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A SENSITIVITY STUDY OF NEAR-FIELD THERMOMECHANICAL CONDITIONS IN TUFF

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ABSTRACT

A study was conducted by the Pacific Northwest Laboratory[a] to investigate the response of a discontinuous rock mass to the combined mechanical and thermal loads from the excavation of repository openings and decay heating of radioactive waste forms. The ANSYS[b] finite element code was used to calculate temperatures and thermal stresses near an emplacement hole as a function of time. The UDEC[c] distinct element code was used to simulate a discontinuous rock mass around the emplacement hole using the finite element stress results as boundary conditions. This approach differs from previous work in its approximation of the near-field geosphere as an assemblage of blocks that are free to slide and rotate relative to one another. The physical properties of the rock joints and fractures were explicitly included in the analysis. Earlier efforts have used continuum models that included the effects of discontinuities by adjusting material properties (reducing elastic modulus and rock strength) or using ubiquitous joints. A range of parameter values were used to represent the upper, lower, and expected conditions for the Yucca Mountain site. Assuming worst case conditions, the calculated displacements around the emplacement hole were only a small fraction of the design air gap between the waste package and the wall of the emplacement hole. Overall, the results confirm that the retrieval option and waste package lifetime will not be adversely affected by borehole instability and excessive rock loads.

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[a]Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.
[b]ANSYS is a product of Swanson Analysis Systems, Inc., Houston, Pennsylvania.
[c]UDEC is a product of ITASCA Consulting Group, Inc., Minneapolis, Minnesota.

BACKGROUND

The objective of this study was to investigate the near-field behavior of a fractured rock mass in a mined geologic repository for high-level waste at the candidate site at Yucca Mountain, Nevada. In particular, the analyses evaluated possible stresses and displacements in the rock surrounding a vertical emplacement hole over the range of expected conditions.

The design and performance considerations related to the stability of the emplacement hole openings and the surrounding rock mass depend on the interval of time being considered. Prior to closure of the repository, the stability and condition of the emplacement hole openings will determine, in part, whether the option to retrieve emplaced waste can be maintained over the required 84-year period. Behavior of the emplacement hole openings is also important during the first 1000 years after closure because rock movement in excess of the design assumptions may mechanically load the waste packages and compromise their ability to achieve substantially complete containment. Stresses and displacements around the openings will also influence the extent of the disturbed zone as it is related to pre-emplacement groundwater travel time calculations. Finally, the post-closure performance of the engineered barrier system could be negatively impacted by instable openings if failed material fills part of the air gap around the waste package providing a direct pathway for radionuclide transport to the geosphere.

The study addresses the initial 200-year time period after closure of the repository over which the maximum temperature and stress gradients are predicted to occur in the near-field environment. The thermal and mechanical properties of the tuff matrix and fractures were varied according to distributions given in The Yucca Mountain Project Reference Information Base

(RIB)[a] and Chapter 6 of the Site Characterization Plan (SCP) for the Yucca Mountain Site.[1] The range of values represents preliminary estimates of the natural variability at Yucca Mountain. However, these data are based on a very limited amount of information obtained from a small number of vertical holes and pavement studies. The appropriateness of these estimates will not be known until the DOE completes the surface-based and underground investigations proposed in the SCP.

Arulmoli and St. John[2] performed stability analyses of the emplacement hole to investigate possible loading conditions the waste package (or borehole liner) may experience and to evaluate the near-field environment during the retrieval period. The analyses assumed a horizontal waste emplacement configuration. The two-dimensional finite element calculations were performed with two numerical codes: VISCOT[1] and JAC.[1] In the VISCOT model, an elastic constitutive relationship was assumed for the rock mass that approximated the presence of discontinuities by using a reduced elastic modulus. The JAC model is based on the compliant joint model[3] and assumed regularly spaced and parallel joints with uniform traction and deformation properties. The displacement field is comprised of three components: deformation of the intact rock, joint dilation, and joint shear displacement. Both models used temperature fields calculated with the DOT[1] code for the first 100 years after emplacement. The elastic analyses predicted a maximum stress of 50 MPa in the top of the borehole with 20 MPa stresses in the sidewall. The inelastic model with orthogonal jointing predicted 75 MPa stresses in the upper portion of the borehole. Both models showed a rapid decrease in the stress magnitude away from the borehole wall. The elastic and inelastic results were approximately the same several centimeters away from the borehole boundary.

The SCP concludes that localized high stresses predicted by the JAC model may exceed the rock mass strength resulting in limited failure around the emplacement hole. The consequence of this failure was concluded to be insignificant if a borehole liner, proposed in the conceptual repository design, is used as part of the engineered barrier design.

This study investigated the conditions in the rock mass surrounding a vertical emplacement hole. The rock is modeled as a discontinuum with the discontinuities (includes both fractures and joints; the terms will be used interchangeably in this paper) explicitly defined in the model. The approach provides a mechanism for exploring how the individual blocks and fractures can behave and provides input for several of the mechanical/hydrologic constitutive models proposed by the geoscience community.

