6 Thermomechanical Analysis of a Waste Emplacement Drift

6.1 Problem Statement

This problem involves the transient thermal-mechanical simulation of the behavior of a waste emplacement drift in which heat-producing waste is placed vertically beneath the floor. The specific problem presented here is adapted from Christianson (1989)*.

The emplacement drift under study is in the center of an emplacement panel. Spent fuel (SF) canisters and defense high-level waste (DHLW) canisters are alternately placed in the floor of the drift at a pitch of 2.3 m. The emplacement of waste in the panel is assumed to be instantaneous.

Figure 6.1 illustrates the conceptual representation of the vertical waste emplacement. Because of symmetry, only one-half of the disposal room and pillar needs to be included in the analysis. The thermal boundary conditions are adiabatic. The top and bottom horizontal boundaries are moved sufficiently far from the heat-generating waste to remain at the initial temperature of 26°C for the time period simulated.

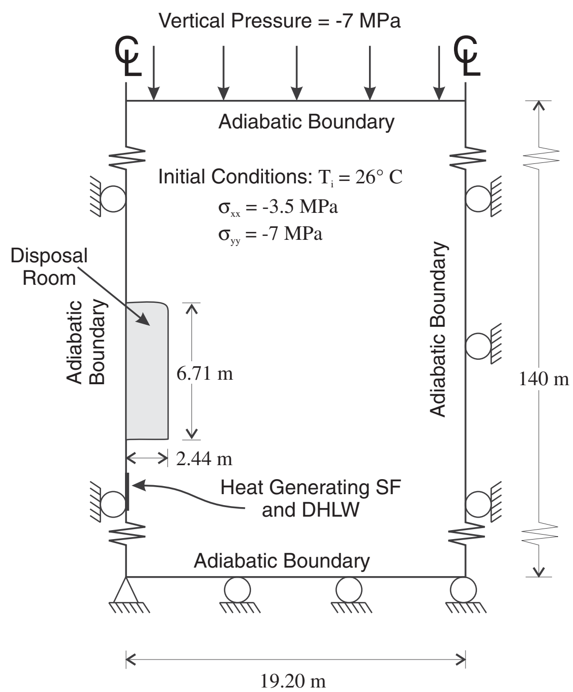

Figure 6.1 Conceptual model of vertical emplacement concept

* This section was prepared for the U.S. Nuclear Regulatory Commission under U.S. NRC Contract No. 02-85-002.

Using two-dimensional models requires that the discrete location of the waste containers be distributed uniformly along the disposal room. In the case of vertical emplacement, this means the location of a vertical heat-generating trench at the center of the floor along the axis of the room. Because of the transient nature of the problem, as well as the geometric layout of the waste, the "trench" concept is expected to be an adequate idealization of the emplacement.

The tributary heating area for the emplacement panel is reported by Christianson (1989) to be 8194.5 m^2. The average thermal loading is considered to be 14.1 W/m^2. For the panel geometry, this results in an initial heat-generating power per meter of room length of 713.5 W.

The initial power of an SF container at the time of emplacement is set to 3.2 kW. The initial power of the DHLW container is chosen as 0.42 kW. The power output of the two waste types is combined and treated as spent fuel, as given by Peters (1983):

$$P(t) = 0.54\, exp(-ln(0.5)t/89.3) + 0.44\, exp(-ln(0.5)t/12.8) \tag{6.1}$$

where $P(t)$ = normalized power, and t = time in years.

Eq. (6.1) is similar to the expression for normalized power as a function of time given by Mansure (1985) for SF.

The thermal and mechanical material properties used in this example are shown in Table 6.1.

Table 6.1 Thermal and mechanical properties used in thermomechanical analysis of a waste emplacement drift

	Property	Units
Intact Rock		
	Bulk density	2.34 g/cc
	Young's modulus	15.1 GPa
	Poisson's ratio	0.20
	Thermal conductivity	2.07 W/m °C
	Specific heat	961 J/kg °C
	Thermal expansion coefficient	10.7×10^{-6} /°C
Joints		
	Normal stiffness	100 GPa/m
	Shear stiffness	100 GPa/m
	Cohesion	1.0 MPa
	Friction	38.7°
	Dilation	0.0°

6.2 *UDEC* Analysis

In *UDEC*, each joint is explicitly modeled with variable spacing and persistence. The blocks are assumed to behave elastically. This means that inelastic behavior is allowed to occur only along the joints. Figures 6.2 and 6.3 illustrate the pattern of joints represented in this example.

