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The Effects of Boundary Conditions On Thermomechanical Calculations: Spent Fuel Test—Climax

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THE EFFECTS OF BOUNDARY CONDITIONS
ON THERMOMECHANICAL CALCULATIONS:
SPENT FUEL TEST--CLIMAX

ABSTRACT

The effects of varying certain boundary conditions on the results of finite-element calculations were studied in relation to the Spent Fuel Test--Climax. The study employed a thermomechanical model with the ADINA structural analysis. Nodal temperature histories were generated with the compatible ADINAT heat flow codes. The boundary conditions studied included:

- The effect of boundary loading on three progressively larger meshes.
- Plane strain vs plane stress conditions.
- The effect of isothermal boundaries on a small mesh and on a significantly larger mesh.

The results showed that different mesh sizes had an insignificant effect on isothermal boundaries up to 5 yr, while on the smallest and largest mesh, the maximum temperature difference in the mesh was $<1^{\circ}\text{C}$. In the corresponding ADINA calculation, these different mesh sizes produce insignificant changes in the stress field and displacements in the region of interest near the heat sources and excavations.

On the other hand, plane stress produces horizontal and vertical stress differences ~9% higher than does plane strain.

INTRODUCTION

Mechanical and thermomechanical calculations of the Spent Fuel Test in Climax stock granite were completed before the emplacement of the spent fuel.¹ Later, another "as-built" calculation was made using adjusted heat output for the spent fuel obtained from calorimetry on two of the spent fuel canisters. The output of electric heaters in the floor of the side drifts were periodically adjusted to simulate the thermal regime of a large storage array. Elastic moduli used to represent the Climax granite were obtained from in situ field measurements.² More recently, measurements of heat flow and drift closure were compared with the as-built calculation.^{3,4}

The Spent Fuel Test--Climax (SFT-C) is a generic test into the effectiveness of geological storage of spent fuel assemblies from an operating nuclear reactor in Climax stock granite at the U.S. Department of Energy's Nevada Test Site. Calculational modeling of the spent fuel repository was done with the ADINA⁵ stress analysis and the compatible ADINAT⁶ heat-flow finite-element codes. The granite was assumed to be isotropic-thermoelastic with temperature-dependent thermal expansion coefficients.

One of the first requirements for any finite-element calculation is to decide on the mesh size and the number of elements. The mesh consists of interconnected elements constructed from corner and side nodes. The mesh must be large enough so that the conditions imposed on the boundaries do not affect the region of interest (near the heat sources and excavations) during the calculation. The accuracy of the results depends on the element and time-step sizes. Regions where temperature and stress gradients are the greatest require smaller elements. Among other things, the total running time of the calculation depends on the number of element-time steps. The desire for efficiency and expeditious use of personnel and computers dictates a prudent choice of mesh size, the number of elements, and the time step.

The question arises, then, as to what effect imposing similar boundary conditions on different size meshes will have on the region of interest around the heat sources and openings. The purpose of this study was to investigate the effect of different boundary conditions on the region where temperature, stress, and displacement are being measured. Three specific cases are reported here:

- The effect of mesh loading on three progressively larger meshes.
- The difference in results from plane strain and plane stress conditions.
- The effect of isothermal boundaries on a small mesh and a significantly larger mesh.

DESIGN OF THE MESH

The mesh was designed so that it could be peeled off in layers like an onion (Fig. 1). The element sizes of the innermost region were similar to those used with the as-built calculation,² consisting of 274 eight-node

elements, exclusive of the degenerated four-node elements used with the excavated openings. Because of the symmetry of the drift geometry, only half the region is modeled, i.e., an 80×80 -m region is modeled as a 40×80 -m region. Figure 2 shows the elements around the drifts and the relative position and lengths of the spent fuel canisters below the floor of the spent fuel drift and of the electrical heaters below the heater drifts. A region 0.5-m thick was included around each opening so that different properties could be assigned to the material identified as having been explosively damaged following the excavations. Table 1 shows the distances and spacings used in constructing the finite-element mesh.

