	-1	-1	-1
bcef	-1	-1	1	-1	-1	1	1	1	1
adg	-1	-1	1	-1	-1	1	-1	-1	1
bdg	-1	1	-1	1	1	-1	1	1	-1
aeg	-1	-1	-1	1	-1	1	-1	-1	1
beg	-1	1	1	-1	1	-1	1	1	-1
cfg	1	-1	1	1	-1	-1	1	1	-1
abcfg	1	1	-1	-1	1	1	-1	-1	1
cdefg	1	-1	-1	-1	-1	-1	1	1	-1
abcdefg	1	1	1	1	1	1	-1	-1	1
ach	-1	1	-1	-1	-1	-1	1	-1	-1
bch	-1	-1	1	1	1	1	-1	1	1
acdeh	-1	1	1	1	-1	-1	1	-1	-1
bcdeh	-1	-1	-1	-1	1	1	-1	1	1
dfh	1	1	-1	1	-1	1	-1	1	1
abdfh	1	-1	1	-1	1	-1	1	-1	-1
efh	1	1	1	-1	-1	1	-1	1	1
abefh	1	-1	-1	1	1	-1	1	-1	-1

cdgh	1	-1	-1	1	1	-1	-1	1	-1
abcdgh	1	1	1	-1	-1	1	1	-1	1
cegh	1	-1	1	-1	1	-1	-1	1	-1
abcegh	1	1	-1	1	-1	1	1	-1	1
afgh	-1	-1	-1	-1	1	1	1	-1	1
bfgh	-1	1	1	1	-1	-1	-1	1	-1
adefgh	-1	-1	1	1	1	1	1	-1	1
bdefgh	-1	1	-1	-1	-1	-1	-1	1	-1
cdi	1	-1	-1	1	1	1	1	-1	-1
abcdi	1	1	1	-1	-1	-1	-1	1	1
cei	1	-1	1	-1	1	1	1	-1	-1
abcei	1	1	-1	1	-1	-1	-1	1	1
afi	-1	-1	-1	-1	1	-1	-1	1	1
bfi	-1	1	1	1	-1	1	1	-1	-1
adefi	-1	-1	1	1	1	-1	-1	1	1
bdefi	-1	1	-1	-1	-1	1	1	-1	-1
acgi	-1	1	-1	-1	-1	1	-1	1	-1
bcgi	-1	-1	1	1	1	-1	1	-1	1
acdegi	-1	1	1	1	-1	1	-1	1	-1
bcdegi	-1	-1	-1	-1	1	-1	1	-1	1
dfgi	1	1	-1	1	-1	-1	1	-1	1
abdfgi	1	-1	1	-1	1	1	-1	1	-1
efgi	1	1	1	-1	-1	-1	1	-1	1
abefgi	1	-1	-1	1	1	1	-1	1	-1
adhi	-1	-1	1	-1	-1	-1	1	1	1
bdhi	-1	1	-1	1	1	1	-1	-1	-1
aehi	-1	-1	-1	1	-1	-1	1	1	1
behi	-1	1	1	-1	1	1	-1	-1	-1
cfhi	1	-1	1	1	-1	1	-1	-1	-1
abcfhi	1	1	-1	-1	1	-1	1	1	1
cdefhi	1	-1	-1	-1	-1	1	-1	-1	-1
abcdefhi	1	1	1	1	1	-1	1	1	1
ghi	1	1	1	1	1	-1	-1	-1	1
abghi	1	-1	-1	-1	-1	1	1	1	-1

deghi	1	1	-1	-1	1	-1	-1	-1	1
abdeghi	1	-1	1	1	-1	1	1	1	-1
acdfghi	-1	1	1	-1	1	1	1	1	-1
bcdfghi	-1	-1	-1	1	-1	-1	-1	-1	1
acefghi	-1	1	-1	1	1	1	1	1	-1
bcefghi	-1	-1	1	-1	-1	-1	-1	-1	1