The analysis ignores any effects of the jointing on the thermal conductivity of the rock mass. Based on the results of field tests involving thermal conductivity of rock masses, this assumption appears reasonable. The analysis also ignores the effects of fluid (i.e., air and water) convection in the rock mass and emplacement room, and the analysis ignores effects of boiling of pore water, which could affect heat transfer rates. The thermal properties assume fully saturated conditions.

A linear-stiffness Coulomb joint model is used in this analysis. While more complex models (such as the continuously yielding model or the Barton-Bandis model) could be used, these models vary in detail of the behavior (though the fundamental effects are similar).

The kinematic boundary conditions used in the *UDEC* model are shown in Figure 6.1, and are such that the two vertical boundaries are restricted from moving in the horizontal direction, but are free to move in the vertical direction. The lower horizontal boundary is restricted from moving in the vertical direction, but free to move in the horizontal direction. The upper horizontal boundary is a free-to-move pressure boundary. The initial vertical and horizontal stresses applied to the models are −7 MPa and −3.5 MPa.

The decaying heat source is applied as a heat flux boundary condition (**block edge apply flux**) to a 4 m length of the boundary beneath the center of the floor. The initial power is divided by the 4 m length, and then split according to the constants given in Eq. (6.1). Note that only half of this power is applied, because of symmetry.

The modeling sequence is as follows.

Excavation of the Drift

Deformations and stresses throughout the jointed rock are determined after the drift is excavated.

Thermomechanical Response at 50 Years

The thermal-mechanical process is performed by alternately calculating the thermal loading and then the mechanical response. The thermal calculation increment is made in 1000 steps with a thermal timestep of 8×10^4 sec, using the implicit solution algorithm. Then, a maximum of 2000 mechanical steps are made to reduce the unbalanced force ratio to approximately 10^{-5}. This two-step process is repeated until the 50-year thermal time is reached. The emplacement drift is not ventilated during this period; adiabatic boundaries are assumed for the drift.

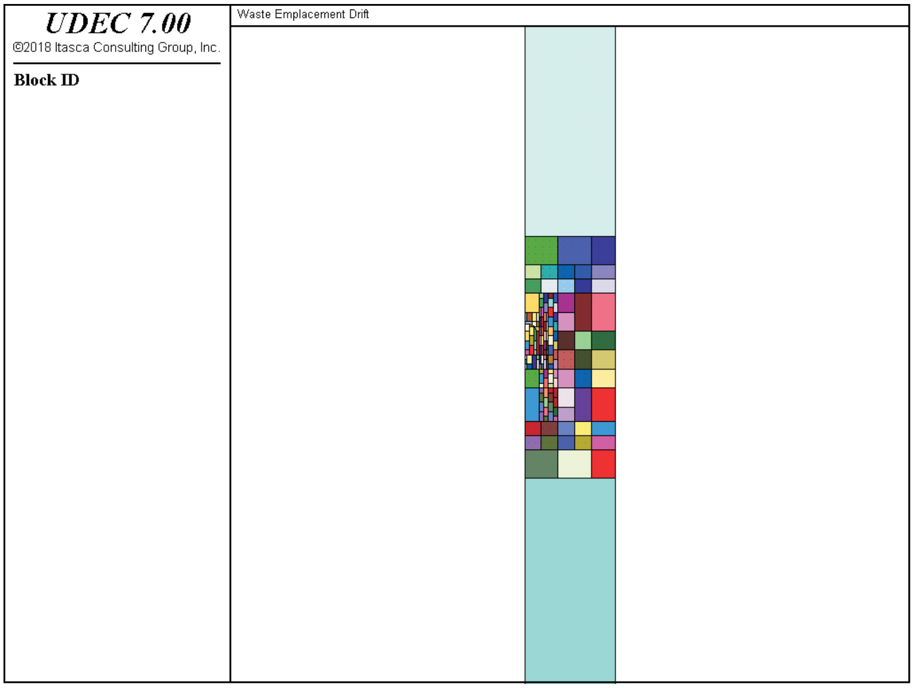

Figure 6.2 UDEC geometry for thermomechanical analysis of a waste emplacement drift