[a]Yucca Mountain Project Office, "Yucca Mountain Project Reference Information Base," Version 4, Revision 0, U.S. Department of Energy, Las Vegas, Nevada (November 1988)

MODELING APPROACH

Two numerical computer codes were used to perform the analyses: ANSYS, a general purpose finite element code;[4] and UDEC, a distinct element code.[5] A three-dimensional ANSYS model of the waste package and surrounding rock was developed to estimate the near-term (i.e., up to 200 years) temperatures and stresses near a vertical emplacement hole. The calculated stresses from the near-field model were used to assign boundary conditions for the UDEC model. The UDEC model simulates a subregion around the emplacement hole that contains discrete discontinuities. The combination of these two modeling techniques provides a method for investigating the local behavior of the discontinuous rock mass around a waste emplacement hole. The method was used in this study to assess the likelihood of blocks of rock being displaced into the borehole. The codes and the respective models are described below.

ANSYS Finite Element Continuum Model

An exploded view of the finite element mesh used to model the waste package and surrounding rock is shown in Figure 1. Adiabatic conditions were assumed in the three-dimensional model at the midplanes between the emplacement rooms and between adjacent boreholes. This allowed using a quarter symmetry model of the waste package and surrounding rock and it is more representative of the emplacement holes located away from the perimeter of the repository. The heat transfer calculations assume intimate contact between the waste package and the borehole wall (radiant heat transfer was neglected) and that the drifts were not ventilated after waste emplacement (convective heat transfer was also neglected). These assumptions result in somewhat higher temperatures and stresses around the openings adding a degree of conservatism to assessments of opening stability.

The geometry of the emplacement hole and the emplacement drift are based on a similar modeling effort that was conducted in support of the PASS Program.[6] The borehole and drift spacings were updated to the values suggested in Chapter 6 of the current SCP.[1] The model does not include effects of the defense high-level waste packages that are considered as a possible design alternative in the SCP.

The waste package model assumes that all containers have identical heat generation rates and are emplaced simultaneously. An initial heat generation rate of 3.3 kW per waste package was assumed based on the expected decay heating rates for spent fuel packages containing nominal

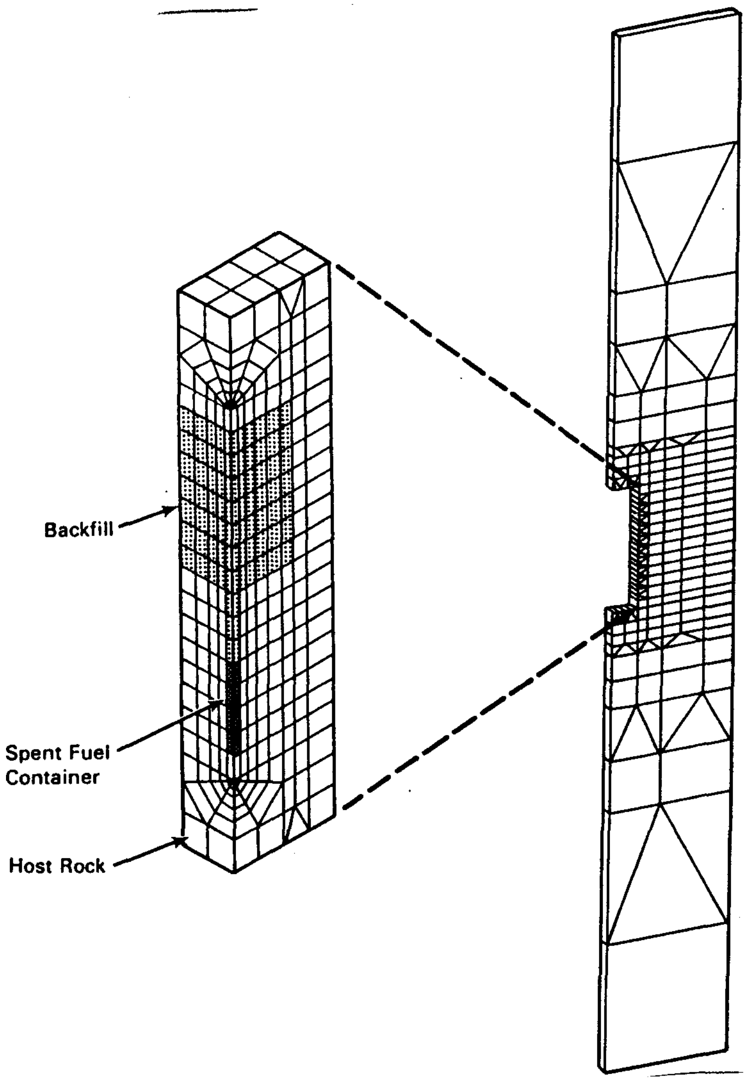

FIGURE 1 EXPLODED VIEW OF FINITE ELEMENT MESH USED TO MODEL THE WASTE PACKAGE AND SURROUNDING ROCK

burnup, 10-year-old, consolidated fuel.[1] Table 1 summarizes the model dimensions, the initial heat generation rate, and the decay heat curve used in the study.

The near-field thermal stresses were calculated by applying the nodal temperatures from the heat transfer analyses to an equivalent structural model. The elements that defined the waste package in the thermal model were removed in the structural model to simulate an air gap between the waste package and the borehole wall. The outside boundaries of the structural model were fixed in the directions normal to each boundary to simulate the confinement induced by the surrounding rock.