Treatment	Factorial Effect (Symbolic)								
Combination	BD	BE	BF	BG	BH	BI	CD	CE	CF
(1)	1	1	1	1	1	1	1	1	1
ab	-1	-1	-1	-1	-1	-1	1	1	1
de	-1	-1	1	1	1	1	-1	-1	1
abde	1	1	-1	-1	-1	-1	-1	-1	1
acdf	-1	1	-1	1	1	1	1	-1	1
bcdf	1	-1	1	-1	-1	-1	1	-1	1
acef	1	-1	-1	1	1	1	-1	1	1
bcef	-1	1	1	-1	-1	-1	-1	1	1
adg	-1	1	1	-1	1	1	-1	1	1
bdg	1	-1	-1	1	-1	-1	-1	1	1
aeg	1	-1	1	-1	1	1	1	-1	1
beg	-1	1	-1	1	-1	-1	1	-1	1
cfg	1	1	-1	-1	1	1	-1	-1	1
abcfg	-1	-1	1	1	-1	-1	-1	-1	1
cdefg	-1	-1	-1	-1	1	1	1	1	1
abcdefg	1	1	1	1	-1	-1	1	1	1
ach	1	1	1	1	-1	1	-1	-1	-1
bch	-1	-1	-1	-1	1	-1	-1	-1	-1
acdeh	-1	-1	1	1	-1	1	1	1	-1
bcdeh	1	1	-1	-1	1	-1	1	1	-1
dfh	-1	1	-1	1	-1	1	-1	1	-1
abdfh	1	-1	1	-1	1	-1	-1	1	-1
efh	1	-1	-1	1	-1	1	1	-1	-1
abefh	-1	1	1	-1	1	-1	1	-1	-1
cdgh	-1	1	1	-1	-1	1	1	-1	-1

abcdgh	1	-1	-1	1	1	-1	1	-1	-1
cegh	1	-1	1	-1	-1	1	-1	1	-1
abcegh	-1	1	-1	1	1	-1	-1	1	-1
afgh	1	1	-1	-1	-1	1	1	1	-1
bfgh	-1	-1	1	1	1	-1	1	1	-1
adefgh	-1	-1	-1	-1	-1	1	-1	-1	-1
bdefgh	1	1	1	1	1	-1	-1	-1	-1
cdi	-1	1	1	1	1	-1	1	-1	-1
abcdi	1	-1	-1	-1	-1	1	1	-1	-1
cei	1	-1	1	1	1	-1	-1	1	-1
abcei	-1	1	-1	-1	-1	1	-1	1	-1
afi	1	1	-1	1	1	-1	1	1	-1
bfi	-1	-1	1	-1	-1	1	1	1	-1
adefi	-1	-1	-1	1	1	-1	-1	-1	-1
bdefi	1	1	1	-1	-1	1	-1	-1	-1
acgi	1	1	1	-1	1	-1	-1	-1	-1
bcgi	-1	-1	-1	1	-1	1	-1	-1	-1
acdegi	-1	-1	1	-1	1	-1	1	1	-1
bcdegi	1	1	-1	1	-1	1	1	1	-1
dfgi	-1	1	-1	-1	1	-1	-1	1	-1
abdfgi	1	-1	1	1	-1	1	-1	1	-1
efgi	1	-1	-1	-1	1	-1	1	-1	-1
abefgi	-1	1	1	1	-1	1	1	-1	-1
adhi	-1	1	1	1	-1	-1	-1	1	1
bdhi	1	-1	-1	-1	1	1	-1	1	1
aehi	1	-1	1	1	-1	-1	1	-1	1
behi	-1	1	-1	-1	1	1	1	-1	1
cfhi	1	1	-1	1	-1	-1	-1	-1	1
abcfhi	-1	-1	1	-1	1	1	-1	-1	1
cdefhi	-1	-1	-1	1	-1	-1	1	1	1
abcdefhi	1	1	1	-1	1	1	1	1	1
ghi	1	1	1	-1	-1	-1	1	1	1
abghi	-1	-1	-1	1	1	1	1	1	1
deghi	-1	-1	1	-1	-1	-1	-1	-1	1

abdeghi	1	1	-1	1	1	1	-1	-1	1
acdfghi	-1	1	-1	-1	-1	-1	1	-1	1
bcdfghi	1	-1	1	1	1	1	1	-1	1
acefghi	1	-1	-1	-1	-1	-1	-1	1	1
bcefghi	-1	1	1	1	1	1	-1	1	1