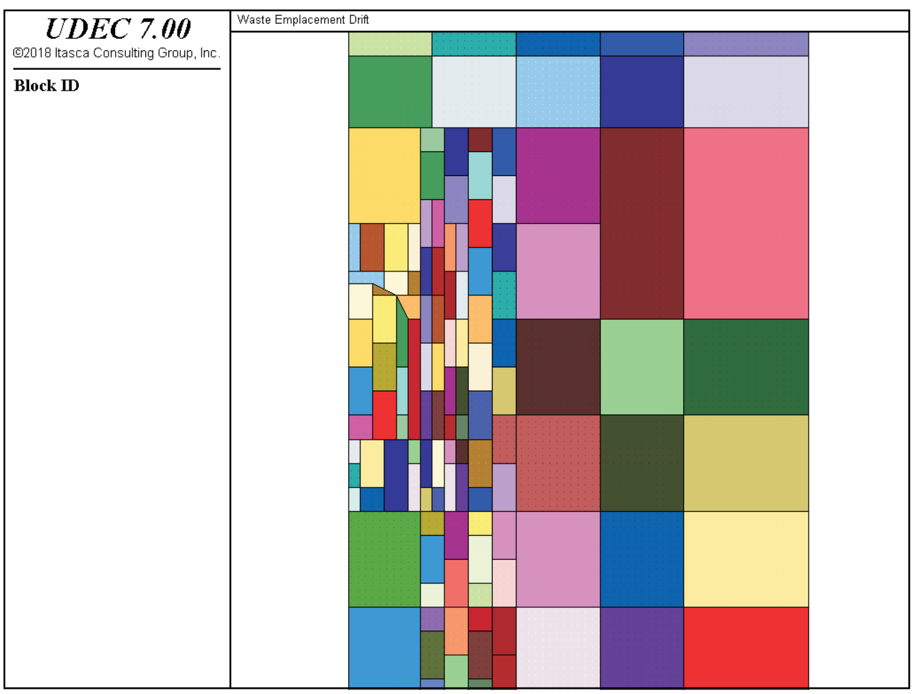

Figure 6.3 Close-up view of waste emplacement drift

6.3 Results

The results of the analyses are shown in Figures 6.4 to 6.8. Figures 6.4 and 6.5 show the stress and displacement distributions that result from drift excavation. The temperature distribution at 50 years is shown in Figure 6.6. Figure 6.7 shows the stress distribution at 50 years. The extent of joint shear displacement is shown in Figure 6.8. In *UDEC*, shear displacement magnitudes are expressed by plotting multiple parallel lines along a joint. The thicker lines represent more shear displacement than thinner lines.