UDEC Discontinuum Models

A two-dimensional UDEC model was used to investigate the behavior of the rock surrounding the emplacement holes. UDEC is based on the distinct element method that was developed to model discontinuum behavior of jointed media subjected to quasi-static or dynamic conditions.[5] The method uses continuum theory to represent the behavior of individual blocks and force displacement laws to treat the forces between the blocks. A motion law is also included to treat the movement of each block caused by unbalanced forces acting on the blocks. The distinct blocks formed by the discontinuities were assumed to be fully deformable and are divided into a network of finite difference zones by UDEC. A Mohr-Coulomb friction model was assumed for the discontinuities (fractures and joints).

Several different UDEC models were used in this analysis, each having a common joint pattern in the region away from the borehole, but different joint patterns closer to the borehole region. The different joint patterns in the

TABLE 1 DIMENSIONS AND OTHER PARAMETERS USED IN THE WASTE PACKAGE SCALE MODEL

Parameter		Value
Dimensions, m		
Waste package		
Length		4.0
Outer diameter		0.70
Borehole		
Diameter		0.762
Depth		5.0
Pitch		4.572 (15 ft)
Emplacement room		
Width		6.10
Height		6.70
Drift pitch		38.405 (126 ft)
Repository depth		300
Ambient temperature, °C		26
Waste Package Data		
Orientation		Vertical
Initial decay heat rate, kW		3.3
Initial area power, W/m^2		18.8
Normalized Decay Heat Data		
Time, years =	0	1.000
	5	0.841
	10	0.750
	20	0.625
	30	0.524
	40	0.457
	50	0.389
	70	0.303
	100	0.240
	200	0.147
	300	0.116
	500	0.087
	1000	0.049

borehole region, shown in Figure 2, are intended to represent varying degrees of damage during construction of the boreholes. In each of the models, the damaged zone extends 0.23 m away from the opening. It is important to note that the model does not include a steel liner, which has been proposed in the conceptual repository design as part of the emplacement hole design. This option would include the partial lining of the hole with a 0.6- to 1.0-cm-thick liner.

The UDEC models were loaded by applying equivalent displacements to the outer boundaries that would give rise to the combined thermal and in situ stress levels calculated in the ANSYS analyses. The equivalent boundary displacements were applied to the model rather than the boundary stresses to correctly model the self-limiting nature of thermal stresses. The classical strength of materials equations relating stress and strain were used:[7]

$$\epsilon_x = \frac{1}{E} (\sigma_x - \nu\sigma_y)$$

$$\epsilon_y = \frac{1}{E} (\sigma_y - \nu\sigma_x)$$

The equivalent displacements were calculated by multiplying the strains by the corresponding x- and y-dimensions of the UDEC model.

Input Data for Models

The thermal and mechanical properties used in the numerical analyses were chosen to provide realistic bounds on the temperatures and stresses that could occur in the waste repository at the Yucca Mountain site. The current conceptual design of the Yucca Mountain site locates the repository in the Topopah Spring Member at a

