Stability of Disposal Rooms During Waste Retrieval

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Prepared by
T. Brandshaug

Itasca Consulting Group, Inc.
Suite 210, 1313 5th Street SE
Minneapolis, MN 55414

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Division of High-Level Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
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ABSTRACT

This report presents the results of a numerical analysis to determine the stability of waste disposal rooms for vertical and horizontal emplacement during the period of waste retrieval. It is assumed that waste retrieval starts 50 years after the initial emplacement of the waste, and that access to and retrieval of the waste containers take place through the disposal rooms. It is further assumed that the disposal rooms are not backfilled. Convective cooling of the disposal rooms in preparation for waste retrieval is included in the analysis. Conditions and parameters used were taken from the Nevada Nuclear Waste Storage Investigation (NNWSI) Project Site Characterization Plan Conceptual Design Report (MacDougall et al., 1987).

Thermal results are presented which illustrate the heat transfer response of the rock adjacent to the disposal rooms. Mechanical results are presented which illustrate the predicted distribution of stress, joint slip, and room deformations for the period of time investigated.

Under the assumption that the host rock can be classified as "fair to good" using the Geomechanics Classification system (Bieniawski, 1974), only light ground support would appear to be necessary for the disposal rooms to remain stable.

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1.0 INTRODUCTION

This report addresses the subject of structural stability of disposal rooms in a geologic radioactive waste repository. This subject is important because of requirements to retrieve any of the emplaced waste if this should become necessary. In this report, it is assumed, strictly for the purpose of analysis, that waste retrieval will take place 50 years after initial waste emplacement, access to and retrieval of the waste will take place through the disposal rooms, and the disposal rooms are not back-filled prior to waste retrieval.

1.1 Background

The Nuclear Waste Policy Act of 1982 (NWPA) which mandates the development of repositories for disposal of high-level waste and spent nuclear fuel also requires the repository to be designed and constructed to permit the retrieval of any emplaced radioactive waste. Regulations concerning waste retrieval are also issued by the Nuclear Regulatory Commission (NRC) in 10 CFR 60, and by the Environmental Protection Agency (EPA) in 40 CFR 191.14(f). These regulations dictate specific requirements which affect repository design and performance objectives.

If access to and retrieval of the waste take place through the disposal rooms, the two most important elements in complying with the regulations are the unobstructed access to the waste container boreholes, and the unobstructed access to the waste containers inside the boreholes. This means the disposal rooms and the container boreholes must remain structurally stable for the time period required to complete the retrieval process. This report addresses only the issue of room stability.

The candidate repository site is at Yucca Mountain, Nevada, where the repository horizon is proposed to be located in a densely welded tuff. The site is being evaluated by the Nevada Nuclear Waste Storage Investigation (NNWSI) Project as potentially the first radioactive waste repository in the United States. The NNWSI project's position paper on waste retrieval is given by Flores (1986) and concludes that the disposal rooms are likely to be stable, but may require a minimal amount of maintenance.

The Site Characterization Plan Conceptual Design Report for Yucca Mountain (MacDougall et al., 1987), subsequently referred to as the SCP-CDR, and the Consultation Draft Site Characterization Plan (U.S. DOE, 1988), subsequently referred to as the CD-SCP,

outline a waste retrieval philosophy and provide a list of design criteria. The retrieval time frame considered in both these documents is shown in Fig. 1. The "retrievability period" is defined as "the time during which the ability to initiate retrieval will be maintained". This period is set to 50 years [U.S. DOE (1986), Appendix D]. The "retrieval period" is defined as "the time period required for removal of the emplaced waste from the underground repository, if a decision to retrieve the waste is made". This period is set to 34 years (Flores, 1986).

FIRST WASTE EMPLACEMENT

Fig. 1 Retrieval Time Frame for Design Purposes
[MacDougall et al., 1987]

The results of the present study will contribute to the evaluation of compliance to some of the design criteria listed in the SCP-CDR and CD-SCP. These are:

- The access and emplacement drifts will remain usable for at least 84 years.
- The rock displacement in the drifts will be less than 0.152 m (6 in).
- In the horizontal emplacement concept, the temperature in the emplacement drifts will not exceed 50°C for 50 years after waste emplacement.
- In the horizontal emplacement concept, the minimum allowable radius of curvature for the horizontal axis of the borehole liner is 34 m (110 ft).

1.2 Objective

The objective of this report is to provide a document which, by example, may serve as a procedure to the type of numerical analyses that are helpful in evaluating the particular issue of stability/instability of waste disposal rooms during the period of retrievability, and if necessary, the period of actual waste retrieval. Access to and retrieval of the waste are assumed to take place through the disposal rooms.

1.3 Scope

The subject of room stability involves the evaluation of inelastic rock behavior such as the creation of new fractures in the intact rock caused by excessive shear stresses, and activities along pre-existing joints such as slip (caused by excessive shear stress along the joints) or opening (caused by tensile stresses across the joints or by a reduction in the compressive stresses). These activities may result from the excavation of the disposal rooms, the continuous heating of the rock because of the presence of the radioactive waste, and from the effects of forced ventilation which may be required to cool the rooms before entry for the purpose of inspection or waste retrieval if necessary.

The present study includes both vertical and horizontal waste emplacement concepts, meaning that single waste containers are placed in vertical boreholes along the disposal room floor, or that multiple waste containers are placed in long horizontal boreholes perpendicular to the room walls. The heat transfer associated with the first 50 years (the retrievability period) of heating is predicted along with the induced thermal stresses, displacements, and inelastic rock behavior. At 50 years (the beginning of the retrieval period), forced convective cooling of the disposal room is initiated to prepare for the retrieval of any emplaced waste. For both the vertical and horizontal emplacement concepts, the convective cooling is continued for a time period sufficient to retrieve all the waste containers from one disposal room. Rock stresses, displacements, and inelastic behavior is also predicted during this period.

2.0 APPROACH

2.1 Assumptions and Idealizations

The effective use of numerical models to predict the thermal/mechanical behavior of rock in the vicinity of a waste disposal room requires a number of assumptions and idealizations. Because the results of the numerical models may effect the repository design, it is important that the assumptions and idealizations, if affecting the outcome of the model, contribute to conservative results. With respect to the heat transfer model, "higher" temperatures are conservative. With respect to the mechanical model, "higher" deviatoric stresses are conservative. In this study, assumptions and idealizations are such that "conservative" or "worst case" conditions are reflected in the results.

The assumptions and idealizations are:

- Instantaneous waste emplacement is used.

Emplacing all the waste instantly results in higher predicted temperatures throughout the rock than if sequential waste emplacement is performed. This is because more energy (in the form of heat generating waste) is immediately present to elevate the rock temperature.

- The disposal room cross-section considered is at the center of a waste emplacement panel.

Choosing a cross-section of a disposal room at the center of a waste emplacement panel ensures that maximum temperatures will be predicted with minimum effect from the stand-off distance between emplacement panels (refer to Fig. 2). If the method suggested by St. John (1985) is applied to determine the radius of influence of a single waste container on rock temperatures as a function of time, it is found to be 164 m after approximately 50 years for the present problem (see Appendix A for this calculation). This means the predicted rock temperatures are not likely to be affected by the panel stand-off distance in the present problem.

Fig. 2 Range of Thermal Influence at Waste Panel Center After 50 Years

- Boiling of pore water is not included.

The welded tuff at the proposed repository horizon is expected to be about 80% saturated (MacDougall et al., 1987, Chapter 2). Therefore, when the rock temperatures reach 100°C, the pore water can be expected to boil (assuming atmospheric boiling). If pore water boiling is not included in the model, the predicted rock temperatures will be conservative, because the energy that would have been expended in the phase change (liquid to vapor) is available to elevate the rock temperatures instead.

- Waste retrieval takes place at the latest possible time.

To assume that waste retrieval will take place at the end of the retrievability period (i.e., 50 years after initial waste emplacement), allows the rock to be heated for a maximum amount of time. This results in the highest possible rock temperatures relative to starting waste retrieval earlier.

- Access to and retrieval of the nuclear waste will take place through the disposal rooms.

This assumption implies that a particular waste retrieval scenario is used.

- The disposal rooms are not backfilled prior to waste retrieval.

If the disposal rooms are backfilled, waste retrieval would require the backfill to be removed to provide access to the waste containers. The effects of backfill are not considered in this study.