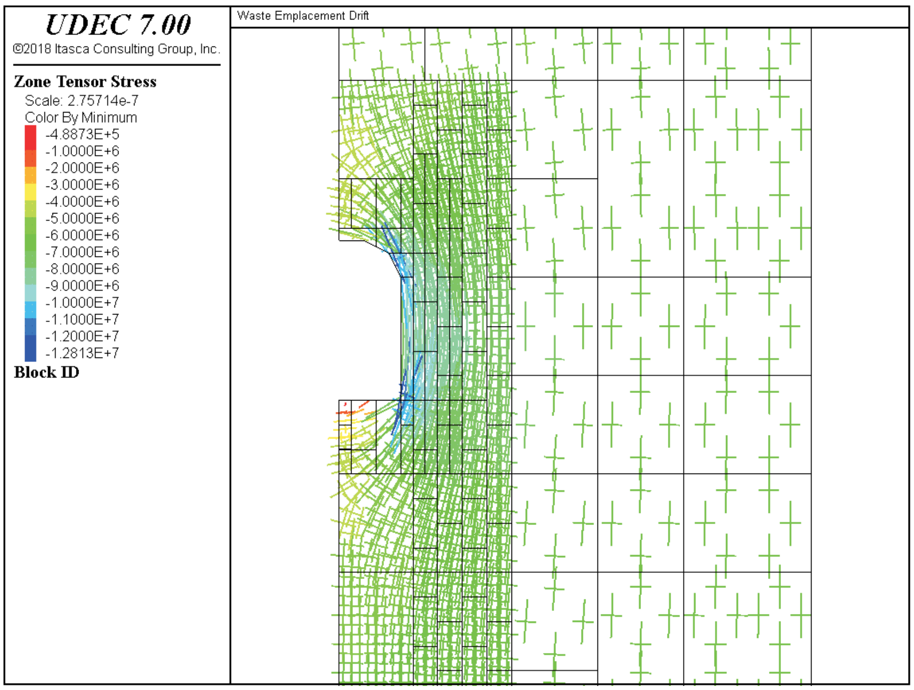

Figure 6.4 Principal stress distribution after excavation of the drift

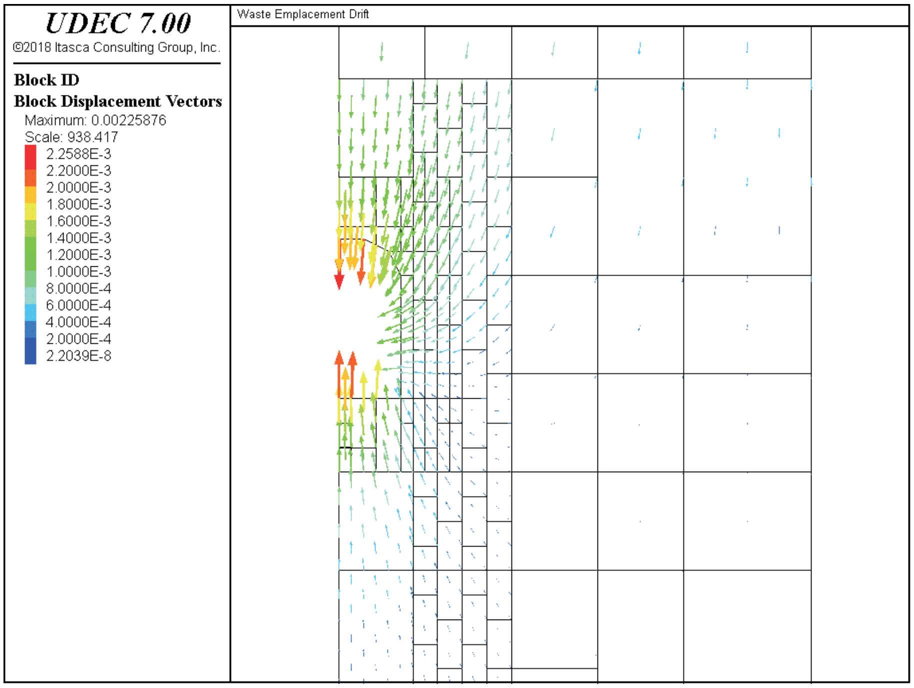

Figure 6.5 Displacement vectors after excavation of the drift

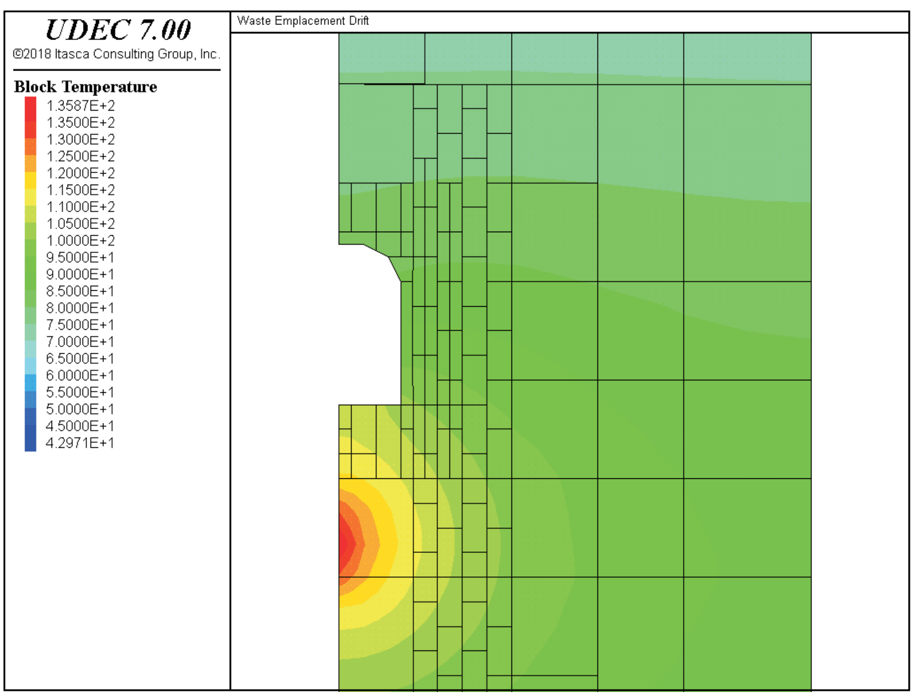

Figure 6.6 Temperature distribution in the rock at 50 years

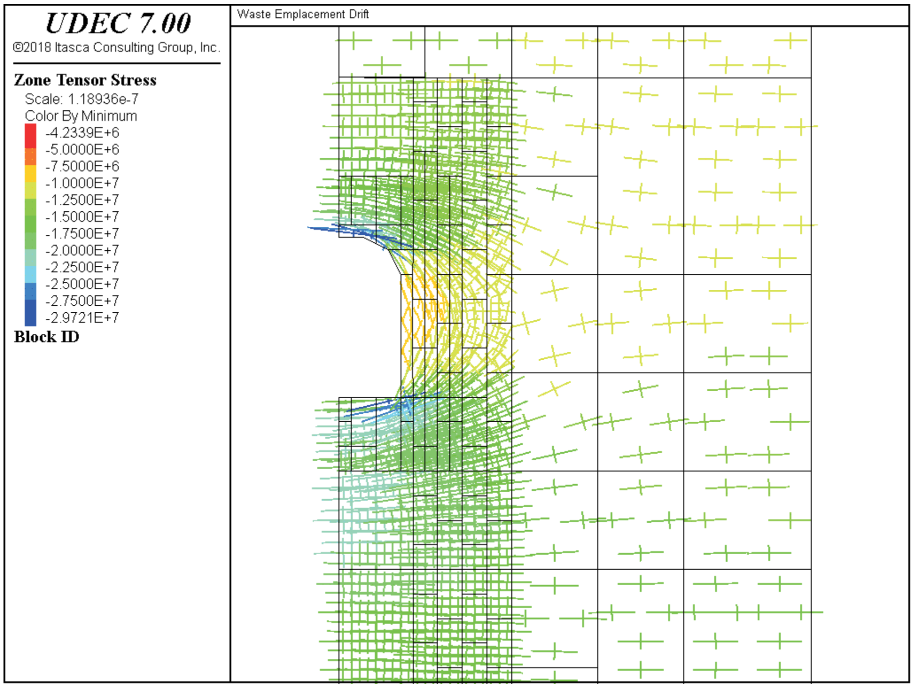