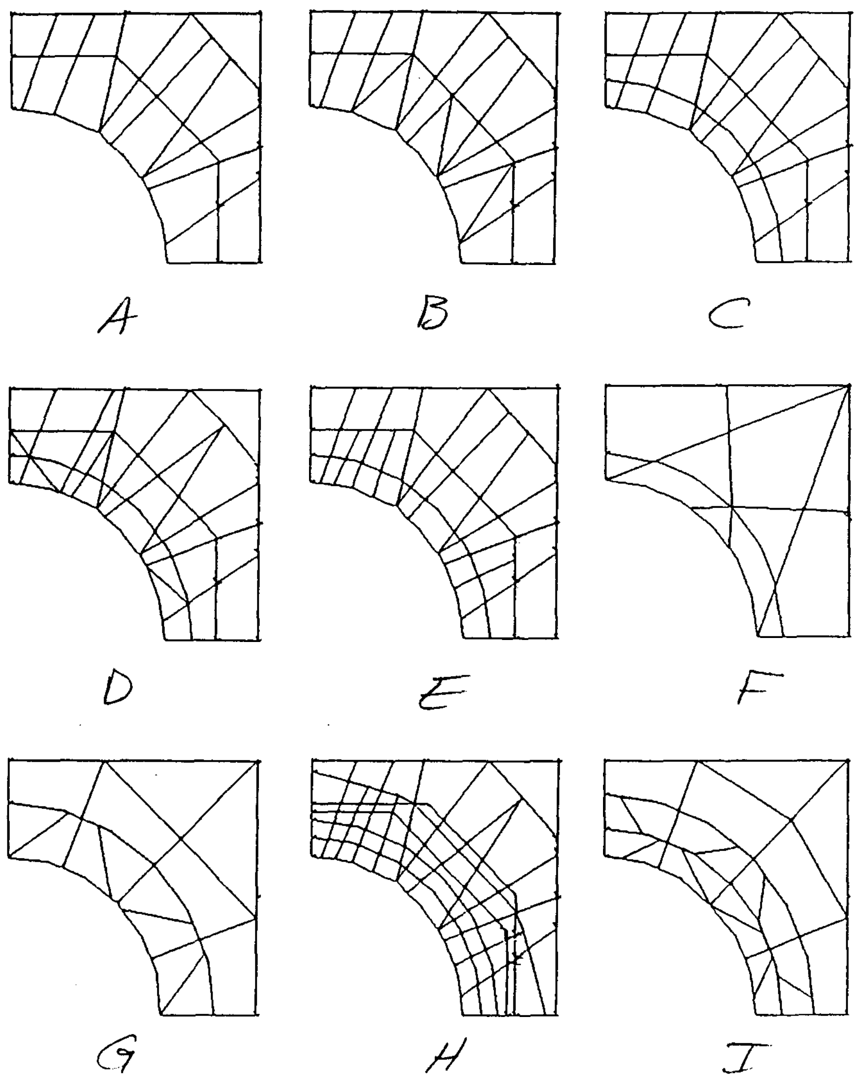

FIGURE 2 NEAR-FIELD FRACTURE PATTERNS (A THROUGH I) USED IN THE UDEC BOREHOLE STABILITY CALCULATIONS

depth of 300 m. The rock at this level is designated as TSw-2 and it is a lithophysae poor, welded, devitrified tuff. The most current draft of the Yucca Mountain Project Reference Information Base was used as the primary source for the physical properties of the TSw-2 layer. The most current version of the SCP[1] was used as the secondary source for data not found in the RIB. Table 2 gives the mean and standard deviation values for each of the properties used in the study.

Three sets of thermal and mechanical properties were used to estimate upper-bound, mean, and lower-bound temperatures and stresses in the near-field around the borehole. The properties assumed in the upper-bound case represent the combination of thermal properties that would give the highest near-field temperatures (i.e., low thermal conductivity, low thermal capacitance, and low bulk density) and the mechanical properties that would give the highest thermal stresses (i.e., high modulus of deformation and high coefficient of thermal expansion). The properties used in the mean temperature and stress case were the mean properties listed in Table 2, and the lower-bound case assumed the properties that would give the lowest near-field temperatures and thermal stresses. Table 3 lists the data assumed in each of the three cases.

The ranges of in situ stress used in this study were developed from data given in Chapter 6 of the SCP.[1] The SCP gives ranges for the maximum and minimum horizontal-to-vertical stress ratios (Table 3). The maximum and minimum horizontal stresses were estimated by multiplying these stress ratios by the vertical stress at the repository level. The vertical stress was estimated by multiplying the average mass density of the rock by the acceleration of gravity, times the depth of the repository.

TABLE 2 THERMAL AND MECHANICAL PROPERTIES FOR TUFF USED IN THE BOREHOLE STABILITY CALCULATIONS

Property	Source	Mean	Standard Deviation
Thermal conductivity, W/m(K)			
Dry tuff	RIB[a]	1.84	0.064
In situ saturated tuff	RIB	1.91	0.083
Bulk density, g/cm^3	RIB	2.297	0.088
Thermal capacitance, $J/cm^3(K)$	RIB		
Temperature = 25°C		1.8539	------
94		2.0912	------
95		3.4612	------
114		3.3589	------
115		2.0065	------
275		2.3410	------
Coefficient of thermal expansion, 10^{-6} °C^{-1}			
Temperature range = 25 to 50°C	RIB	9.1	1.3
50 to 100	RIB	8.2	0.8
100 to 150	RIB	6.8	0.5
150 to 200	RIB	9.7	---
200 to 250	SCP[b]	24.	---
Rock mass elastic modulus, GPa	SCP	15.2	4.2
Rock mass Poisson's ratio	SCP	0.22	0.05
Intact rock elastic modulus, GPa	RIB	32.7	4.6
Intact rock Poisson's ratio	RIB	0.22	0.05
Unconfined compressive strength, MPa	RIB	155	59
In situ stress			
Minimum horizontal to vertical stress ratio	SCP	0.55	0.25
Maximum horizontal to vertical stress ratio	SCP	0.65	0.35

[a]RIB = Reference Information Base
[b]SCP = Site Characterization Plan

TABLE 3 THERMAL AND MECHANICAL PROPERTIES USED IN THE UPPER-BOUND, MEAN, AND LOWER-BOUND NEAR-FIELD TEMPERATURE AND STRESS EVALUATIONS

Item	Temperature and Stress Evaluations Properties		
	Upper-Bound	Mean	Lower-Bound
Input Data to Finite Element Model			
Thermal conductivity, W/m(K)	1.776	1.875	1.993
Bulk density, g/cm^3	2.209	2.297	2.385
Thermal capacitance, J/cm^3(K)	1.854	2.097	2.341
Coefficient of thermal expansion, 10^{-6} °C^{-1}			
Temperature range = 25 to 50°C	10.4	9.1	7.8
50 to 100	9.0	8.2	7.4
100 to 150	7.3	6.8	6.3
150 to 200	9.7	9.7	9.7
200 to 250	24.	24.	24.
Rock mass elastic modulus, GPa	19.4	15.2	11.0
Rock mass Poisson's ratio	0.22	0.22	0.22
Input data to UDEC models (joint properties are from the SCP)			
Intact rock elastic modulus, GPa	37.3	32.7	28.1
Intact rock Poisson's ratio	0.22	0.22	0.22
Unstressed aperture, micrometers	36	18	3
Joint shear stiffness, MPa/m	10^7	10^6	10^5
Joint cohesion, MPa	0.2	0.1	0
Joint friction coefficient	0.8	0.54	0.2
Stress Results			
Maximum in situ stress (Sy_I), MPa	6.8	4.4	2.0
Minimum in situ stress (Sx_I), MPa	5.4	3.7	2.0
Maximum thermal boundary stress (Sy_T) from finite element model, MPA	31.1	20.3	12.6
Minimum thermal boundary stress (Sx_T) from finite element model, MPA	25.7	16.7	10.4
Total maximum stress (Sy), MPa	37.9	24.7	14.6
Total minimum stress (Sx), MPa	31.1	20.4	12.4