Being conservative in the predictions of the rock temperatures results (because of thermal expansion of the rock) in conservative estimates of rock displacements and deviatoric stresses. In addition, when convective cooling of the disposal rooms begin, the largest possible thermal gradients will develop, bringing about the largest possible deviatoric stresses in the rock around the room periphery, and thus, the greatest potential for room instability.

2.2 Numerical Models

The finite difference computer code FLAC [Fast Lagrangian Analysis of Continua, (ITASCA, 1988)] is used to simulate the thermal/mechanical response of the rock. A plane strain model is used, and the rock is characterized as an elastic perfectly plastic material with ubiquitous vertical joints (planes of weakness). A Mohr-Coulomb failure criterion is used to determine if new fractures are created in the rock matrix (e.g., Brady and Brown, 1985). Figure 3 illustrates the Mohr-Coulomb failure criterion for the rock matrix for an arbitrary state of stress.

Fig. 3 Mohr-Coulomb Failure Criterion for a Rock Matrix

Slip or opening along the vertical planes of weakness is determined by a Mohr-Coulomb criterion for joints [e.g., Goodman (1980)]. Figure 4 illustrates the Mohr-Coulomb criterion for the ubiquitous vertical joints. By allowing inelastic rock behavior to occur, the potential and extent of room instability may be evaluated.

Fig. 4 Mohr-Coulomb Failure Criterion for a Rock Joint

The simultaneous mass and heat transfer (coupled convection/diffusion process) which occurs in forced ventilation of a waste disposal room is not included in FLAC. However, FLAC allows the use of convective boundaries by applying Newton's law of cooling (e.g., Pitts and Sissom, 1977). This requires the specification of a convective heat transfer coefficient and a temperature of the cooling "fluid", which in this case is air. Svalstad and Brandshaug (1981) compared the thermal response of a waste disposal room during forced ventilation, using separately, coupled convection/diffusion heat transfer and Newton's law of cooling. They found the thermal response to be similar when properly specifying the heat transfer coefficient and the temperature of the ventilating air.

2.3 Conceptual Considerations

Emplacement of waste in vertical or horizontal boreholes are alternatives considered in the SCP-CDR for Yucca Mountain; therefore, both concepts are included in this report. Figures 5 and 6 illustrate the vertical and the horizontal emplacement concepts, respectively.

Because two-dimensional models are used, the waste containers and emplacement boreholes cannot be modeled explicitly. Therefore, the discrete thermal power of the waste containers is distributed uniformly along the disposal room. In the case of vertical emplacement, this means the presence of a heat generating vertical plane along the axis of the room at the center of the floor. For the horizontal emplacement, the heat generating plane is horizontal along the axis of the room at the mid-height of both walls. The potential problem of room instability results from the compounded effect of heat transfer from individual waste containers at some distance. Because of the distance, the heat transfer effect of the individual waste containers to the rock around the room will be damped. Therefore, the concept of using a heat generating plane is an adequate idealization for both emplacement concepts.

Fig. 5 Plan and Cross-Sectional Views of the Vertical Commingled SF and DHLW Emplacement Configuration [MacDougall et al., 1987, Chapter 4]

Fig. 6 Plan and Cross-Sectional Views of the Horizontal Commingled SF and DHLW Emplacement Configuration [MacDougall et al., 1987, Chapter 4]

The Areal Power Density (APD), also called thermal loading (dimensions used are W/m^2 and kW/acre), may vary depending on the geometric scale of the numerical model being considered. On a far-field scale, which includes the total repository area, the APD being considered is 14.1 W/m^2 (57 kW/acre) (Johnstone et al., 1984). On the scale of the present model (one waste emplacement panel), the APD is approximately 20 W/m^2 (81 kW/acre) for the current layout of commingled SF and DHLW (MacDougall et al., 1987, Chapter 4). Because waste emplacement panel stand-off distances are not included in the present model, the APD is higher than in the far-field model. Appendix B describes in detail the calculation used to determine the thermal loading for both the vertical and horizontal emplacement concepts.

Figure 7 illustrates the conceptual models of the vertical and horizontal waste emplacement. Because of symmetry, only one half of the disposal room and pillar needs to be included. The thermal boundary conditions are adiabatic. The two horizontal boundaries have been removed sufficiently far from the heat generating waste to remain at the initial temperature of 26°C for the time period simulated.

The kinematic boundary conditions are also shown in Fig. 7, and are such that the two vertical boundaries are restricted from moving in the horizontal direction, while free to move in the vertical direction. The lower horizontal boundary is restricted from moving in the vertical direction, while 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 , respectively (MacDougall et al., 1987, Chapter 2). Note, that compressive stresses are negative.

The following describes the sequence of events which are simulated, and explains some of the specifics related to the heat transfer in the disposal rooms.

Fig. 7 Conceptual Models of the Disposal Rooms for Vertical and Horizontal Waste Emplacement

- EXCAVATION OF THE DISPOSAL ROOM AT TIME = 0

Deformations and stresses are determined throughout the rock.

- INITIAL WASTE EMPLACEMENT AT TIME = 0

Heat transfer calculations start.

- WASTE ISOLATION FROM 0 TO 50 YEARS

The thermal/mechanical response of the rock is predicted, and results are recorded at selected times frequently enough to provide a perspective of the transient behavior of the temperatures and stresses in the rock. The disposal room is not ventilated during this period; therefore, the heat transfer in the room is by thermal radiation, and some probably by free convection. FLAC does not include simulation of explicit thermal radiation; therefore, to simulate some of these effects by conduction heat transfer, the material in the room is modeled (only with respect to heat transfer) as tuff from the repository horizon, except the thermal conductivity is increased from 2.29 W/m-K to 50 W/m-K.

- WASTE RETRIEVAL FROM 50 YEARS TO 50 YEARS PLUS THE TIME REQUIRED TO RETRIEVE ALL THE WASTE FROM ONE DISPOSAL ROOM

The thermal/mechanical response of the rock is predicted during the period of forced convective cooling of the disposal room and the period of actual waste retrieval. It is only necessary to consider waste retrieval from one disposal room, because retrieval from subsequent rooms is identical. Forced ventilation to cool the disposal room starts at 50 years by applying Newton's law of cooling with the room periphery as a convective boundary. Determination of the convective heat transfer coefficient used is shown in Appendix C. If 12 waste containers can be removed per day (MacDougall et al., 1987, Appendix L-2), it will take approximately 14 days to complete the waste retrieval of a disposal room for vertical emplacement, and about 65 days for horizontal emplacement. To be conservative, the convective cooling of the disposal rooms is continued for 120 days.

3.0 MODEL INPUT PARAMETERS

3.1 Material Properties

The material properties used in the numerical models are taken from Chapter 2 of the SCP-CDR and are specific to the rock at the repository horizon (designated as thermal/mechanical unit TSw2 in the SCP-CDR, Chapter 2).

The mean value of the thermal properties and a range (where available) of one standard deviation from the mean are given in Table 1. Determination of the convective heat transfer coefficient is shown in Appendix C.

Table 1

THERMAL PROPERTIES

[MacDougall et al., 1987]

<u>PROPERTY</u>	<u>ROCK</u>	<u>DISPOSAL ROOM</u>
Thermal Conductivity (W/m-K)	2.29 ± 0.17	50.
Specific Heat Capacity (J/kg-K)	931	931.
Convective Heat Transfer Coefficient (W/m ² -K)	--	(a)
Coefficient of Thermal Expansion ($\times 10^{-6}$ K ⁻¹)	8.8	--

(a) Refer to Appendix C for the value of this parameter.

The mechanical properties of the rock mass are given in Table 2. The mean property value and a range (where available) of one standard deviation from the mean are given. Note, that only the mean values are used for the thermal and mechanical properties in these analyses.

Table 3-2

MECHANICAL PROPERTIES

[MacDougall et al., 1987]

<u>PROPERTY</u>	<u>ROCK</u>	<u>JOINTS</u>
Density (kg/m ³)	2320.	--
Deformation Modulus (GPa)	15.2 ± 4.2	--
Poisson's Ratio	0.22 ± 0.05	--
Cohesion (MPa)	17.8 ± 5.7	0.1 ± 0.1
Angle of Internal Friction (degrees)	23.5 ± 0.15	28.4 (11.8 to 38.7) *
Uniaxial Compressive Strength (MPa)	166 ± 65	--

*This is a range.