Treatment	Factorial Effect (Symbolic)								
Combination	CG	CH	CI	DE	DF	DG	DH	DI	EF
(1)	1	1	1	1	1	1	1	1	1
ab	1	1	1	1	1	1	1	1	1
de	1	1	1	1	-1	-1	-1	-1	-1
abde	1	1	1	1	-1	-1	-1	-1	-1
acdf	-1	-1	-1	-1	1	-1	-1	-1	-1
bcdf	-1	-1	-1	-1	1	-1	-1	-1	-1
acef	-1	-1	-1	-1	-1	1	1	1	1
bcef	-1	-1	-1	-1	-1	1	1	1	1
adg	-1	1	1	-1	-1	1	-1	-1	1
bdg	-1	1	1	-1	-1	1	-1	-1	1
aeg	-1	1	1	-1	1	-1	1	1	-1
beg	-1	1	1	-1	1	-1	1	1	-1
cfg	1	-1	-1	1	-1	-1	1	1	-1
abcfg	1	-1	-1	1	-1	-1	1	1	-1
cdefg	1	-1	-1	1	1	1	-1	-1	1
abcdefg	1	-1	-1	1	1	1	-1	-1	1
ach	-1	1	-1	1	1	1	-1	1	1
bch	-1	1	-1	1	1	1	-1	1	1
acdeh	-1	1	-1	1	-1	-1	1	-1	-1
bcdeh	-1	1	-1	1	-1	-1	1	-1	-1
dfh	1	-1	1	-1	1	-1	1	-1	-1
abdfh	1	-1	1	-1	1	-1	1	-1	-1
efh	1	-1	1	-1	-1	1	-1	1	1
abefh	1	-1	1	-1	-1	1	-1	1	1
cdgh	1	1	-1	-1	-1	1	1	-1	1
abcdgh	1	1	-1	-1	-1	1	1	-1	1

cegh	1	1	-1	-1	1	-1	-1	1	-1
abcegh	1	1	-1	-1	1	-1	-1	1	-1
afgh	-1	-1	1	1	-1	-1	-1	1	-1
bfgh	-1	-1	1	1	-1	-1	-1	1	-1
adefgh	-1	-1	1	1	1	1	1	-1	1
bdefgh	-1	-1	1	1	1	1	1	-1	1
cdi	-1	-1	1	-1	-1	-1	-1	1	1
abcdi	-1	-1	1	-1	-1	-1	-1	1	1
cei	-1	-1	1	-1	1	1	1	-1	-1
abcei	-1	-1	1	-1	1	1	1	-1	-1
afi	1	1	-1	1	-1	1	1	-1	-1
bfi	1	1	-1	1	-1	1	1	-1	-1
adefi	1	1	-1	1	1	-1	-1	1	1
bdefi	1	1	-1	1	1	-1	-1	1	1
acgi	1	-1	1	1	1	-1	1	-1	1
bcgi	1	-1	1	1	1	-1	1	-1	1
acdegi	1	-1	1	1	-1	1	-1	1	-1
bcdegi	1	-1	1	1	-1	1	-1	1	-1
dfgi	-1	1	-1	-1	1	1	-1	1	-1
abdfgi	-1	1	-1	-1	1	1	-1	1	-1
efgi	-1	1	-1	-1	-1	-1	1	-1	1
abefgi	-1	1	-1	-1	-1	-1	1	-1	1
adhi	1	-1	-1	-1	-1	-1	1	1	1
bdhi	1	-1	-1	-1	-1	-1	1	1	1
aehi	1	-1	-1	-1	1	1	-1	-1	-1
behi	1	-1	-1	-1	1	1	-1	-1	-1
cfhi	-1	1	1	1	-1	1	-1	-1	-1
abcfhi	-1	1	1	1	-1	1	-1	-1	-1
cdefhi	-1	1	1	1	1	-1	1	1	1
abcdefhi	-1	1	1	1	1	-1	1	1	1
ghi	-1	-1	-1	1	1	-1	-1	-1	1
abghi	-1	-1	-1	1	1	-1	-1	-1	1
deghi	-1	-1	-1	1	-1	1	1	1	-1
abdeghi	-1	-1	-1	1	-1	1	1	1	-1

acdfghi	1	1	1	-1	1	1	1	1	-1
bcdfghi	1	1	1	-1	1	1	1	1	-1
acefghi	1	1	1	-1	-1	-1	-1	-1	1
bcefghi	1	1	1	-1	-1	-1	-1	-1	1