In most instances, the upper- and lower-bound values of each physical property were taken as the mean value plus-or-minus one standard deviation. This approach is consistent with the ranges represented by the "variability evaluation values" given in Chapter 6 of the SCP.[1] In the case of thermal capacitance, however, the lower-bound value was taken as the value given for 25°C, the mean as the average of the 25 and 275°C values, and the upper-bound was taken as the 275°C value. Also, the mean thermal conductivity was assumed to be the average of the dry and in situ saturated values because the two values differ by less than 4%. The lower-bound thermal conductivity was taken as the mean value for dry tuff minus the dry standard deviation, and the upper-bound was taken as the mean value at in situ saturation plus the standard deviation for in situ saturation.

ANSYS HEAT TRANSFER AND THERMAL STRESS RESULTS

The heat transfer analysis estimates the near-field temperatures around the borehole during the first 200 years after emplacement. Figure 3 shows the upper-bound, mean, and lower-bound borehole temperatures during this period. The maximum borehole temperature is predicted to occur at approximately 10 years after emplacement with temperatures between 225 and 264°C. These results are consistent with the maximum borehole temperature of 275°C specified in Chapter 7 of the SCP.[1]

Near-field thermal stresses were evaluated to provide boundary conditions for the UDEC borehole stability calculations. Figure 4 shows a schematic of the UDEC submodel in relation to a plane cut perpendicularly through the borehole.