3.2 Waste Form Characteristics

The initial power of a SF container at the time of emplacement may range from 2.3 kW to 3.4 kW (O'Brian, 1985). In this study, the initial power is set conservatively to 3.2 kW. The initial power of the DHLW container is chosen as 0.42 kW after Peters (1983).

The thermal decay characteristics of SF and DHLW are given by Peters (1983) for waste ten years out of the reactor:

$$\begin{array}{ll} \text{Spent Fuel} & P(t) = 0.54 \exp(\ln(0.5)t/89.3) + \\ & 0.44 \exp(\ln(0.5)t/12.8) \end{array}$$

$$\begin{array}{ll} \text{DHLW} & P(t) = 0.86 \exp(\ln(0.5)t/34.2) + \\ & 0.14 \exp(\ln(0.5)t/15.2) \end{array}$$

where $P(t)$ = normalized power, and

t = time in years.

The normalized power as a function of time, as described from the above equations as well as that given by Mansure (1985) for SF are shown in Fig. 8. As seen, the two approximations for SF are very similar.

Comparison of Power Decay Characteristics For Spent Fuel and Defense High Level Waste

Fig. 8 Waste Form Normalized Power Decay

4.0 DISCUSSION OF RESULTS

In preparation for waste retrieval, convective cooling of the disposal room is started 50 years after waste emplacement. In this study, it is assumed that waste retrieval will start when the disposal room floor temperature has decreased to less than 50°C. To be conservative, the convective cooling of a disposal room (horizontal or vertical emplacement) continues during and beyond the period assumed to be necessary for retrieval of the waste. If twelve waste containers can be removed per day (MacDougall et al., 1987, Appendix L-2), it will require about 14 days to completely remove the waste from a disposal room with vertical emplacement, and about 65 days for a room with horizontal emplacement. In the results that follow, the convective cooling of the disposal room has been continued for a period of 120 days.

4.1 Thermal Results

Rock temperatures are predicted at every nodal location throughout the time period simulated. Results are presented as temperature contours and straight line temperature profiles at different times, and as temperature histories for specific locations. The initial temperature of the rock is 26°C.

4.1.1 Vertical Emplacement

Figures 9 to 11 show the predicted temperatures in the rock surrounding the waste containers and the disposal room. The temperatures are illustrated as contours (isotherms) at 1, 25, and 50 years after waste emplacement. During this period, more and more of the rock is heated by the nuclear waste, and temperatures are increasing. Because of the short distance between the waste containers and the disposal room, the temperature of the rock around the room starts to increase soon after waste emplacement. There is no ventilation of the disposal room until the end of 50 years. When ventilation is initiated, it has a dramatic effect on the room surface temperature as seen in Fig. 12. The immediate and substantial reduction of the temperature of the room floor, wall, and roof is consistent with the results obtained by Svalstad and Brandshaug (1981). The results in Fig. 12 are shown for ventilation air temperatures of 10°C and 20°C. Figure 12 also shows that the maximum temperature reached in the floor prior to ventilation is 126°C.

Fig. 9 Predicted Temperature Contours (°C) Around the Waste Disposal Room for Vertical Emplacement 1 Year After Initial Waste Emplacement

Fig. 10 Predicted Temperature Contours ($^{\circ}\text{C}$) Around the Waste Disposal Room for Vertical Emplacement 25 Years After Initial Waste Emplacement

Fig. 11 Predicted Temperature Contours ($^{\circ}\text{C}$) Around the Waste Disposal Room for Vertical Emplacement 50 Years After Initial Waste Emplacement

Fig. 12 Predicted Temperature Histories in the Floor, Wall and Roof of the Waste Disposal Room for Vertical Emplacement.

A different perspective of the predicted heat transfer in the rock is provided in Fig. 13, as temperatures along a horizontal straight line from the room wall into the pillar are shown at various times. It is obvious from Fig. 13 that high thermal gradients develop in the rock adjacent to the disposal room from the time when ventilation starts. The cool rock at the room surface and the high thermal gradients may result in a differential thermal contraction of the rock adjacent to the room. Therefore, the potential for falling rocks exists at the time of ventilation and waste retrieval.

Fig. 13 Predicted Temperature Profiles into the Pillar of the Waste Disposal Room for Vertical Emplacement

4.1.2 Horizontal Emplacement

For horizontal waste emplacement, the containers are located at much greater distance from the disposal room than for vertical emplacement. Because of the distance and the horizontal waste lay-out, more of the thermal energy diffuses in the vertical direction, and therefore, does not reach the disposal room. This results in lower temperatures of the rock around the disposal room than in the case of vertical emplacement.

Figures 14 to 16 illustrate the predicted temperatures as isotherms in the rock around the disposal room after 10, 25, and 50 years (i.e., prior to the initiation of forced ventilation). After 50 years, a considerable region of rock has been heated because of the presence of the waste. Figure 17 shows the predicted thermal history of the disposal room floor, wall, and roof. The results indicate that the room surface temperature will exceed the maximum temperature criterion of 50°C after 50 years, as listed in Chapter 2 of the SCP-CDR, and repeated in Chapter 1 of this report. However, the forced ventilation starting at 50 years substantially reduces the room surface rock temperature.

Temperatures are shown in Fig. 18 for various times up to 50 years along the horizontal straight line from the room wall into the pillar. The different curves illustrate the effect of the transient heat transfer.

Figure 19 shows the substantial thermal gradients in the rock around the room as a result of convective cooling for 120 days beyond 50 years. The results of ventilation air temperatures of 10 and 20°C are included.

Fig. 14 Predicted Temperature Contours ($^{\circ}\text{C}$) Around the Waste Disposal Room for Horizontal Emplacement 10 Years After Initial Waste Emplacement

Fig. 15 Predicted Temperature Contours ($^{\circ}\text{C}$) Around the Waste Disposal Room for Horizontal Emplacement 25 Years After Initial Waste Emplacement

Fig. 16 Predicted Temperature Contours ($^{\circ}\text{C}$) Around the Waste Disposal Room for Horizontal Emplacement 50 Years After Initial Waste Emplacement

Fig. 17 Predicted Temperature Histories in the Floor, Wall and Roof of the Waste Disposal Room for Horizontal Emplacement

Fig. 18 Predicted Temperature Profiles in the Pillar of the Waste Disposal Room for Horizontal Emplacement Prior to Waste Retrieval

Fig. 19 Predicted Temperature Profiles Into the Pillar of the Waste Disposal Room for Horizontal Emplacement During Waste Retrieval

4.2 Mechanical Results

Displacements, stresses, and joint slip are predicted in the mechanical model. Results are presented, which show portions of the rock around the room where the vertical joints have slipped (failed in shear). Contours of predicted horizontal and shear stresses are shown, as well as the predicted roof to floor closure and wall to wall closure.

4.2.1 Vertical Emplacement

The results of the mechanical model show that no new fractures are created in the rock around the disposal room as a result of room excavation or thermal expansion of the rock in the period following the emplacement of the waste. Figure 20 illustrates the predicted slip along pre-existing vertical joints as a result of room excavation. The slip is initiated because the shear stresses induced by excavating the room exceed the shear strength of the joints. Figure 21 illustrate the predicted shear and horizontal stresses in the rock as a result of excavation. Because the joints are vertical, these stresses are the same as the shear and normal stresses acting on the joints.

In Fig. 22, the predicted slip along the pre-existing vertical joints is shown after 50 years, and also after an additional 120 days of forced ventilation. There is very little additional joint slip induced as a result of the thermomechanical response of the rock for 50 years after room excavation and 120 days of forced ventilation beyond the 50 years. Using air of 10°C or 20°C during ventilation has the same effect on the predicted joint slip.

The predicted 50 year history of roof to floor closure, and wall to wall closure are shown in Figure 23. Both the roof/floor and wall/wall close as a result of excavation. The deformations predicted are very small, and far below the maximum amount of 0.152 m currently listed as a criterion in the SCP-CDR, Chapter 2.

Fig. 20 Predicted Slip Along Vertical Joints as a Result of Excavation of the Waste Disposal Room for Vertical Emplacement

Fig. 21 Predicted Shear and Horizontal Stresses As a Result of Excavation of the Waste Disposal Room for Vertical Emplacement

Fig. 22 Predicted Slip Along Vertical Joints Around the Waste Disposal Room for Vertical Emplacement at the Time of Waste Retrieval and After Waste Retrieval

Fig. 23 Predicted History of the Roof to Floor Closure and Wall to Wall Closure of the Waste Disposal Room for Vertical Emplacement

As forced ventilation is initiated, the temperatures of the room surface rock decrease, resulting in thermal contraction of the rock. Depending on the system of rock fractures around the room, this effect may cause individual blocks of rock to become unstable. The kinematics of individual blocks of rock is not included in the mechanical model; thus, this phenomenon is not predicted in this study.