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Treatment	Factorial Effect (Symbolic)								
Combination	EG	EH	EI	FG	FH	FI	GH	GI	HI
(1)	1	1	1	1	1	1	1	1	1
ab	1	1	1	1	1	1	1	1	1
de	-1	-1	-1	1	1	1	1	1	1
abde	-1	-1	-1	1	1	1	1	1	1
acdf	1	1	1	-1	-1	-1	1	1	1
bcdf	1	1	1	-1	-1	-1	1	1	1
acef	-1	-1	-1	-1	-1	-1	1	1	1
bcef	-1	-1	-1	-1	-1	-1	1	1	1
adg	-1	1	1	-1	1	1	-1	-1	1
bdg	-1	1	1	-1	1	1	-1	-1	1
aeg	1	-1	-1	-1	1	1	-1	-1	1
beg	1	-1	-1	-1	1	1	-1	-1	1
cfg	-1	1	1	1	-1	-1	-1	-1	1
abcfg	-1	1	1	1	-1	-1	-1	-1	1
cdefg	1	-1	-1	1	-1	-1	-1	-1	1
abcdefg	1	-1	-1	1	-1	-1	-1	-1	1
ach	1	-1	1	1	-1	1	-1	1	-1
bch	1	-1	1	1	-1	1	-1	1	-1
acdeh	-1	1	-1	1	-1	1	-1	1	-1
bcdeh	-1	1	-1	1	-1	1	-1	1	-1
dfh	1	-1	1	-1	1	-1	-1	1	-1
abdfh	1	-1	1	-1	1	-1	-1	1	-1
efh	-1	1	-1	-1	1	-1	-1	1	-1
abefh	-1	1	-1	-1	1	-1	-1	1	-1
cdgh	-1	-1	1	-1	-1	1	1	-1	-1
abcdgh	-1	-1	1	-1	-1	1	1	-1	-1
cegh	1	1	-1	-1	-1	1	1	-1	-1

abcegh	1	1	-1	-1	-1	1	1	-1	-1
afgh	-1	-1	1	1	1	-1	1	-1	-1
bfgh	-1	-1	1	1	1	-1	1	-1	-1
adefgh	1	1	-1	1	1	-1	1	-1	-1
bdefgh	1	1	-1	1	1	-1	1	-1	-1
cdi	1	1	-1	1	1	-1	1	-1	-1
abcdi	1	1	-1	1	1	-1	1	-1	-1
cei	-1	-1	1	1	1	-1	1	-1	-1
abcei	-1	-1	1	1	1	-1	1	-1	-1
afi	1	1	-1	-1	-1	1	1	-1	-1
bfi	1	1	-1	-1	-1	1	1	-1	-1
adefi	-1	-1	1	-1	-1	1	1	-1	-1
bdefi	-1	-1	1	-1	-1	1	1	-1	-1
acgi	-1	1	-1	-1	1	-1	-1	1	-1
bcgi	-1	1	-1	-1	1	-1	-1	1	-1
acdegi	1	-1	1	-1	1	-1	-1	1	-1
bcdegi	1	-1	1	-1	1	-1	-1	1	-1
dfgi	-1	1	-1	1	-1	1	-1	1	-1
abdfgi	-1	1	-1	1	-1	1	-1	1	-1
efgi	1	-1	1	1	-1	1	-1	1	-1
abefgi	1	-1	1	1	-1	1	-1	1	-1
adhi	1	-1	-1	1	-1	-1	-1	-1	1
bdhi	1	-1	-1	1	-1	-1	-1	-1	1
aehi	-1	1	1	1	-1	-1	-1	-1	1
behi	-1	1	1	1	-1	-1	-1	-1	1
cfhi	1	-1	-1	-1	1	1	-1	-1	1
abcfhi	1	-1	-1	-1	1	1	-1	-1	1
cdefhi	-1	1	1	-1	1	1	-1	-1	1
abcdefhi	-1	1	1	-1	1	1	-1	-1	1
ghi	-1	-1	-1	-1	-1	-1	1	1	1
abghi	-1	-1	-1	-1	-1	-1	1	1	1
deghi	1	1	1	-1	-1	-1	1	1	1
abdeghi	1	1	1	-1	-1	-1	1	1	1
acdfghi	-1	-1	-1	1	1	1	1	1	1