Figure 6.7 Principal stress distribution in the rock at 50 years

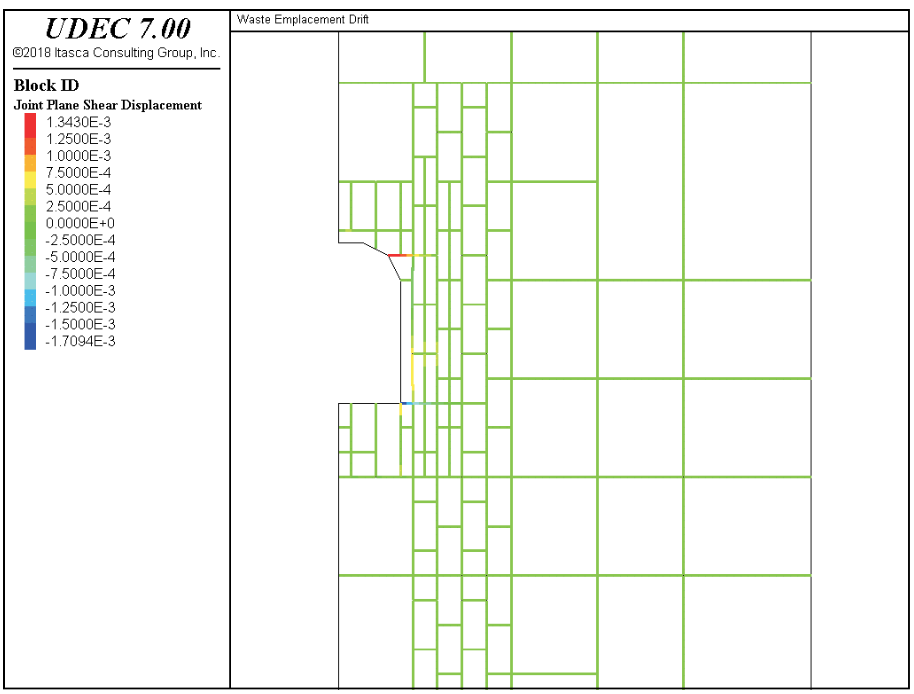

Figure 6.8 Shear displacement along the joints at 50 years

6.4 References

Christianson, Mark. "Sensitivity of the Stability of a Waste Emplacement Drift to Variation in Assumed Rock Joint Parameters in Welded Tuff," U.S. Nuclear Regulatory Commission, NUREG/CR-5336 (April 1989).

Mansure, A. J. "Expected Temperatures for Spent Fuel Borehole Walls and Drifts," Memo to R. J. Flores, Sandia National Laboratories, Sandia Keystone Memo 6310-85-8 (April 15 1985).

Peters, R. R. "Thermal Response to Emplacement of Nuclear Waste in Long, Horizontal Boreholes," SAND82-2497 (April 1983).