The first layer consists of 52 eight-node elements. When added to the innermost mesh, the effective mesh size becomes 110×110 m, modeled as a 55×110 -m mesh. When the outermost layer of 56 eight-node elements is added, the effective size mesh increases to 140×140 m, modeled by a 70×140 -m mesh.

THERMAL CALCULATIONS

The ADINAT⁶ finite-element code was used to calculate the nodal temperature histories that drive the ADINA thermomechanical model. The histories were obtained in 260 one-week time steps for a total of 5 yr. Table 2 shows the material thermal properties used in the calculations.

Radiative heat transfer in the drifts was modeled by assigning the drift material a high value of thermal conductivity and a low density so that it would agree with a properly modeled TRUMP code calculation. Ventilation was modeled with convective heat transfer from a central node in each drift.⁷ Table 3 presents drift material properties derived to simulate radiation and ventilation with ADINAT.

Table 4 shows the heat input values used in the calculations. The power level decay for the spent fuel was assumed to be proportional to that for PWR fuel, with a burn-up of 33,000 megawatt days thermal per metric ton of uranium (MWD/MTU) at a specific power of 37.5 MW/MTU .¹¹ Calorimetric measurements showed the power level at the beginning of the test at 2.46 yr out of core to be 1546 W.¹² Figure 3 is the decay curve for the spent fuel canisters. Table 5 shows the variation in time for power levels of the electrical resistance heaters in the floor of the heater drifts planned at the start of the test. Some modifications to this list were made during the interim.

Table 1. Distances and dimensions used in ADINA and ADINAT calculations.

<u>Spent fuel drift</u>	<u>Distances and dimensions</u>
Floor position	417.58 m below surface 1.75 m above top of canister
Cross section	4.58 × 6.25-m domed roof
<u>Heater drift</u>	
Floor position	417.58 m below surface 2.66 m above top of heater
Cross section	3.35 × 3.35-m rounded corner
<u>Spent fuel canisters and electrical simulators</u>	
Spacing	3 m on center
Length	3.66 m
<u>Electrical resistance heaters</u>	
Spacing	6 m on center
Length	1.83 m

Two separate ADINAT calculations were made with the boundary temperature condition set to a constant ambient temperature of 23°C. One calculation used the full mesh with the fixed temperature condition on the outermost boundary, the other used the smaller mesh with the temperature condition on the innermost boundary. This boundary condition can act with time as a heat sink, since the temperature is held constant. Since the same heat sources are used in both sets of calculations, the temperature profile at early times is the same for both.

Figure 4A shows the temperature profiles at 0.25 and 0.5 yr and Fig. 4B at 0.75 and 1.0 yr.

At later times the profiles are different. Figure 5A shows the temperature profiles at 2.0 and 3.0 yr and Fig. 5B at 4.0 and 5.0 yr for ambient conditions at the outermost boundary. The temperature contours for 23.5° and 24.0°C are superimposed on each plot, in addition to those labeled per temperature scale. In each case of temperature plots, a 40 × 40-m portion of the innermost mesh is shown, which is common to all mesh sizes (see Fig. 1).

Table 2. Values of Climax granite and air properties used in relation to the ADINAT thermal calculations.

<u>Climax granite</u>	
Heat capacity ^a	$\frac{\text{J/kg} - \text{K}}{930}$
<u>Thermal conductivity ($^{\circ}\text{C}$)</u> ^{8,9}	<u>W/m - K</u>
0	3.1679
23	3.1104
477	2.1104
<u>Thermal expansion coefficient ($^{\circ}\text{C}$)</u> ¹⁰	<u>K⁻¹</u>
0	10×10^{-6}
23	10×10^{-6}
40	8.9×10^{-6}
80	7.4×10^{-6}
125	8.0×10^{-6}
175	9.6×10^{-6}
225	12.7×10^{-6}
<u>Air</u> ^b	
Density	1 kg/m ³
Heat capacity	1000 J/kg - K
Thermal conductivity	0.03 W/m - K

^a Derived from diffusivity measurements.