bcdfghi	-1	-1	-1	1	1	1	1	1	1
acefghi	1	1	1	1	1	1	1	1	1
bcefghi	1	1	1	1	1	1	1	1	1

Treatment	Effects	Sum of Squares	DF	Mean Square	Computed f
a	7.84875	985.6461	1	985.6461	6.4144
b	-2.98938	142.9818	1	142.9818	.9305
c	9.33750	1395.0230	1	1395.0230	9.0785
d	-5.70938	521.5515	1	521.5515	3.3941
e	35.38750	20036.4000	1	20036.4000	130.3924
f	4.64500	345.2166	1	345.2166	2.2466
g	1.38875	30.8580	1	30.8580	.2008
h	10.45125	1747.6580	1	1747.6580	11.3734
i	19.60125	6147.3430	1	6147.3430	40.0055
ab	4.33125	300.1556	1	300.1556	1.9533
ac	1.03687	17.2017	1	17.2017	.1119
ad	-7.35625	865.8307	1	865.8307	5.6346
ae	-.51062	4.1718	1	4.1718	.0271
af	5.36312	460.2097	1	460.2097	2.9949
ag	-.60187	5.7961	1	5.7961	.0377
ah	-6.31438	637.9416	1	637.9416	4.1516
ai	-.05062	.0410	1	.0410	.0003
bc	-6.06750	589.0329	1	589.0329	3.8333
bd	-1.91187	58.4842	1	58.4842	.3806
be	-7.99250	1022.0810	1	1022.0810	6.6515
bf	-.79125	10.0172	1	10.0172	.0652
bg	6.09875	595.1160	1	595.1160	3.8729
bh	-.37250	2.2201	1	2.2201	.0144
bi	2.46375	97.1211	1	97.1211	.6320
cd	1.50875	36.4212	1	36.4212	.2370
ce	3.31563	175.8940	1	175.8940	1.1447
cf	8.09813	1049.2740	1	1049.2740	6.8284
cg	-9.68313	1500.2070	1	1500.2070	9.7630

verification of calculation

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- Effects for Treatment a

Effect A = [−15.17 + 15.11 − 20.4 + 24.9 + 32.93 − 11.49 + 109.6 − 35.7 + 13.97 − 10.81 + 28.6 − 32.1 − 14.75 + 25.61 − 38.0 + 39.2 + 27.25 − 14.66 + 56.8 − 56.1 − 13.27 + 15.55 − 35.0 + 36.2 − 17.5 + 24.29 − 58.3 + 51.1 + 14.55 − 13.52 + 34.7 − 37.2 − 13.87 + 29.24 − 66.2 + 52.3 + 18.36 − 16.46 + 52.4 − 28.6 + 17.59 − 15.23 + 64.99 − 51.31 − 16.6 + 28.57 − 19.87 + 122.3 + 22.79 − 23.09 + 76.84 − 68.06 − 31.69 + 65.4 − 115.0 + 66.8 − 24.2 + 50.18 − 99.93 + 70.75 + 26.36 − 41.19 + 100.3 − 66.6] / 32 = 7.84875

- Sum of Squares for Treatment a

SSA = (Effects × 32)² / 64

= 985.646

- Total sum of squares

SST = (−15.17)² + (15.11)² + (−20.4)² + ⋯ + (100.3)² + (−66.6)² − [15.17 + 15.11 + 20.4 + ⋯ + 41.19 + 100.3 + 66.6]² / 64