6.5 Listing of Data File

Example 6.1 DRIFT.DAT

```
model new
;                                                                    ;
;      T H E R M A L / M E C H A N I C A L    A N A L Y S I S        ;
;                                                                    ;
;  Input file for determining emplacement room behavior.             ;
;  Vertical emplacement scheme ...                                   ;
;                                                                    ;
;
model title 'Waste Emplacement Drift'
block config thermal
block tolerance corner-round-length 0.005
block tolerance minimum-edge-length 0.01
block create polygon 0 -40 0 100 19.2 100 19.2 -40
;;;;;;;;;;;;;;;;;;;;;;
; large block cracks
;;;;;;;;;;;;;;;;;;;;;;
block cut crack (0,43) (19.2,43)
block cut crack (0,16) (19.2,16)
;;;;;;;;;;;;;;;;;;;;;;;;;
; emplacement room cracks
;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack 0.0,36.5  1.0,36.5
block cut crack 1.0,36.5  2.0,36.0
block cut crack 2.0,36.0  2.5 35.0
block cut crack 2.5,27.0  2.5,40.0
block cut crack 0.0,30.0  6.0,30.0
;;;;;;;;;;;;;;;;;;;;;;;;;
; heavily jointed region
;;;;;;;;;;;;;;;;;;;;;;;;;
```

```
jregion id 1 0.0,16.0 0.0,43.0 7.0,43.0 7.0,16.0
bl cut joint-set angle 0 trace 1 gap 1 spacing 2 origin 1,0 range jregion 1
bl cut joint-set angle 0 trace 1 gap 1 spacing 2 origin 0,1 range jregion 1
bl cut joint-set angle 90 spacing 1 origin 1,0 range jregion 1
bl cut crack 7,16 7,43
;;;;;;;;;;;;;;;;;;;;;;;;;;
; make crack for heaters
;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack (0,28) (1,28)
block cut crack (0,27) (7,27)
block cut crack (0,26) (1,26)
block cut crack (0,24) (1,24)
block cut crack (0,23) (7,23)
;;;;;;;;;;;;;;;;;;;;;;;;;;
; additional fine cracks
;;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack  0.5,27 0.5,30
block cut crack  0.5,37 0.5,40
block cut crack  1.5,27 1.5,30
block cut crack  1.5,36.1 1.5,40
block cut crack  2.5,27 2.5,30
block cut crack  2,27   3,27
block cut crack  3.5,27 3.5,40
block cut crack  4.5,27 4.5,40
block cut crack  1,37 2,37
block cut crack  1,39 2,39
block cut crack  2,36 3,36
block cut crack  2.5,35.9 2.5,40
;;;;;;;;;;;;;;;;;;;;;;;;;
; bottom region
;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack 0,4 19.2,4
block cut crack 0,10 19.2,10
block cut crack 0,13 19.2,13
block cut crack 3.5,10 3.5 16
block cut crack 7,4 7,16
block cut crack 10.5,10 10.5,16
block cut crack 14,4 14,16
;;;;;;;;;;;;;;;;;;;;;;;;;
; top region
;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack 0,46 19.2,46
block cut crack 0,49 19.2,49
block cut crack 0,55 19.2,55
block cut crack 3.5,49 3.5 43
block cut crack 7,55 7,43
```

```
block cut crack 10.5,49 10.5,43
block cut crack 14,55 14,43
;;;;;;;;;;;;;;;;;;;;;;;;;
; right side
;;;;;;;;;;;;;;;;;;;;;;;;;
block cut crack 10.5,16 10.5,43
block cut crack 14,16 14,43
block cut crack 7,19 10.5 19
block cut crack 7,23 19.2 23
block cut crack 7,27 19.2 27
block cut crack 7,31 19.2 31
block cut crack 7,35 19.2 35
block cut crack 7,39 10.5 39
;
; generate zones
;
block zone generate  quad 1.4 range pos-x 0 7 pos-y 16 43
block zone generate  edge 1.4 range pos-x 0 7 pos-y 16 43
block zone generate  edge 4.2 range pos-x 7 20 pos-y 16 43
block zone generate  edge 4.2 range pos-x 0 20 pos-y 4 16
block zone generate  edge 14 range pos-x 0 20 pos-y -40 4
block zone generate  edge 4.2 range pos-x 0 20 pos-y 43 55
block zone generate  edge 14 range pos-x 0 20 pos-y 55 100
;
;--- ASSIGN MATERIAL PROPERTIES (REF: SCP-CDR CHAP. 2, SEC. 2.3.1)
;--- USING THE JOINT PROPERTIES AND "ROCK MASS" PROPERTIES.
;--- USING THE 'DESIGN' VALUES FROM
;--- TABLES 2-4, 2-6, AND 2-7.
;--- THE ROCK IS CHARACTERIZED AS AN ELASTIC/PLASTIC MATERIAL
;--- WITH VERTICAL AND HORIZONTAL.  A COULOMB FAILURE CRITERION
;--- IS USED FOR THE JOINTS ...
;
;--- THERMAL PROPERTIES OF THE ROCK ...