^b Used to derive input values shown in Table 3 (Ref. 7).

Figures 6A and 6B show temperature profiles at 2.0 and 3.0 yr and 4.0 and 5.0 yr, respectively, for temperature boundary conditions with ambient conditions at the innermost boundaries. Note how the 23.5 and 24°C contours become flatter with time at the 40-m vertical boundary, i.e., the innermost boundary.

EFFECT OF MESH SIZE ON DISPLACEMENTS AND STRESSES

In this part of the study ADINA thermomechanical plane strain calculations were made out to 1.0 yr using the nodal point temperature

Table 3. Derived values of drift material properties used to simulate radiation and ventilation with ADINAT.

Properties	Values
Thermal conductivity:	
Spent fuel drift	70 W/m - K
Heater drift	40 W/m - K
Volumetric heat capacity	$8 \times 10^4 \text{ J/m}^3 - \text{K}$
Convection coefficient (H)	
Temp (K)	H(W/m ² - K)
0	0
0.272	4.5
0.445	5.0
0.903	5.5
1.878	6.0
4.074	6.5
9.427	7.0
24.042	7.5

histories generated by the ADINAT calculation with the ambient temperature boundary condition at the outermost boundaries. Three separate calculations were made on each mesh: full, full less the outer layer, and full less the outer two layers. Table 6 shows the elastic properties used in the ADINA calculations derived from field measurements.¹³ Vertical loading equaled ρgh and horizontal loading equaled $1.2 \rho gh$ --the same values used in the as-built calculations.² The left vertical ($Y = 0$), and the lower horizontal ($Z = -485, -470, \text{ or } -455 \text{ m}$, respectively) were roller boundaries. In each of the calculations, the first four cycles were used to simulate loading of the mesh and excavation of the drifts.

Figure 7 shows the displacement vectors in the region around the drifts during the excavation sequence. Figures 8A and 8B show the horizontal and vertical stress contours, respectively, after the excavation of both drifts. Minor differences occur in the stress contours for different mesh loading, particularly around the spent fuel drift. In each case of displacement and stress plots--a $25 \times 25\text{-m}$ portion of the innermost mesh, common to all mesh sizes (see Fig. 1)--is shown.

Table 4. Parameters used in ADINAT heat flow calculations.

Parameters	Values
<u>Spent fuel canisters and electrical simulators</u>	
Length	3.66 m (12 ft)
Power at start	1.527 kW (decaying)
Start	May 6, 1980 ^a (2.46 YOC ^b)
<u>Electrical resistance heaters</u>	
Length	1.83 m (6 ft)
Power at start	1.850 kW ^c
Turn-on	June 27, 1980 (0.14 yr after start)

^a Installation date of center canister.

^b YOC = years out of core.

^c See Table 5.

Table 5. Variation in power level in electrical resistance heaters.

Time since emplacement (yr)	Date	Power level (kW)
0	May 6, 1980	0
0.14	June 27, 1980	1.850
0.16	July 2, 1980	0.925
0.60	December 17, 1980	1.300
1.84	March 8, 1982	1.400

Figure 9 shows the displacement vectors for the region of the heaters and drifts from the thermal load at 0.25, 0.5, and 1.0 yr. Note the displacement scale is different than that for the excavation sequence. Figures 10A and 10B show the horizontal and vertical stress contours, respectively, after 1 yr of heating. Again, only minor differences can be seen for the different mesh loadings.

Table 6. Mechanical properties for Climax granite used in ADINA calculations.