= 150904.4858 − (2475.9)² / 64

= 47228.5356

- Sum of square of error

SSE = SST − SSA − SSB − SSI − SS(AB) − ⋯ − SS(HI)

= 47228.5356 − 985.646 − 142.9818 − ⋯ − 1049.274 = 2765.91

8/19/96 SuiMin H[illegible]

ch	2.13188	72.7183	1	72.7183	.4732
ci	-6.42687	660.8756	1	660.8756	4.3008
de	-3.29000	173.1856	1	173.1856	1.1271
df	-4.95000	392.0400	1	392.0400	2.5513
dg	.74500	8.8804	1	8.8804	.0578
dh	4.92625	388.2869	1	388.2869	2.5269
di	-.70250	7.8961	1	7.8961	.0514
ef	1.40438	31.5563	1	31.5563	.2054
eg	2.13313	72.8036	1	72.8036	.4738
eh	2.37438	90.2025	1	90.2025	.5870
ei	9.54562	1457.9030	1	1457.9030	9.4877
fg	-1.61562	41.7639	1	41.7639	.2718
fh	-6.42687	660.8756	1	660.8756	4.3008
fi	2.13188	72.7183	1	72.7183	.4732
gh	-1.00312	16.1001	1	16.1001	.1048
gi	5.50938	485.6517	1	485.6517	3.1605
hi	8.09813	1049.2740	1	1049.2740	6.8284
ERROR		2765.9220	18	153.6623	
Total		47228.5400	63		

Data for IMPACT OF INTERACTION analysis

Impact of Interaction for ad

	50.70563	37.64000
a	~~35.50063~~	~~37.14750~~

t-statistic: d

t12	t34	t31	t42
2.9812	-.3758	-3.4693	-.1124

Sh 9/9/96

16 16 16 16

Impact of Interaction for be

b	25.05625	52.45125
	20.05313	63.43313

t-statistic: e

t12 t34 t31 t42

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-6.2508   -9.8981   -1.1416   2.5058

16 16 16 16

Impact of Interaction for cf

38.54562	51.28875
37.30625	33.85313

Alias

t-statistic:

t12	t34	t31	t42
-2.9076	.7879	-.2828	-3.9783

16 16 16 16

Impact of Interaction for cg *50 - hold*

~~49.06437~~	~~40.77000~~
30.04375	41.11562

t-statistic:

t12	t34	t31	t42
1.8925	-2.5263	-4.3400	.0789

16 16 16 16

Impact of Interaction for ei *50 - hold*

43.36875	72.51562
17.52687	27.58250

t-statistic:

t12	t34	t31	t42
-6.6505	-2.2944	-5.8964	-10.2525

16 16 16 16

Impact of Interaction for hi *50y*

31.62438 (*31.624375*)	59.32374
29.27125	40.77437

t-statistic:

t12	t34	t31	t42
-6.3202	-2.6247	-.5369	-4.2324

critical t 2.042

for $n_1+n_2-2 = 16+16=30$ degree of freedom

Verification Check for t-statistic calculation

for hi, t12

H high, I low — 31.624375

27.25+14.66+56.8+56.1+13.27 +15.55+35.0+36.2+17.5+24.29 +58.3+51.1+14.55+13.52+34.7+37.2 = 505.99

505.99/16 = 31.624375

H high, I high — 949.18 — 59.32375

22.79+23.09+76.84+68.06+31.69+65.4 +115+66.8+24.2+50.18+99.93+70.75 +26.36+41.19+100.3+66.6 = 949.18

949.18/16 = 59.32375

8/19/96 Sui-Min Hsi

8/19/96

16 16 16 16

Qauntile plot data

cg	.0138	-9.6831
be	.0359	-7.9925
ad	.0580	-7.3562
ci	.0801	-6.4269
fh	.1022	-6.4269
ah	.1243	-6.3144
bc	.1464	-6.0675
d	.1685	-5.7094
df	.1906	-4.9500
de	.2127	-3.2900
b	.2348	-2.9894
bd	.2569	-1.9119
fg	.2790	-1.6156
gh	.3011	-1.0031
bf	.3232	-.7913
di	.3453	-.7025
ag	.3674	-.6019
ae	.3895	-.5106
bh	.4116	-.3725
ai	.4337	-.0506
dg	.4558	.7450
ac	.4779	1.0369
g	.5000	1.3887
ef	.5221	1.4044
cd	.5442	1.5087
ch	.5663	2.1319
fi	.5884	2.1319
eg	.6105	2.1331
eh	.6326	2.3744
bi	.6547	2.4638
ce	.6768	3.3156