Joint movement may not result in room instability, however, it does result in the potential of such an event. Because most of the joint slip results from the effect of excavation, the chart in Fig. 24 (after Hoek, 1979) can be used to approximate the required ground support for the disposal rooms. When applied to the vertical emplacement rooms, assuming that the quality of the rock can be classified as "fair to good" according to the Geomechanics Classification system (Bieniawski, 1974), only light ground support such as rockbolts, wire mesh, or shotcrete is estimated to be required to maintain room stability.

Fig. 24 Suggested Ground Support As a Function of Induced Stresses and Rock Mass Quality [after Hoek, 1979]

4.2.2 Horizontal Emplacement

The results of the mechanical model show that no new fractures are created in the rock around the disposal room for horizontally emplaced waste as a result of room excavation or rock thermal expansion in the period following the emplacement of the waste. However, slip is predicted along the pre-existing vertical joints. Figure 25 illustrates the predicted joint slip as a result of room excavation (at time = 0), and 50 years after initial waste emplacement. The amount of joint slip predicted is about the same as for the disposal room with vertically emplaced waste. There is very little additional joint slip induced as a result of 50 years of thermomechanical rock response.

Figure 26 illustrates the predicted joint slip after 120 days of ventilation for air temperatures of 10°C and 20°C. Very little additional joint slip results from the effect of ventilation.

Figure 27 illustrates the predicted shear and horizontal stresses in the rock after excavation. Because the joints are vertical, these stresses are the same as the shear and normal stresses that act on the joints.

The predicted closure history between the roof and floor as well as that of the walls is illustrated in Fig. 28. The deformations predicted are very small, and below the maximum amount of 0.152 m currently listed as a criterion in the SCP-CDR, Chapter 2.

Assuming that the quality of the rock can be classified as "fair to good" according to the Geomechanics Classification system (Bieniawski, 1974), the chart in Fig. 24 (after Hoek, 1979) can be used to estimate the required ground support. When applied to the rooms for horizontal waste emplacement, only light ground support such as rockbolts, wire mesh, or shotcrete is likely to be required to maintain room stability.

Fig. 25 Predicted Slip Along Vertical Joints Around the Waste Disposal Room for Horizontal Emplacement After Excavation and at the Time of Waste Retrieval

Fig. 26 Predicted Slip Along Vertical Joints Around the Waste Disposal Room for Horizontal Emplacement After 120 Days of Ventilation

Fig. 27 Predicted Shear and Horizontal Stresses As a Result of Excavation of the Waste Disposal Room for Horizontal Emplacement

Fig. 28 Predicted History of the Roof to Floor Closure and the Wall to Wall Closure of the Waste Disposal Room for Horizontal Emplacement

5.0 SUMMARY AND CONCLUSIONS

The response of the rock to the excavation of the disposal rooms, heating by the nuclear waste, and cooling by forced ventilation has been investigated, considering separately vertical and horizontal emplacement of the waste. The focus of the analyses has been toward effects that may compromise the structural stability of the rooms. Because two-dimensional models were used, the stability of individual container boreholes could not be investigated. The effects of particular interest, therefore, have been the predictions of any inelastic behavior of the rock around the disposal room, such as the creation of new fractures from excessive shear stresses, and also slip or opening of pre-existing vertical joints.

From the results of the analyses a set of conclusions can be made which apply to both disposal rooms (i.e., vertical or horizontal waste emplacement) investigated, unless specifically stated otherwise.

- No new fractures are created from excessive shear stresses in the rock around the disposal room as a result of room excavation, 50 years of thermomechanical rock response, or 120 days of convective cooling in preparation for waste retrieval. Fracturing may occur around the boreholes, but this could not be examined in this study.
- Slip along pre-existing vertical joints in the rock is predicted around the disposal room as a result of room excavation.
- Fifty (50) years of thermomechanical rock response has little effect on the development of joint slip beyond that predicted from room excavation alone.
- Assuming that the rock can be classified as "fair to good" according to the Geomechanics Classification system (Bieniawski, 1974), only light ground support such as rockbolts, wire mesh, or shotcrete is estimated to be necessary to maintain rock stability.

Conclusions which relate specifically to some of the design criteria listed in the SCP-CDR, Chapter 2, can also be stated:

- After 50 years, the maximum predicted rock surface temperature of the disposal room for horizontal waste emplacement is 60°C, which exceeds the allowable maximum of 50°C according to the design criterion.
- The maximum predicted deformation of the disposal room is of the order of 0.005 m, which is substantially below the maximum of 0.152 m, according to the design criterion.
- The radius of curvature of the axis of the horizontal borehole is significantly larger than the minimum of 34 m allowed by the design criterion.

Note that all of the above conclusions reflect the current understanding of the in-situ conditions, thermal and mechanical properties, and structure of the rock at the proposed repository site as reported in the SCP-CDR. Should any of these parameters change, the results of this study will change, which may affect the conclusions. No attempt was made in this study to determine the effects of uncertainties in the parameters on the predicted thermal/mechanical rock response.

The input files used for FLAC in these analyses are included in Appendix D.

6.0 RECOMMENDATIONS FOR FUTURE STUDIES

In this study, the thermal/mechanical response of the rock was determined using an average set of input parameters. However, uncertainties are associated with the input parameters to the numerical model (e.g., thermal rock properties, mechanical rock properties, initial conditions). To provide for a repository design that has a high probability of meeting the performance objectives, it is necessary to understand what the effects of parameter uncertainties are with respect to the thermal/mechanical response of the rock. Future studies, therefore, should include an assessment of the effect of these uncertainties on the rock response and ability to isolate the nuclear waste.

The current study characterizes the rock as a continuum. Although ubiquitous vertical joints are included, the presence of these joints is initiated only by a critical state of stress (i.e., a state of stress that exceeds the strength of the joints according to a Mohr-Coulomb criterion). Future studies should also include discontinuum models (e.g., Shi and Goodman, 1988; Cundall, 1980; Cundall, 1988; Williams et al., 1985), which are capable of explicitly characterizing the intact rock and the rock joints and, therefore, provide additional information that may help to resolve the issue of stability/instability of the rock around the disposal rooms.

7.0 REFERENCES

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APPENDIX A

DETERMINATION OF THE RADIUS OF THERMAL INFLUENCE

St. John (1985) examined the radius of thermal influence of a single waste container as a function of time, so that the size of the area required in a model could be determined. The equation for temperature change at a distance, R , from a decaying point source of initial strength Q_0 is given by (Christianson, 1979):

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

where A = decay constant,

κ = thermal diffusivity,

t = time, and

$w(z)$ = complex error function.

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

$$\exp\left(-\frac{R^2}{4\kappa t}\right)$$

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

$$R \geq 4(\kappa t)^{1/2} \quad (A-2)$$

where t is time in years.

Applying Equation A-2 to the present problem for a time period of 50 years, and a thermal diffusivity of tuff of $33.44 \text{ m}^2/\text{year}$, the radius of thermal influence, R , is determined to be approximately 164 m.

REFERENCE

Christianson, Mark. TEMP3D: A Computer Program for Determining Temperatures Around Single or Arrays of Constant or Decaying Heat Sources—Users' Guide and Manual. University of Minnesota Report to BWIP. December 1979.

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APPENDIX B

DETERMINATION OF THE THERMAL LOADING

Figure B-1 illustrates the lay-out of the waste containers for vertical emplacement (MacDougall et al., 1987). The appropriate thermal loading at the center of the waste panel for times of 50 years or less can be determined from this figure. The shaded area in Fig. B-1 represents a unit area, over which the initial power of one half SF and one half DHLW container should be averaged. The shaded area is 87.8 m^2 . With an initial power of 3200 W per SF container and 420 W per DHLW container, the thermal loading is determined to be 20.6 W/m^2 or 83.3 kW/acre .

Fig. B-1 Layout of Waste Containers for Vertical Emplacement
[after MacDougall et al., 1987, Chapter 4]

In Fig. B-2, the lay-out of the waste is shown for horizontal emplacement (MacDougall et al., 1987, Chapter 4). The shaded area in the figure represents the unit area, over which the initial power of 28 SF and 18 DHLW containers should be averaged. The shaded area is 4864 m². With an initial power of 3200 W per SF container, and 420 W per DHLW container, the thermal loading is determined to be 20 W/m² or 80.8 kW/acre.