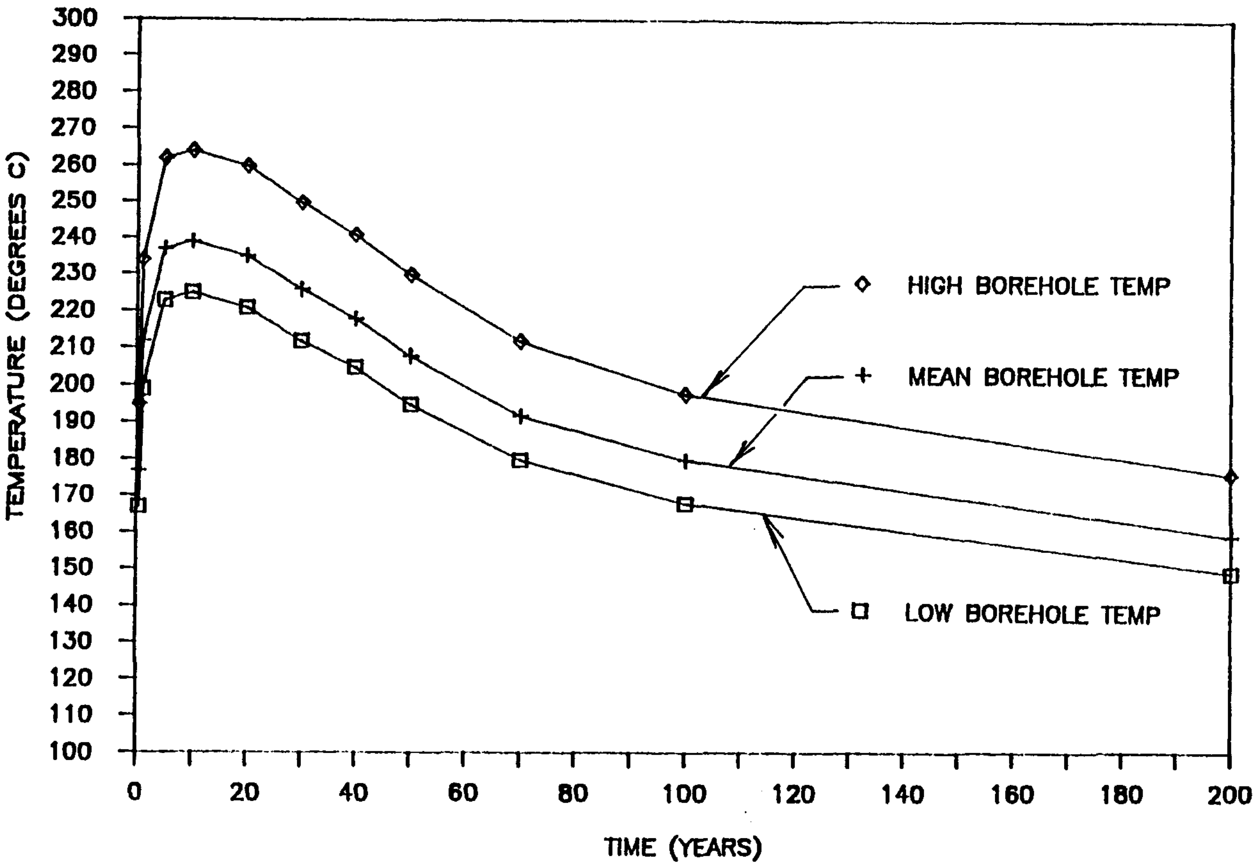

FIGURE 3 BOREHOLE TEMPERATURES AS A FUNCTION OF TIME FROM THE FINITE ELEMENT THERMAL ANALYSIS

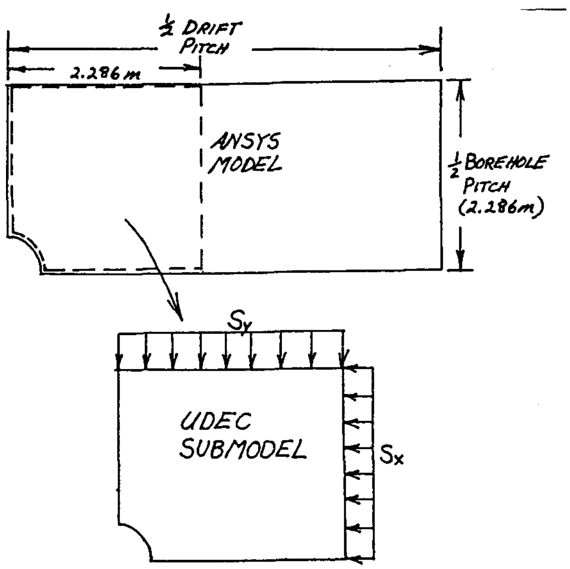

FIGURE 4 RELATIONSHIP OF UDEC SUBMODEL TO A PLANE CUT PERPENDICULARLY THROUGH THE BOREHOLE IN THE ANSYS MODEL

The horizontal boundary stress in the direction of the emplacement drift is designated Sy and the horizontal stress perpendicular to the drift is designated Sx. Figure 5 shows time histories of the thermal boundary stresses (Sx and Sy). The maximum thermal stresses occur at about 30 years after emplacement (see Table 3). The thermal stress in the direction of the drift (Sy) is somewhat higher than the stress perpendicular to the drift (Sx) due to the close spacing of the boreholes relative to the drift spacing.

When combining the in situ and thermal stresses, the larger of the two orthogonal in situ stresses was added to the larger of the two thermal stresses. Similarly, the smaller in situ stress was added to the smaller of the thermal stresses. This gave the maximum difference in the two orthogonal boundary stresses and, thus, the maximum deviatoric stress. The combined in situ and thermal stresses for the lower-bound, mean, and upper-bound analyses were input as boundary stresses to the UDEC borehole stability analysis (see Table 3).

UDEC STRUCTURAL ANALYSIS

A matrix of UDEC calculations was initially envisioned that would apply the upper-bound, mean, and lower-bound stresses to models with