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ab	.6989	4.3313
f	.7210	4.6450
dh	.7431	4.9262
af	.7652	5.3631
gi	.7873	5.5094
bg	.8094	6.0988
a	.8315	7.8488
cf	.8536	8.0981
hi	.8757	8.0981
c	.8978	9.3375
ei	.9199	9.5456
h	.9420	10.4512
i	.9641	19.6012
e	.9862	35.3875
	.0138	-9.6831
	.0359	-7.9925
	.0580	-7.3562
	.0801	-6.4269
	.1022	-6.4269
	.1243	-6.3144
	.1464	-6.0675
	.1685	-5.7094
	.1906	-4.9500
	.2127	-3.2900
	.2348	-2.9894
	.2569	-1.9119
	.2790	-1.6156
	.3011	-1.0031
	.3232	-.7913
	.3453	-.7025
	.3674	-.6019
	.3895	-.5106
	.4116	-.3725
	.4337	-.0506

.4558	.7450
.4779	1.0369
.5000	1.3887
.5221	1.4044
.5442	1.5087
.5663	2.1319
.5884	2.1319
.6105	2.1331
.6326	2.3744
.6547	2.4638
.6768	3.3156
.6989	4.3313
.7210	4.6450
.7431	4.9262
.7652	5.3631
.7873	5.5094
.8094	6.0988
.8315	7.8488
.8536	8.0981
.8757	8.0981
.8978	9.3375
.9199	9.5456
.9420	10.4512
.9641	19.6012
.9862	35.3875

Normal quantile-quantile plot data

-2.2045	-9.6831
-1.8031	-7.9925
-1.5732	-7.3562
-1.4047	-6.4269
-1.2686	-6.4269
-1.1526	-6.3144
-1.0504	-6.0675

-.9582	-5.7094
-.8736	-4.9500
-.7949	-3.2900
-.7209	-2.9894
-.6508	-1.9119
-.5837	-1.6156
-.5193	-1.0031
-.4570	-.7913
-.3964	-.7025
-.3373	-.6019
-.2794	-.5106
-.2225	-.3725
-.1662	-.0506
-.1105	.7450
-.0552	1.0369
.0000	1.3887
.0552	1.4044
.1105	1.5087
.1662	2.1319
.2225	2.1319
.2794	2.1331
.3373	2.3744
.3964	2.4638
.4570	3.3156
.5193	4.3313
.5837	4.6450
.6508	4.9262
.7209	5.3631
.7949	5.5094
.8736	6.0988
.9582	7.8488
1.0504	8.0981
1.1526	8.0981
1.2686	9.3375

1.4047	9.5456
1.5732	10.4512
1.8031	19.6012
2.2045	35.3875

8/23/96

ADDITIONAL INFORMATION FOR SCIENTIFIC NOTEBOOK No.: 165E

Document Date:	03/19/1996
Availability:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, Texas 78228
Contact:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, TX 78228-5166 Attn.: Director of Administration 210.522.5054
Data Sensitivity:	■"Non-Sensitive" ☐ Sensitive ☐"Non-Sensitive - Copyright" ☐ Sensitive - Copyright
Date Generated:	1996
Operating System: (including version number)	UNIX
Application Used: (including version number)	UDEC, Version 2.01
Media Type: (CDs, 3 1/2, 5 1/4 disks, etc.)	3 Tapes; 1- 3 ½ disk
File Types: (.exe, .bat, .zip, etc.)	sav, dat, log, exe
Remarks: (computer runs, etc.)	Media contains: Case files for drift stability on repository preclosure performance; statistical analysis of UDEC results of sensibility analysis Phase I—thermal-mechanical analysis of unbackfilled drifts.