Fig. B-2 Layout of Waste Containers for Horizontal Emplacement [after MacDougall et al., 1987, Chapter 4]

REFERENCE

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APPENDIX C

DETERMINATION OF CONVECTIVE HEAT TRANSFER COEFFICIENTS

The convective heat transfer coefficient used to simulate forced ventilation of the disposal rooms is determined from the Sieder-Tate equation (Pitts and Sissom, 1977):

$$\overline{Nu} \equiv \frac{\bar{h}D_h}{k} = 0.023 Re^{0.8} Pr^{1/3} \left[\frac{\mu_b}{\mu_s} \right]^{0.14} \quad (C-1)$$

where $\overline{Nu}$ = the average Nusselt number,

$\bar{h}$ = the average convective heat transfer coefficient,

D_h = the hydraulic diameter of the disposal room,

k = thermal conductivity of the air,

Re = Reynolds number,

Pr = Prandtl number,

μ_b = dynamic viscosity of the bulk air, and

μ_s = dynamic viscosity of the air at the convective boundary (the air is assumed to be 50°C at the boundary)

Equation C-1 is valid for $Re > 10,000$ and $l/D > 60$, where "l" is the length of the duct (in this case, the disposal room). The properties of air used are taken from Pitts and Sissom (1977), p. 314.

The Reynolds number, Re , for the disposal rooms is determined from

$$Re = \frac{VD_h}{\nu} \quad (C-2)$$

where V = air velocity,

D_h = hydraulic diameter of the disposal rooms, and

ν = kinematic air viscosity.

Because the disposal rooms are not circular, the hydraulic diameter is determined from

$$D_h = \frac{4A}{P} \quad (C-3)$$

where A = the cross-sectional area of the disposal room, and

P = length of the room perimeter.

The hydraulic diameter, D_h , determined for the disposal rooms of vertical and horizontal waste emplacement (MacDougall et al., 1987, Chapter 4) are given in Table C-1.

Table C-1
HYDRAULIC DIAMETER

Waste Emplacement Concept	A (m^2)	P (m)	D_h (m)
Vertical	30.64	21.32	5.75
Horizontal	23.94	19.49	4.91

Reynolds number, Re , is determined from Eq. (C-2). An air velocity of 1 m/s is assumed, and two air temperatures, 10°C and 20°C, are considered.

Table C-2
REYNOLDS NUMBER

Waste Emplacement Concept	V (m/s)	D _h (m)	ν (m ² /s)	Re
Vertical T _{air} = 10°C	1.	5.75	1.36e-5	423,469
Vertical T _{air} = 20°C	1.	5.75	1.48e-5	388,099
Horizontal T _{air} = 10°C	1.	4.91	1.36e-5	361,029
Horizontal T _{air} = 20°C	1.	4.91	1.48e-5	331,757

The Reynolds numbers listed in Table C-2 are all greater than 10,000 and, therefore, satisfy the conditions of Eq. (C-1). The second condition that must be satisfied to use Eq. (C-1) is $l/D_h > 60$. The length, l , of the disposal rooms are approximately 400 m (MacDougall et al., 1987, Chapter 4). Table C-3 shows that this ratio is satisfied for the disposal rooms of vertical and horizontal waste emplacement.

Table C-3
RATIO OF l/D

Waste Emplacement Concept	l (m)	D_h (m)	l/D_h
Vertical	400	5.75	70
Horizontal	400	4.91	81

The average Nusselt number and convective heat transfer coefficient determined are listed in Table C-4.

Table C-4.

AVERAGE NUSSELT NUMBER AND CONVECTIVE HEAT TRANSFER COEFFICIENT

Waste Emplacement Concept	$\frac{\mu_b}{\mu_s}$	Pr	Re	k (W/m-K) $\times 10^{-2}$	D_h (m)	$\overline{Nu}$	$\overline{h}$ (W/m ² -K)
Vertical $T_{air} = 10^\circ C$	0.99	0.713	423,469	2.49	5.75	645	2.79
Vertical $T_{air} = 20^\circ C$	0.99	0.710	388,099	2.57	5.75	601	2.68
Horizontal $T_{air} = 10^\circ C$	0.99	0.713	361,029	2.49	4.91	568	2.88
Horizontal $T_{air} = 20^\circ C$	0.99	0.710	331,757	2.57	4.91	530	2.78

REFERENCE

MacDougall, Hugh R., Leo W. Scully, and Joe R. Tillerson (Compilers). Site Characterization Plan Conceptual Design Report. SAND84-2641. September 1987.

Pitts, Donald R., and Leighton E. Sissom. Schaum's Outline of Theory and Problems of Heat Transfer. New York: McGraw-Hill Book Company, 1977,

APPENDIX D

FLAC INPUT FILES

D-1. FLAC INPUT FILE FOR VERTICAL EMPLACEMENT

```

*****
*
*      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 to FLAC for determining the effect of ventilation      *
*   (Blast Cooling) on disposal room stability during waste retrieval. *
*   Vertical emplacement scheme ...                                     *
*   NRC Contract 02-85-002, Task Order No. 006.                       *
*
*****
*
GR 13,40
MOD UBIQUITOUS ;(ubiquitous rock joint model)
THMOD ISO      ;(isotropic thermal model)
*
*---- CONSTRUCT THE FINITE DIFFERENCE MESH BY VARIOUS
*---- GEOMETRIC ADJUSTMENTS
GEN 0.,-150. 0.,150. 19.2,150. 19.2,-150.
GEN 0.,0. 0.,6.71 2.44,6.71 2.44,0. I=1,6 J=20,28
GEN 2.44,0. 2.44,6.71 19.2,6.71 19.2,0. R 1.5,1. I=6,14 J=20,28
*
*---- The borehole above the waste container ...
GEN 0.,-3.1 0.,0. .37,0. .37,-3.1 I=1,2 J=15,20
*---- To the right of borehole and under floor ...
GEN .37,-3.1 .37,0. 2.44,0. 2.44,-3.1 I=2,6 J=15,20
*---- The container inside the borehole ...
GEN 0.,-7.62 0.,-3.1 .37,-3.1 .37,-7.62 I=1,2 J=10,15
*---- To the right of the container and under floor .....
GEN .37,-7.62 .37,-3.1 2.44,-3.1 2.44,-7.62 I=2,6 J=10,15
*---- To the right of borehole and under pillar ...
GEN 2.44,-3.10 2.44,0. 19.2,0. 19.2,-3.1 R 1.5,1. I=6,14 J=15,20
GEN 2.44,-7.62 2.44,-3.1 19.2,-3.1 19.2,-7.62 R 1.5,1. I=6,14 J=10,15
*---- Below the container and under pillar ...
GEN 0.,-30. 0.,-7.62 2.44,-7.62 2.44,-30. R 1.,.67 I=1,6 J=5,10
GEN 2.44,-30. 2.44,-7.62 19.2,-7.62 19.2,-30. R 1.5,.67 I=6,14 J=5,10
GEN 0.,-150. 0.,-30. 19.2,-30. 19.2,-150. R 1.,.80 I=1,14 J=1,5
*---- Adjusting the lower part of mesh to achieve better

```

* element aspect ratios ...

GEN R 1.2,1. I=1,14 J=5

GEN R 1.05,1. I=1,14 J=4

GEN R 1.,1. I=1,8 J=6

*--- Adjusting the mesh above the disposal room ...

GEN 0.,7. 0.,30. 2.44,30. 2.44,7. R 1.,1.7 I=1,6 J=29,35

GEN 2.44,7. 2.44,30. 19.2,30 19.2,7. R 1.5 1.7 I=6,14 J=29,35

*--- Adjusting the mesh to the top of the model ...

GEN 0.,30. 0.,150. 19.2,150. 19.2,30. R 1.,1.3 I=1,14 J=35,41

GEN R 1.3,1. I=1,14 J=35

GEN R 1.25,1. I=1,14 J=36

GEN R 1.2,1. I=1,14 J=37

GEN R 1.1,1. I=1,14 J=38

*

*--- Constructing the crown of the room by indiv. nodal adjustments ...