;    (Ref: SCP-CDR Chap. 2, Sec. 2.3.1.9, Table 2-9)
;
block zone group 'intact rock'
block zone cmodel assign elastic density 2.34E3 bulk 8.39E9 ...
  shear 6.29E9 cond 2.07 specheat 961 thexp 1.07E-5 ...
  range group 'intact rock'
;
;--- Rock Joints:
block contact group 'joints'
block contact cmodel assign residual st-s 1E11 st-n 1E11 ...
  friction 39 cohesion 1E6 range group 'joints'
; new contact default
block contact cmodel default residual stiffness-shear 1E11 ...
```

```
  stiffness-normal 1E11 friction 39 cohesion 1E6
;
;--- DEFINE THE INITIAL STRESS FIELD (MPa)...
;--- REFERENCE:  SCP-CDR CHAP. 2, SEC. 2.3.1.9
;    (The initial vertical stress is about -7 MPa at
;     the disposal room horizon.  The horizontal stress
;     is determined as 0.5 pos-x SYY.)
;
block insitu  stress -3500000.0 0.0 -7000000.0 ...
  gradient-x 0.0 0.0 0.0 gradient-y 11700.0 0.0 23400.0
block gridpoint init temperature 26.0
model gravity 0.0 -9.81
;
;--- SET KINEMATIC BOUNDARY CONDITIONS ...
;    (The two vertical boundaries are symmetry planes, thus,
;     they are restricted from moving in the horizontal (x)
;     direction.  The bottom horizontal boundary is restricted
;     from moving in the vertical (y) direction.  The top
;     horizontal boundary is a free-to-move pressure boundary.
;     The pressure is acting downward, and is equal to the
;     initial vertical stress.)
;
block gridpoint apply velocity-x 0 range pos-x -0.1 0.1 pos-y -40.1 100.1
block gridpoint apply velocity-x 0 range pos-x 18.9 19.2 pos-y -40.1 100.1
block gridpoint apply velocity-y 0 range pos-x -0.1 19.3 pos-y -40.1 -39.9
block edge apply stress -3500000.0 0.0 -7000000.0 ...
  gradient-x 0.0 0.0 0.0 gradient-y 11700.0 0.0 23400.0 ...
  range pos-x -0.1 19.3 pos-y 99.9 100.1
;
model save 'cycle0.sav'
;
block solve ratio 1.0E-5
model save 'm0e.sav'
;
;--- EXCAVATE THE DISPOSAL ROOM ...
;
block contact reset displacement
block gridpoint init displacement-x 0
block gridpoint init displacement-y 0
block delete range pos-x 0 2.5 pos-y 30 35
block delete range pos-x 2 2.3 pos-y 35 35.5
block delete range pos-x 0 1.55 pos-y 35 36.2
block solve ratio 1.0E-5
model save 'm0d.sav'
;
;--- ASSIGN THE DECAYING HEAT SOURCE WHICH SIMULATES THE
```

```
;--- COMMINGLED SF AND DHLW ...
;    (The thermal decay characteristics are from Peters, 1983,
;     SAND-2497.  The initial heat generating power per meter
;     of room length is 713.5 W.  Because of symmetry only half
;     of this power is applied.  Note that the decay coefficients
;     have dimension 1/sec and not 1/year, which is commonly
;     used in the literature ...
;     decay constants for SF are also used for the DHLW.
;
block edge apply flux 48.16 -2.46E-10 range pos-x -0.1 0.1 pos-y 23 27
block edge apply flux 41.03 -1.72E-9 range pos-x -0.1 0.1 pos-y 23 27
hist reset
block gridpoint history temperature 0.0 30.0
block gridpoint history temperature 0.0 36.7
block gridpoint history temperature 2.5 30.0
block gridpoint history temperature 1.0 25.0
block gridpoint history temperature 2.0 25.0
block gridpoint history temperature 3.0 25.0
block gridpoint history temperature 5.0 25.0
block gridpoint history temperature 9.0 25.0
block gridpoint history temperature 18.0 25.0
block gridpoint history displacement-y 0.0 36.5
block gridpoint history displacement-y 0.0 30.0
block gridpoint history displacement-x 2.5 33.0
block gridpoint history displacement-y 1.5 36.2
block zone history stress-xx 0.0 36.5
block zone history stress-xx 0.0 30.0
block zone history stress-yy 2.5 33.0
block thermal history time-total
;
;--- START THE HEAT TRANSFER SOLUTION USING THE IMPLICIT SCHEME ...
;
block thermal substep-mechanical 2000
block thermal substep-thermal 1000
block thermal timestep 80000.0
bl thermal cycle implicit age 1.58E9 step 100000 temperature-change 200.0
block solve age 0.0 ratio 1.0E-5
model save 't50c.sav'
```