<u>Elastic modulus</u> ¹³	
Rock mass	27 GPa
Explosively damaged zone	13 GPa
 <u>Poisson's ratio</u> ¹³	
Rock mass	0.25
Explosively damaged zone	0.35

Actual differences can be discerned by numerical rather than graphic analysis of the results. As an example, calculated horizontal and vertical drift closure measurements are shown in Table 7.

Examination of the plots and drift closure values indicate that different size mesh loadings produce rather insignificant differences in results in the regions of interest near the heaters and drifts.

PLANE STRESS VS PLANE STRAIN BOUNDARY CONDITION

In a two-dimensional plane strain calculation, no out-of-plane motion is allowed. At a given point in the mesh, the out-of-plane stress attains a value dependent on the in-plane stresses and Poisson's ratio. In a plane stress calculation, the out-of-plane stress equals zero everywhere in the mesh. In this comparison, ADINA plane stress calculations were made to 1 yr for the three mesh loadings with the same nodal point temperature histories.

Figures 11A and B show the horizontal and vertical stress contours, respectively, after excavation of both drifts. Figures 12A and B show the horizontal and vertical stress contours, respectively, after 1 yr of heating. As with the plane strain calculation, only minor differences between the various loadings can be seen from the plots. The displacements and stresses were compared numerically. Table 8 compares displacements from mining the spent fuel drift at anchor points in the rib relative to a hole collar at midheight in the heater drifts.

Table 7. Drift closures from heating calculated in plane strain with different mesh sizes.

Time (yr)	Full ^a	Full - 1 ^{a,b}	Full - 1 and 2 ^{a,b}
SPENT FUEL DRIFT (Horizontal)			
0.25	3.23	3.36	3.38
0.5	3.57	3.69	3.70
0.75	3.72	3.84	3.83
1	3.84	3.95	3.93
(Vertical)			
0.25	3.17	3.18	3.19
0.5	3.40	3.42	3.42
0.75	3.41	3.42	3.42
1	3.37	3.38	3.37
HEATER DRIFTS (Horizontal)			
0.25	0.95	0.97	0.97
0.5	0.90	0.92	0.92
0.75	0.83	0.82	0.84
1	0.79	0.80	0.78
(Vertical)			
0.25	1.70	1.72	1.74
0.5	1.87	1.89	1.90
0.75	1.97	1.99	1.99
1	2.03	2.05	2.04

^a Closures in mm.

^b Full - 1 refers to full mesh minus the outermost layer. Full - 1 and 2 refers to full mesh minus the two outermost layers.

Table 9 compares horizontal and vertical stresses during the mining and the later heating phase at two points in the mesh--one at 1.12 m horizontally from the mid-position of a spent fuel canister, the other at heater drift midheight in the middle of the ribs. All results are from full-mesh calculations.

Table 8. Mine-by rib motion at various points in the rib relative to a hole collar at midheight in heater drifts.

Distance from hole collar (m)	Relative displacements (mm)		
	Full	Full - 1	Full - 1 and 2
<u>Plane strain calculations</u>			
1.72	0.458	0.471	0.469
2.94	0.636	0.656	0.653
4.16	0.681	0.807	0.802
5.38	0.918	0.948	0.942
<u>Plane stress calculations</u>			
1.72	0.510	0.526	0.524
2.94	0.693	0.716	0.713
4.16	0.845	0.874	0.869
5.38	0.991	1.025	1.019

Table 9. Horizontal and vertical stresses calculated for two points in full mesh at various times during mining and heating phases.