INI X=2.44 I=6 J=26

INI Y=5.22 I=6 J=26

INI X=2.30 I=6 J=27

INI Y=5.50 I=6 J=27

INI X=2.10 I=6, J=28

INI Y=5.90 I=6 J=28

INI X=1.65 I=5 J=28

INI Y=6.20 I=5 J=28

INI X=1.30 I=4 J=28

INI Y=6.40 I=4 J=28

INI X=1.00 I=3 J=28

INI Y=6.55 I=3 J=28

INI X=0.50 I=2 J=28

INI Y=6.65 I=2 J=28

INI X=2.50 I=7 J=28

INI Y=6.00 I=7 J=28

INI Y=6.43 I=8 J=28

INI Y=5.60 I=7 J=27

INI Y=5.15 I=7 J=26

*

*--- Second row of nodal points above crown ...

INI X=0.55 I=2 J=29

INI Y=6.95 I=2 J=29

INI X=1.10 I=3 J=29

INI Y=6.85 I=3 J=29

INI X=1.45 I=4 J=29

INI Y=6.70 I=4, J=29

INI X=1.75 I=5 J=29

INI Y=6.55 I=5 J=29

INI X=2.10 I=6 J=29

INI Y=6.35 I=6 J=29

INI X=2.50 I=7 J=29

INI Y=6.35 I=7 J=29

*

*--- Third row of nodal points above crown ...

INI Y=7.60 I=1 J=30
 INI X=0.60 I=2 J=30
 INI Y=7.55 I=2, J=30
 INI X=1.15 I=3 J=30
 INI Y=7.50 I=3, J=30
 INI X=1.60 I=4 J=30
 INI Y=7.40 I=4 J=30
 INI X=2.00 I=5 J=30
 INI Y=7.30 I=5 J=30
 INI X=2.40 I=6 J=30
 INI Y=7.20 I=6 J=30
 INI X=2.75 I=7 J=30
 INI Y=7.30 I=7 J=30

*

*--- Forth row of nodal points above crown ...

GEN LINE 0., 8.6 2.78, 8.3

*

*--- Some additional mesh adjustments ...

GEN LINE 3.291, 6.43 19.2, 6.43

*

*--- ASSIGN MATERIAL PROPERTIES (REF: SCP-CDR CHAP. 2, SEC. 2.3.1)

*--- USING THE JOINT PROPERTIES AND "ROCK MASS" PROPERTIES.

*--- ALSO USING THE MOST RECENT RESULTS FROM DATA ANALYSIS,

*--- TABLES 2-4, 2-6, AND 2-7.

*--- THE ROCK IS CHARACTERIZED AS AN ELASTIC/PLASTIC MATERIAL

*--- WITH UBIQUITOUS JOINTS. A MOHR-COULOMB FAILURE CRITERION

*--- IS USED FOR BOTH THE INTACT ROCK AND THE JOINTS ...

*

*--- Rock Mass:

PROP SHEAR=6.23E3 BULK=9.05E3 COH=17.8 ; (MPa)

PROP DENS=2320. ; (kg/m³)

PROP FRIC=23.5 ; (degrees)

*

*--- Rock Joints:

PROP JCOH=0.1 ; (MPa)

PROP JFRIC=28.4 JANG=90. ; (degrees)

*

*--- THERMAL PROPERTIES OF THE ROCK ...

* (Ref: SCP-CDR Chap. 2, Sec. 2.3.1.9, Table 2-9)

PROP CON=2.29 ; (W/mK)

PROP SPE=931. ; (J/kgK)

PROP THEX=8.8E-6 ; (1/K)

*

```

*--- 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.)
FIX Y I=1,14 J=1
FIX X I=1 J=1,41
FIX X I=14 J=1,41
*
*--- 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 x SYY.)
INI SXX=-3.5 ; (MPa)
INI SYY=-7.0 ; (MPa)
APPLY PRES=7.0 I=1,14 J=41 ; (MPa)
*
*--- SET THE INITIAL TEMPERATURE TO 26 DEG. CELSIUS ...
INI TEMP=26. ; (Degree Celsius)
*
*--- SET THERMAL BOUNDARY CONDITIONS ...
*--- THE BOUNDARIES ARE BY DEFAULT ADIABATIC (thermally insulated)
*
*--- SET THE CRITERIA FOR AUTOMATIC TERMINATION OF EXECUTION ...
SET F=1E-2 ; Out-of-balance force (Mega Newton)
SET CLOCK=120 ; Maximum execution time (minutes)
SET STEP=5000 ; Maximum number of time steps
*
*--- EXCAVATE THE DISPOSAL ROOM (save results) ...
MOD NULL I=1,5 J=20,27
TIT
    Time is After Initial Excavation, Vert. Empl. (NRC-F)
SOLVE
SAVE NRCV_M0.SAV
*
*--- THERMAL PROPERTIES OF THE DISPOSAL ROOM FROM 0 TO 50 YEARS.
*   (The maximum thermal time step in FLAC is determined from
*   the element size and associated thermal diffusivity. Using
*   air in the disposal room with an "equivalent" conductivity
*   results in a maximum time step of insufficient length to
*   complete the analysis within a reasonable time period.
*   Therefore, the room is given thermal properties of TSw2 tuff,
*   but with the thermal conductivity increased about 22 times
*   to 50 W/mK. The size of the room elements are also increased.
*

```



```

*--- CHANGE THE ELEMENT SIZES IN THE ROOM SO THAT AS LARGE A TIME STEP
*--- AS POSSIBLE MAY BE USED ...
*   (This is done by restoring a thermal region in the room, and
*   surrounding it by null zones, and then "stretching" the thermal
*   region to fit the entire room.)
*
THMOD ISO I=2,3 J=24,26
*
*--- Fit the restored thermal region to the entire room ...
*
GEN 0.,0. 0.,6.71 1.65,6.2 2.44,0. I=2,4 J=24,27
INI X=1.0 Y=6.55 I=3 J=27
INI X=2.44 Y=5.22 I=4 J=26
INI X=2.44 Y=2.516 I=4 J=25
INI X=1.405 Y=0.0 I=3 J=24
INI X=2.250 Y=5.456 I=6 J=27
INI X=0.5 Y=6.63 I=2 J=28
INI X=1.325 Y=6.375 I=4 J=28
INI X=2.045 Y=5.71 I=6 J=28
*
*--- Assign thermal properties to the restored thermal region ...
*
PROP CON=50. I=1,5 J=20,27 ; (W/mK)
PROP SPE=931. I=1,5 J=20,27 ; (J/kgK)
PROP DENS=2320. I=1,5 J=20,27 ; (kg/m^3)
PROP THEX=0. I=1,5 J=20,27 ; (1/K)
*
*--- DEFINE INTERFACE BETWEEN THE THERMAL REGION AND THE
*--- DISPOSAL ROOM SURFACE ...
*
INTER 1 ASIDE 1,20 2,20 3,20 4,20 5,20 6,20 6,21 6,22 6,23 6,24
INTER 1 ASIDE 6,25 6,26 6,27 6,28 5,28 4,28 3,28 2,28 1,28
INTER 1 BSIDE 2,27 3,27 4,27 4,26 4,25 4,24 3,24 2,24
*
*--- Assign properties to the interface ...
*   (Make sure the stiffness properties are small so that
*   no interaction with the mechanical behavior of the
*   room occurs. Also make sure strength properties
*   are high so that no failure occurs.)
*
INTER 1 KS=1.E-6 KN=1.E-6 TB=1.E2 COH=1.E2 FRIC=45. GLUED
*
*--- 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 792 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 ...
THAPP FLUX 41.8 -2.46E-10 I=1 J=10,15 ;(SPENT FUEL FIRST TERM)
THAPP FLUX 34.1 -1.72E-9 I=1 J=10,15 ;(SPENT FUEL SECOND TERM)
THAPP FLUX 8.8 -6.43E-10 I=1 J=10,15 ;(DHLW FIRST TERM)
THAPP FLUX 1.4 -1.45E-9 I=1 J=10,15 ;(DHLW SECOND TERM)
*
*---- DEFINE NODAL POINTS FOR WHICH TEMP. HISTORIES ARE RECORDED ...
*
THIS NSTEP=10 ;Record results every 10 time steps ...
THIS TEMP I=1 J=20 ;Location at the floor center ...
THIS TEMP I=6 J=23 ;Location at the rib center ...
THIS TEMP I=1 J=28 ;Location at the crown center ...
THIS TEMP I=1 J=12 ;Location at the waste container center ...
*
*---- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
TIT
    Predicted temperatures after 1 year, Vert. Empl. (NRC-F)
SAVE NRCV_T1.SAV
*
*---- PREDICT THE MECHANICAL RESPONSE OF 1 YEAR OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 1 year. Vert. Empl. (NRC-F)
SAVE NRCV_M1.SAV
*
*---- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...
SET THDT=64800. ; Time step of 18 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years
TIT
    Predicted temperatures after 2.5 years, Vert. Empl. (NRC-F)
SAVE NRCV_T2.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 2.5 YEARS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 2.5 years. Vert. Empl. (NRC-F)
SAVE NRCV_M2.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...

SET THDT=86400. ; Time step of 24 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years

TIT

Predicted temperatures after 5 years, Vert. Empl. (NRC-F)
SAVE NRCV_T5.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 5 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 5 years. Vert. Empl. (NRC-F)
SAVE NRCV_M5.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...

SET THDT=86400. ; Time step of 24 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years

TIT

Predicted temperatures after 7.5 years, Vert. Empl. (NRC-F)
SAVE NRCV_T7.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 7.5 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 7.5 years. Vert. Empl. (NRC-F)
SAVE NRCV_M7.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...

SET THDT=86400. ; Time step of 24 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years

TIT

Predicted temperatures after 10 years, Vert. Empl. (NRC-F)
SAVE NRCV_T10.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 10 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 10 years. Vert. Empl. (NRC-F)
SAVE NRCV_M10.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...

SET THDT=345600. ; Time step of 4 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years

TIT

Predicted temperatures after 15 years, Vert. Empl. (NRC-F)

SAVE NRCV_T15.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 15 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 15 years. Vert. Empl. (NRC-F)

SAVE NRCV_M15.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years

TIT

Predicted temperatures after 20 years, Vert. Empl. (NRC-F)

SAVE NRCV_T20.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 20 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 20 years. Vert. Empl. (NRC-F)

SAVE NRCV_M20.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years

TIT

Predicted temperatures after 25 years, Vert. Empl. (NRC-F)

SAVE NRCV_T25.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 25 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 25 years. Vert. Empl. (NRC-F)

SAVE NRCV_M25.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years

TIT

Predicted temperatures after 30 years, Vert. Empl. (NRC-F)

SAVE NRCV_T30.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 30 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 30 years. Vert. Empl. (NRC-F)

SAVE NRCV_M30.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years

TIT

Predicted temperatures after 35 years, Vert. Empl. (NRC-F)

SAVE NRCV_T35.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 35 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 35 years. Vert. Empl. (NRC-F)

SAVE NRCV_M35.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years

TIT

Predicted temperatures after 40 years, Vert. Empl. (NRC-F)

SAVE NRCV_T40.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 40 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 40 years. Vert. Empl. (NRC-F)

SAVE NRCV_M40.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...

SET THDT=604800. ; Time step of 7 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years

TIT

Predicted temperatures after 45 years, Vert. Empl. (NRC-F)

SAVE NRCV_T45.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 45 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 45 years. Vert. Empl. (NRC-F)

SAVE NRCV_M45.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=604800. ; Time step of 7 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
TIT

Predicted temperatures after 50 years, Vert. Empl. (NRC-F)
SAVE NRCV_T50.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TIT

Predicted T/M response after 50 years. Vert. Empl. (NRC-F)
SAVE NRCV_M50.SAV