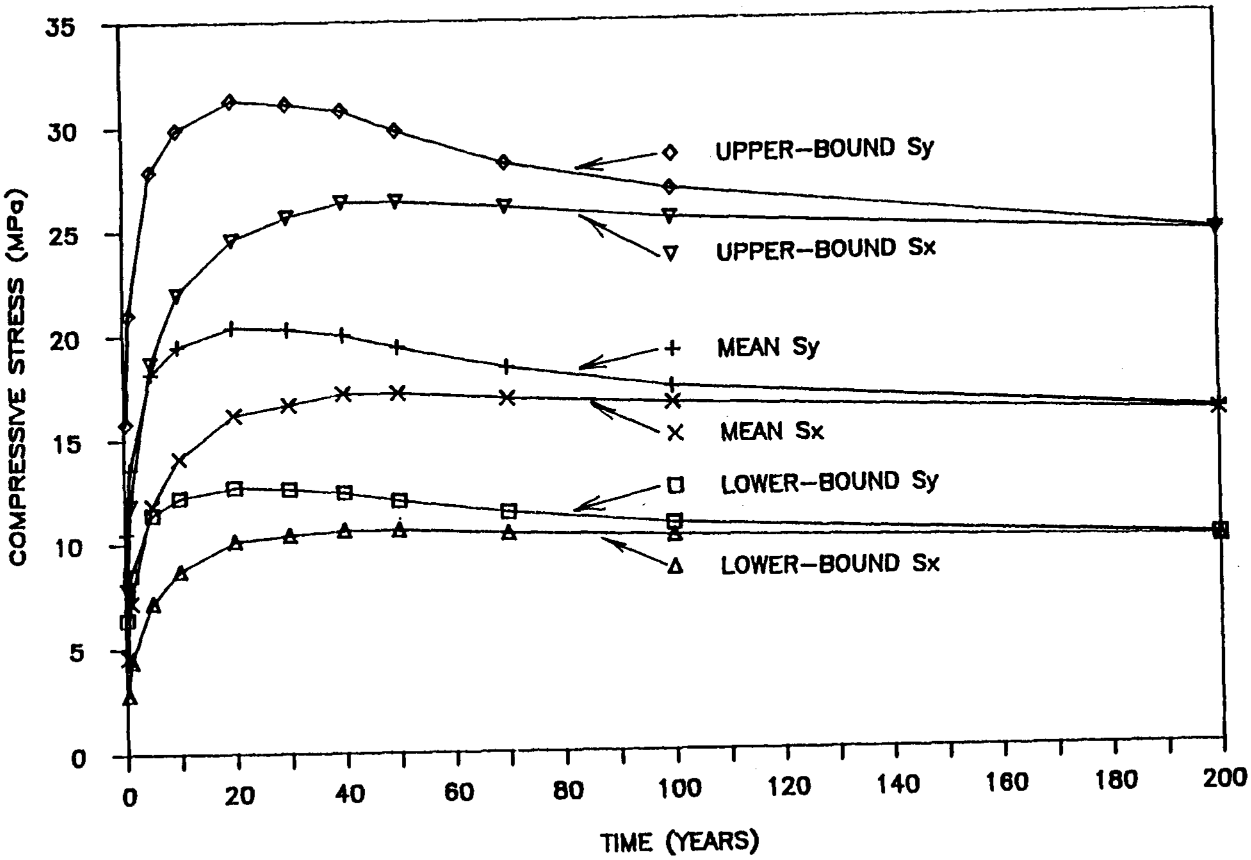

FIGURE 5 THERMAL BOUNDARY STRESSES (Sx and Sy) AS A FUNCTION OF TIME FROM THE FINITE ELEMENT THERMAL STRESS ANALYSIS

three different joint patterns and various joint friction coefficients and joint apertures. However, after beginning with the upper-bound stress (Sx = 31.1 MPa and Sy = 37.9 MPa) and the lower-bound joint friction (zero cohesion and a joint friction coefficient of 0.2), it soon became apparent that none of the joint patterns would sustain sufficient block displacement to close the 5.0-cm air gap between the waste package and the emplacement hole. Six additional joint patterns were developed that were expected to give larger block displacements than the initial three. Although the displacements did increase (up to 6 mm for fracture pattern "F"), the largest was still less than the 5.0-cm air gap. Table 4 gives a summary of the results for the nine fracture patterns shown in Figure 2. These results assume the upper-bound stress conditions except where noted.

Table 4 also contains the results of several runs that investigated the sensitivity of borehole displacement to the joint coefficient of friction. The coefficient of friction was varied between 0.00001 and 0.84 for joint pattern "I". The borehole displacement varied between 3.8 and 1.3 mm, respectively. The fracture pattern giving the largest displacement (pattern "F" was also rerun for stresses up to three times the upper-bound values with a resulting borehole displacement of 1.4 cm (see Table 4).

A look at the stress distribution along the symmetry boundaries provides an explanation for the small displacements that were observed. Figure 6 shows the stresses normal to the horizontal plane of symmetry (y-direction stresses) for the finite element (continuum) model and the UDEC (discontinuum) models with fracture patterns "C" and "D". The finite element results show the classical stress concentration that occurs near a hole in an infinite media under stress. The UDEC stress results, however, show pronounced blunting of the stress concentration at the borehole surface. This occurs because the blocks at the borehole surface displace and the stresses are redistributed farther away from the borehole surface. A comparison of the borehole displacements listed in Table 4 shows that the displacements predicted by the finite element model are much smaller than those of the UDEC models (0.8 mm versus up to 6.0 mm).

INTERPRETATION OF THE RESULTS

The relatively small displacements that result from the thermomechanical loading of the rock mass surrounding the emplacement holes

TABLE 4 UDEC BOREHOLE STABILITY RESULTS FOR NINE DIFFERENT JOINT PATTERNS IN THE DAMAGE ZONE

	Damage Zone Joint Pattern	Joint Cohesion, MPa	Joint Coefficient of Friction	Radial Displacement of Borehole, mm	Tangential Stress at Borehole, MPa	UDEC y-Direction Remote Boundary Stress, MPa
Sensitivity to Damage Zone Fracture Pattern	A	0.0	0.20	1.1	42	34
	B	0.0	0.20	2.6	0	34
	C	0.0	0.20	1.2	42	34
	D	0.0	0.20	2.1	0	36
	E	0.0	0.20	1.2	36	33
	F	0.0	0.20	6.0	3	35
	G	0.0	0.20	2.2	5	39
	H	0.0	0.20	1.5	30	36
	I	0.0	0.20	2.5	5	34
Sensitivity to Joint Coefficient of Friction	I	0.0	0.00001	3.8	0	35
	I	0.0	0.0001	3.7	0	34
	I	0.0	0.05	3.3	0	34
	I	0.0	0.20	2.5	5	34
	I	0.0	0.50	1.9	10	34
	I	0.0	0.84	1.3	10	34
Results of Finite Element Continum Model	--	---	----	0.8	83	38
	Joint Pattern	**Sx, MPa**	**Sy, MPa**			
Upper-Bound Stresses Increased by Factors of 2 and 3	F	31.1	37.9	6.0	3	35
	F	62.2	75.8	9.0	0	70
	F	93.3	113.7	13.6	0	90