	Near spent fuel canister		Mid-rib	
	Horizontal (MPa)	Vertical (MPa)	Horizontal (MPa)	Vertical (MPa)
<u>Plane strain calculation</u>				
Mesh loading	12.83	10.70	11.83	11.17
Heater drift mining	12.77	10.74	10.93	11.90
Spent fuel drift mining	13.42	10.22	8.89	13.63
0.25 yr heating	17.25	11.34	6.78	16.33
0.5 yr heating	18.15	11.40	6.74	17.13
0.75 yr heating	18.60	11.37	6.77	17.60
1.0 yr heating	18.85	11.33	6.80	17.91
<u>Plane stress calculation</u>				
Mesh loading	12.74	10.80	12.18	10.86
Heater drift mining	12.69	10.82	11.30	11.53
Spent fuel drift mining	13.30	10.36	9.29	13.16
0.25 yr heating	18.09	12.08	7.08	16.21
0.50 yr heating	19.28	12.21	7.09	17.23
0.75 yr heating	19.87	12.17	7.15	17.93
1.0 yr heating	20.21	12.13	7.20	18.34

Table 10 shows the drift closure results for the three mesh loadings obtained with plane stress calculations. These calculations can be compared directly with the plane strain calculations shown in Table 7.

Plots of horizontal and vertical stress contours, and numerical values of rock displacements surrounding the openings show only slight variations for different mesh sizes with either plane stress or plane strain boundary conditions. As a matter of fact this is true for a comparison between the plane stress and the plane strain sets. On the other hand, the differences in the calculated horizontal and vertical stresses at the two points shown are about 9% higher with the plane stress calculations.

AMBIENT THERMAL BOUNDARY POSITION

Two ADINA thermomechanical calculations were run using the smallest mesh, i.e., mesh loading on the innermost mesh. One calculation used the nodal thermal histories obtained with an ambient temperature condition on the outermost boundary, and the other with the ambient temperature condition on the innermost boundary. Comparisons of temperature contours to 5 yr (see Figs. 4A and B, 5A and B, and 6A and B) show a gradual flattening with time of the 23.5° and 24°C contours at the 40-m vertical boundary for ambient equal to 23°C. The temperature contour for 25°C is, however, only slightly different. Table 11 shows the thermal history of a node at -417.58 m (depth of the floor of the drift) and at the 40-m vertical (innermost) boundary for the two calculations. This is the location where the greatest temperature difference between the two cases was found (in the time spans being considered).

Both ADINA calculations were run in plane strain. Figure 13A shows the thermal load displacement vectors obtained by calculating the ambient condition on the innermost boundary at 2, 3, and 5 yr. Figures 13B, 14A and B show the horizontal, vertical, and out-of-plane stress contours, respectively, obtained with this calculation. Figure 15A shows the displacement vectors from the thermal load calculated with the ambient condition on the outermost boundary at 2, 3, and 5 yr. Figures 15B, 16A and B show the horizontal, vertical, and out-of-plane stress contours, respectively, obtained with this calculation. These plots, again, show insignificant differences.

Table 10. Drift closures from heating with different mesh loadings.^a

yr	Full ^b	Full - 1 ^b	Full - 1 and 2 ^b
SPENT FUEL DRIFT			
<u>(Horizontal)</u>			
0.25	3.40	3.53	3.55
0.5	3.74	3.88	3.90
0.75	3.87	4.02	4.02
1	3.98	4.11	4.10
<u>(Vertical)</u>			
0.25	2.88	2.89	2.90
0.5	3.13	3.13	3.14
0.75	3.15	3.15	3.16
1	3.10	3.13	3.13
HEATER DRIFTS			
<u>(Horizontal)</u>			
0.25	0.88	0.91	0.93
0.5	0.84	0.87	0.87
0.75	0.79	0.81	0.81
1	0.75	0.77	0.76
<u>(Vertical)</u>			
0.25	1.70	1.79	1.73
0.5	1.88	1.90	1.91
0.75	1.96	1.98	1.98
1	2.02	1.95	2.03

^a Plane stress calculations.

^b Closures in mm.

Table 11. Thermal history of a node at the depth of drift floor (~418 m) and at 40-m vertical (innermost) boundary with different thermal boundary conditions.

yr	Temperatures (°C)	
	Ambient = 23°C (innermost boundary)	Ambient = 23°C (outermost boundary)
0.5	23	23.000
1	23	23.003
2	23	23.063
3	23	23.246
4	23	23.532
5	23	23.864

The drift closures and stresses at selected points in the mesh were also chosen for a numerical comparison. Table 12 shows drift closures from ADINA plane strain calculations at different times with different thermal boundary conditions.