*

```

*****
*
*      S T A R T      C O N V E C T I V E      C O O L I N G      T O      *
*
*      P R E P A R E      F O R      W A S T E      R E T R I E V A L      *
*
*****
*
*--- APPLY THE CONVECTIVE HEAT TRANSFER COEFFICIENT (h=2.68 W/mmK)
*--- TO THE ROOM PERIPHERY, AND ASSIGN THE TEMPERATURE OF THE COOLING
*--- AIR (20 degrees C) AT THE TIME OF WASTE RETRIEVAL (50 YEARS) ...
*
THMOD NULL I=2,3 J=24,26
THAPP CONV 2.68 20. I=1,6 J=20
THAPP CONV 2.68 20. I=6 J=20,28
THAPP CONV 2.68 20. I=1,6 J=28
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18255
TIT
    Predicted temperatures after 50 yrs & 5 ds.  Vert. Empl. (NRC-F)
SAVE NRCV_T51.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 5 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 5 ds.  Vert. Empl. (NRC-F)
SAVE NRCV_M51.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18260
TIT
    Predicted temperatures after 50 yrs & 10 ds.  Vert. Empl. (NRC-F)
SAVE NRCV_T52.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 10 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 10 ds.  Vert. Empl. (NRC-F)
SAVE NRCV_M52.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18270
TIT
    Predicted temperatures after 50 yrs & 20 ds.  Vert. Empl. (NRC-F)
SAVE NRCV_T53.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 20 DAYS OF HEATING ...
SOLVE
TIT
 Predicted T/M response after 50 yrs 20 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M53.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18290
TIT
 Predicted temperatures after 50 yrs & 40 ds. Vert. Empl. (NRC-F)
SAVE NRCV_T54.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 40 DAYS OF HEATING ...
SOLVE
TIT
 Predicted T/M response after 50 yrs 40 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M54.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18310
TIT
 Predicted temperatures after 50 yrs & 60 ds. Vert. Empl. (NRC-F)
SAVE NRCV_T55.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 60 DAYS OF HEATING ...
SOLVE
TIT
 Predicted T/M response after 50 yrs 60 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M55.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18330
TIT
 Predicted temperatures after 50 yrs & 80 ds. Vert. Empl. (NRC-F)
SAVE NRCV_T56.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 80 DAYS OF HEATING ...
SOLVE
TIT
 Predicted T/M response after 50 yrs 80 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M56.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18350
TIT
 Predicted temperatures after 50 yrs & 100 ds. Vert. Empl. (NRC-F)
SAVE NRCV_T57.SAV
*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 100 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 100 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M57.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18370

TIT

Predicted temperatures after 50 yrs & 120 ds. Vert. Empl. (NRC-F)
SAVE NRCV_T58.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 120 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 120 ds. Vert. Empl. (NRC-F)
SAVE NRCV_M58.SAV

*

*

```

*****
*
*   S T A R T   C O N V E C T I V E   C O O L I N G   T O
*
*   P R E P A R E   F O R   W A S T E   R E T R I E V A L
*
*   U S I N G   A   C O O L I N G   A I R   T E M P   O F
*
*           1 0   D E G R E E S   C E L S I U S
*
*****
*
*
*--- Restart the thermomechanical analysis performed up to 50 years ...
*
res nrcv_m50.sav
*
*
*--- APPLY THE CONVECTIVE HEAT TRANSFER COEFFICIENT (h=2.79 W/mmK)
*--- TO THE ROOM PERIPHERY, AND ASSIGN THE TEMPERATURE OF THE COOLING
*--- AIR (10 degrees C) AT THE TIME OF WASTE RETRIEVAL (50 YEARS) ...
*--- NOTE THAT THE CONVECTIVE HEAT TRANSFER COEFFICIENT IS DIFFERENT
*--- FOR DIFFERENT TEMPERATURES OF THE COOLING AIR ...
*
THMOD NULL I=2,3 J=24,26
THAPP CONV 2.79 10. I=1,6 J=20
THAPP CONV 2.79 10. I=6 J=20,28
THAPP CONV 2.79 10. I=1,6 J=28
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18255
TIT
    Predicted temperatures after 50 yrs & 5 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T61.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 5 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 5 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M61.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18260
TIT
    Predicted temperatures after 50 yrs & 10 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T62.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 10 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 10 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M62.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18270

TIT

Predicted temperatures after 50 yrs & 20 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T63.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 20 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 20 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M63.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18290

TIT

Predicted temperatures after 50 yrs & 40 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T64.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 40 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 40 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M64.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18310

TIT

Predicted temperatures after 50 yrs & 60 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T65.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 60 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 60 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M65.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18330

TIT

Predicted temperatures after 50 yrs & 80 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T66.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 80 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 80 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M66.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18350

TIT

Predicted temperatures after 50 yrs & 100 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T67.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 100 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 100 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M67.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18370

TIT

Predicted temperatures after 50 yrs & 120 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_T68.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 120 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 120 ds. 10°C Vert. Empl. (NRC-F)
SAVE NRCV_M68.SAV

D-2 FLAC Input File for Horizontal Emplacement