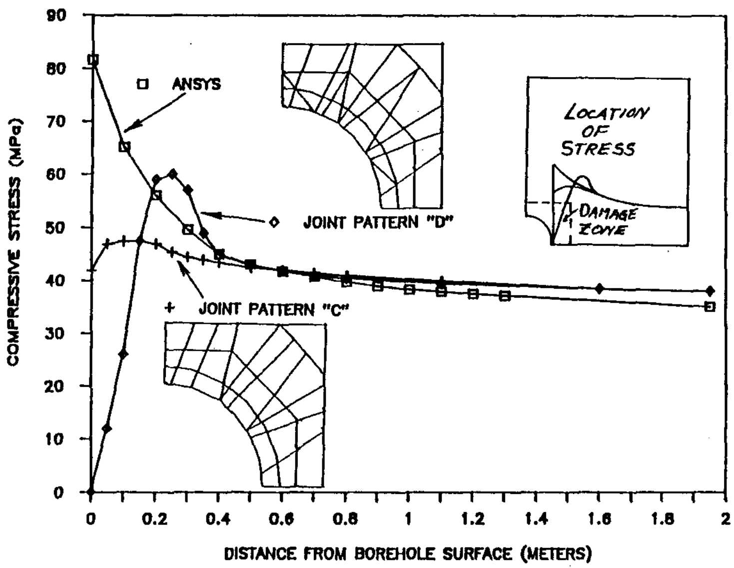

FIGURE 6 COMPARISON OF ANSYS (CONTINUUM MODEL) AND UDEC (DISCONTINUUM MODEL) STRESSES NEAR THE BOREHOLE

indicates that the waste package loads will not be excessive with or without a liner in the emplacement hole. In the case of an unlined emplacement hole, the 5.0-cm air gap provides for limited movement of the blocks of rock intersecting the borehole and a reduction in the localized stress field. Occasional failure of the intact blocks would result in only small gravitational loads on the waste package but would provide a direct pathway between the package and the geosphere for radionuclide transport. The failed material may also result in increased shear resistance if the package needed to be retrieved.

The consequences of localized failure could be mitigated or eliminated if the emplacement hole is lined. The liner loads could be controlled, in part, by using a liner with a slightly smaller diameter than the emplacement borehole to allow for limited displacement of the rock over the thermal loading period. Assuming low uniform corrosion rates for the liner material (0.15 micrometer/year),[1] the air gap would be maintained for thousands of years. Unfortunately, the uncertainty associated with this type of conclusion is very large and cannot be resolved until the completion of the site characterization program when more representative properties and conditions of the site become available.

It is tempting to use the UDEC results to assess the impact waste emplacement will have on the intrinsic properties of the rock mass in the near-field, particularly the hydrologic behavior of the rock. This type of assessment is of particular interest when performing the pre-waste-emplacement groundwater travel time calculations required by 10 CFR Part 60.[8] This performance objective pertains to the fastest path of likely radionuclide transport from the boundary of the "disturbed zone" and the accessible environment. The stresses and displacements of the tuff matrix and the discontinuities are likely to have some affect on the hydrologic behavior of the rock mass. For example, the hydraulic conductivity of the fractures is often assumed to be proportional to the cube of the aperture (assuming a parallel plate model) and some permanent deformation of the fractures is likely depending on the stress level, temperature, etc. Unfortunately, the small amount of coupled-process data (e.g., mechanical/hydrologic) available, particularly for tuffaceous rocks, does not warrant a detailed analysis at this time. Studies are planned during site characterization to provide the data to address this need.[1]

CONCLUSIONS

The UDEC model using the distinct element approach resulted in significantly greater displacements (700% greater in one case) and lower stresses than the ANSYS continuum approach. The appropriateness of one method over the other is determined by the problem being considered and the failure criteria being used. This study addressed the suitability of certain aspects of the engineered barrier design; that is, the stability of the rock mass adjacent to the emplacement hole during peak thermomechanical loading and its interaction with the waste package. The fractured and interlocked nature of the tuff rock mass combined with the relatively low confining stresses suggest that the behavior of the rock will be structurally controlled and, therefore, the discontinuum approach is considered to be particularly relevant.

The results of the study indicate that the stresses and displacements in the rock surrounding the waste emplacement holes are not likely to adversely impact the structural behavior of the waste package. This conclusion is contingent on the validity of the modeling assumptions and rock properties that were used and the inclusion of an emplacement hole liner in the final repository design. Whereas the liner is inconsequential as far as the structural integrity of the emplacement hole is concerned, by isolating the waste package from even small volumes of failed (rubblized) material, it provides two important functions: 1) it minimizes the shear resistance between the package and the emplacement hole if waste retrieval becomes necessary; and 2) it prevents the creation of a direct pathway for radionuclide transport between the waste package and the surrounding geosphere.

Current estimates of the uniaxial compressive strength of the TSw-2 tuff at ambient temperature suggest there is little likelihood that the thermomechanical stresses in the rock around the emplacement hole will result in failure of the tuff matrix. Insufficient data are available to hypothesize whether the strength will be significantly decreased by the elevated temperatures or thermal cycling.

The analyses tend to confirm the conclusions reached from the preliminary design calculations;[1] specifically, the retrieval option and the structural integrity of the waste package are not likely to be adversely affected by borehole instability or excessive mechanical stress. Additional analyses are recommended to investigate the behavior of the emplacement hole environment during the cool down period and to consider the effect permanent deformation of the discontinuities will have on the overall performance of the rock mass.

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