Table 13 shows calculated values of horizontal and vertical stress at various positions and times with different thermal boundaries. The positions are at the depth of the excavations and various distances from the plane of symmetry ($y = 0$ in Fig. 1).

The position of the ambient thermal boundary, whether at 40 m or at 70 m from the plane of symmetry, does not significantly affect the calculated stresses or drift closures from the thermal load out to 5 yr. Temperature differences between the two thermal boundary positions are zero at 1 yr, and increase to a maximum of slightly less than 1°C at 5 yr.

Table 12. Drift closures from heating with different ambient = 23°C thermal boundaries at various times (loading on innermost boundary).^a

yr	Ambient = 23°C (innermost boundary)	Ambient = 23°C (outermost boundary)
SPENT FUEL DRIFT		
(Horizontal)		
1	3.93	3.93
2	4.04	4.04
3	4.06	4.03
4	4.05	4.03
5	4.01	3.99
(Vertical)		
1	3.37	3.37
2	3.20	3.20
3	3.07	3.07
4	2.97	2.96
5	2.92	2.90
HEATER DRIFT		
(Horizontal)		
1	0.78	0.78
2	0.64	0.64
3	0.54	0.54
4	0.47	0.46
5	0.42	0.41
(Vertical)		
1	2.05	2.05
2	2.15	2.15
3	2.19	2.18
4	2.20	2.19
5	2.20	2.19

^a All closure values in mm.

Table 13. Horizontal and vertical stresses at various positions and times calculated with different ambient = 23°C thermal boundaries.^a

yr	Distance from plane of symmetry (m)							
	5.4		12.5		20.4		29.0	
	H	V	H	V	H	V	H	V
Ambient = 23°C (innermost boundary)								
1	-5.48	-19.12	-21.99	-16.46	-12.59	-11.11	-13.10	-10.63
2	-5.48	-19.68	-22.32	-17.24	-12.83	-11.26	-13.23	-10.25
3	-5.46	-19.80	-22.62	-17.63	-12.92	-11.45	-13.30	-10.12
4	-5.42	-19.77	-22.72	-17.80	-12.95	-11.62	-13.33	-10.10
5	-5.40	-19.74	-22.80	-17.88	-12.95	-11.74	-13.34	-10.12
Ambient = 23°C (outermost boundary)								
1	-5.48	-19.12	-21.99	-16.46	-12.59	-11.11	-13.10	-10.63
2	-5.48	-19.67	-22.31	-17.23	-12.82	-11.25	-13.23	-10.25
3	-5.45	-19.72	-22.59	-17.61	-12.92	-11.45	-13.30	-10.11
4	-5.41	-19.75	-22.67	-17.78	-12.93	-11.60	-13.32	-10.10
5	-5.39	-19.69	-22.72	-17.84	-12.93	-11.71	-13.23	-10.11

^a All stresses are in MPa; H = horizontal and V = vertical.

SUMMARY AND CONCLUSIONS

In thermal and thermomechanical ADINAT and ADINA calculations such as those conducted for the Spent Fuel Test--Climax, various boundary conditions are imposed on the finite-element mesh. Since these boundary conditions can affect the results produced by the calculation, a study was undertaken to determine the sensitivity of the results to various boundary conditions, primarily in the immediate vicinity of the excavation.

Obviously, the mesh size itself must be so large that boundary effects will not influence the region of interest near the excavations and heat sources. Several boundary effects were studied:

- The effect of boundary loading on three progressively larger meshes.
- Plane strain vs plane stress conditions.
- The effect of isothermal boundaries on a small mesh and on a significantly larger mesh.

In the mesh sizes chosen, 40×80 , 55×110 , and 70×140 m, boundary loading had an insignificant effect on the results near the heat sources and excavations. When comparing the effect of different isothermal boundaries up to 5 yr on the smallest and largest mesh, the maximum temperature difference occurred at the 40-m boundary and was less than 1°C . In the corresponding ADINA calculations, the temperature differences produce insignificant changes in stress and displacement in the region of interest.

On the other hand, the use of plane strain or plane stress criteria produces significantly different horizontal and vertical stresses in the region of the heaters and excavations. However, this might be expected because of the different out-of-plane stress conditions for the two cases.

It must be pointed out also that these results refer only to the size of mesh and time spans actually used. With significantly smaller meshes or longer time spans, the conclusions would be different.

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Figure 1. Mesh construction allows layers to be peeled off like onion skins (boundary coordinates in metres).

Figure 2. Finite-element mesh in vicinity of openings. Positions of heat sources are shown by heavy lines beneath openings (all dimensions in metres).

Figure 3. Spent fuel decay curve used in ADINAT calculations.

Figure 4A. Temperature profiles at 0.25 and 0.5 yr (temperature is 23°C at outermost boundary).

Figure 4B. Temperature profiles at 0.75 and 1.0 yr (temperature is 23°C at outermost boundary).

Figure 5A. Temperature profiles at 2.0 and 3.0 yr (temperature is 23°C at outermost boundary).

Figure 5B. Temperature profiles at 4.0 and 5.0 yr (temperature is 23°C at outermost boundary).

Figure 6A. Temperature profiles at 2.0 and 3.0 yr (temperature is 23°C at innermost boundary).

Figure 6B. Temperature profiles at 4.0 and 5.0 yr (temperature is 23°C at innermost boundary).

Figure 7. Calculated displacements during various phases of mining.

Figure 8A. Horizontal stress contours after excavation of both drifts. Plane strain calculations with different boundary loadings.

Figure 8B. Vertical stress contours after excavation of both drifts. Plane strain calculations with different boundary loadings.

Figure 9. Calculated displacements after given periods of heating.

Figure 10A. Horizontal stress contours after 1.0 yr of heating. Plane strain calculations with different boundary loadings.

Figure 10B. Vertical stress contours after 1.0 yr of heating. Plane strain calculations with different boundary loadings.

Figure 11A. Horizontal stress contours after excavation of both drifts. Plane stress calculations with different boundary loadings.

Figure 11B. Vertical stress contours after excavation of both drifts. Plane stress calculations with different boundary conditions.

Figure 12A. Horizontal stress contours after 1.0 yr of heating. Plane stress calculations with different boundary loadings.

Figure 12B. Vertical stress contours after 1.0 yr of heating. Plane stress calculations with different boundary loadings.

Figure 13A. Calculated displacements at various times. Plane strain calculation with loading on the innermost boundary (temperature is 23°C at innermost boundary).

Figure 13B. Horizontal stress contours at various times. Plane strain calculation with loading on innermost boundary (temperature is 23°C at innermost boundary).

Figure 14A. Vertical stress contours at various times. Plane strain calculation with loading on innermost boundary (temperature is 23°C at innermost boundary).

Figure 14B. Out-of-plane stress contours at various time. Plane strain calculations with loading on innermost boundary (temperature is 23°C at innermost boundary).

Figure 15A. Calculated displacement after given periods of heating. plane strain calculation with loading on innermost boundary (temperature is 23°C at outermost boundary).

Figure 15B. Horizontal stress contours at various times. Plane strain calculation with loading on innermost boundary (temperature is 23°C at outermost boundary).

Figure 16A. Vertical stress contours at various times. plane strain calculation with loading on innermost boundary (temperature is 23°C at outermost boundary).

Figure 16B. Out-of-plane stress contours at various times. Plane strain calculation with loading on the innermost boundary (temperature is 23°C at outermost boundary).