```

*****
*
*      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 to FLAC for determining the effect of ventilation      *
*   (Blast Cooling) on disposal room stability during waste retrieval. *
*   Horizontal emplacement scheme ...                                  *
*   NRC Contract 02-85-002, Task Order No. 006.                      *
*
*****
*
GR 25,32
MOD UBIQUITOUS ;(ubiquitous rock joint model)
THMOD ISO      ;(isotropic thermal model)
*
*--- CONSTRUCT THE FINITE DIFFERENCE MESH BY VARIOUS
*--- GEOMETRIC ADJUSTMENTS
gen 0.,-150. 0.,150. 114.,150. 114.,-150.
*
*--- Generate the room region ...
gen 0.,0. 0.,2. 114.,2. 114.,0. i=1,26 j=15,19
*
*--- Generate the region 50 m above the room ...
gen 0.,2. 0.,50. 3.51,50. 3.51,2. r .9,1.4 i=1,6 j=19,27
*
*--- Generate the region 50 m below the room ...
gen 0.,-50 0.,0. 3.51,0. 3.51,-50 r 0.9,0.65 i=1,6 j=7,15
*
*--- Generate the region off the roof/wall corner ...
gen 3.51,2. 3.51,50. 17.5,50 17.5,2. r 1.5,1.4 i=6,12 j=19,27
*
*--- Generate the disposal room ...
gen 0.,0. 0.,2. 3.51,2. 3.51,0. r 0.9,1 i=1,6 j=15,19
*
*--- Generate the region off the wall/floor corner ...
gen 3.51,-50. 3.51,0. 17.5,0. 17.5,-50. r 1.5,.65 i=6,12 j=7,15
*
*--- Generate the region next to the wall ...
gen 3.51,0. 3.51,2. 17.5,2. 17.5,0. R 1.5,1. I=6,12 J=15,19
*
*--- Generate the region above borehole ...
gen 17.5,2. 17.5,50. 32.16,50. 32.16,2. r 0.7,1.4 i=12,15 j=19,27
*

```

```

*--- Generate the region below borehole ...
gen 17.5,-50. 17.5,0. 32.16,0. 32.16,-50. r 0.7,0.65 i=12,15 j=7,15
*
*--- Generate the region next to borehole ...
gen 17.5,0. 17.5,2. 32.16,2. 32.16,0. r 0.7,1. i=12,15 j=15,19
*
*--- Generate the region above borehole ...
gen 32.16,2. 32.16,50. 44.35,50. 44.35,2. r 1.,1.4 i=15,17 j=19,27
*
*--- Generate the region below borehole ...
gen 32.16,-50 32.16,0. 44.35,0. 44.35,-50. r 1.,0.65 i=15,17 j=7,15
*
*--- Generate the region next to borehole ...
gen 32.16,0. 32.16,2. 44.35,2. 44.35,0. i=15,17 j=15,19
*
*--- Generate the region above borehole ...
gen 44.35,2. 44.35,50. 92.51,50. 92.51,2. r 1.,1.4 i=17,23 j=19,27
*
*--- Generate the region below borehole ...
gen 44.35,-50 44.35,0. 92.51,0. 92.51,-50. r 1.,0.65 i=17,23 j=7,15
*
*--- Generate the region next to borehole ...
gen 44.35,0. 44.35,2. 92.51,2. 92.51,0. i=17,23 j=15,19
*
*--- generate the region above borehole ...
gen 92.51,2. 92.51,50. 114.,50. 114.,2. r 1.,1.4 i=23,26 j=19,27
*
*--- Generate the region below borehole ...
gen 92.51,-50 92.51,0. 114.,0. 114.,-50. r 1.,0.65 i=23,26 j=7,15
*
*--- Generate the region next to borehole ...
gen 92.51,0. 92.51,2. 114.,2. 114.,0. i=23,26 j=15,19
*
*--- It appears there are more than sufficient elements in the vertical
*--- direction. Therefore, null zones are introduced, and the remaining
*--- mesh "stretched" to fit ...
*
mod null i=1,25 j=30,32
mod null i=1,25 j=1,3
*
*--- "Stretching" above the room ...
*
gen 0.,50. 0.,150. 10.,150. 3.51,50. r 1.,1.5 i=1,6 j=27,30
gen 3.51,50. 10.,150. 114.,150. 114.,50. r 1.1,1.5 i=6,26 j=27,30
*

```

```

*--- Change some of the aspect ratios ...
gen r 1.05,1. i=14,26 j=27
gen r 1.,1. i=20,26 j=27
*
*--- "Stretching" below the room ...
*
gen 0.,-150. 0.,-50. 3.51,-50. 10.,-150. r 1.,.67 i=1,6 j=4,7
gen 10.,-150. 3.51,-50. 114.,-50. 114.,-150. r 1.1,.67 i=6,26 j=4,7
*
*--- Change some of the aspect ratios ...
gen r 1.05,1. i=14,26 j=7
gen r 1.,1. i=20,26 j=7
*--- Construct room by individual nodal adjustments ...
*   (First row of nodal points ...)
ini x=0. y=3.96 i=1 j=19
ini x=.85 y=3.772 i=2 j=19
ini x=1.63 y=3.6 i=3 j=19
ini x=2.323 y=3.01 i=4 j=19
ini x=2.948 y=2.478 i=5 j=19
*   (Second row of nodal points ...)
ini x=0. y=4.4 i=1 j=20
ini x=.90 y=4.20 i=2 j=20
ini x=1.70 y=4.0 i=3 j=20
ini x=2.40 y=3.40 i=4 j=20
ini x=3.05 y=2.90 i=5 j=20
ini x=3.70 y=2.40 i=6 j=20
*   (Improve refinement ...)
ini x=4.18 y=2.46 i=7 j=20
ini x=5.19 y=2.57 i=8 j=20
ini x=6.71 y=2.74 i=9 j=20
ini x=8.98 y=3.01 i=10 j=20
*   (Third row of nodal points ...)
ini x=0.00 y=5.40 i=1 j=21
ini x=1.00 y=5.20 i=2 j=21
ini x=1.80 y=5.00 i=3 j=21
ini x=2.50 y=4.40 i=4 j=21
ini x=3.15 y=3.90 i=5 j=21
ini x=3.80 y=3.40 i=6 j=21
*   (Improve refinement ...)
ini x=4.18 y=3.49 i=7 j=21
ini x=5.19 y=3.72 i=8 j=21
ini x=6.71 y=4.06 i=9 j=21
ini x=8.98 y=4.58 i=10 j=21
*   (Forth row of nodal points ...)

```

```

ini x=0.00 y=7.4 i=1 j=22
ini x=1.00 y=7.20 i=2 j=22
ini x=1.80 y=7.00 i=3 j=22
ini x=2.50 y=6.40 i=4 j=22
ini x=3.15 y=5.90 i=5 j=22
ini x=3.80 y=5.40 i=6 j=22
*   (Improve refinement ...)
ini x=4.18 y=5.52 i=7 j=22
ini x=5.19 y=5.83 i=8 j=22
ini x=6.71 y=6.31 i=9 j=22
ini x=8.98 y=7.02 i=10 j=22
*   (Fifth row of nodal points ...)
ini x=1.00 y=11.70 i=2 j=23
ini x=1.80 y=11.50 i=3 j=23
ini x=2.50 y=10.90 i=4 j=23
ini x=3.15 y=10.40 i=5 j=23
ini x=3.90 y=9.90 i=6 j=23
*   (Improve refinement ...)
ini x=4.18 y=9.97 i=7 j=23
ini x=5.19 y=10.21 i=8 j=23
ini x=6.71 y=10.57 i=9 j=23
ini x=8.98 y=11.10 i=10 j=23
*
*--- ASSIGN MATERIAL PROPERTIES (REF: SCP-CDR CHAP. 2, SEC. 2.3.1)
*--- USING THE JOINT PROPERTIES AND "ROCK MASS" PROPERTIES.
*--- ALSO USING THE MOST RECENT RESULTS FROM DATA ANALYSIS,
*--- TABLES 2-4, 2-6, AND 2-7.
*--- THE ROCK IS CHARACTERIZED AS AN ELASTIC/PLASTIC MATERIAL
*--- WITH UBIQUITOUS JOINTS. A MOHR-COULOMB FAILURE CRITERION
*--- IS USED FOR BOTH THE INTACT ROCK AND THE JOINTS ...
*
*--- Rock Mass:
PROP SHEAR=6.23E3 BULK=9.05E3 COH=17.8 ; (MPa)
PROP DENS=2320. ; (kg/m^3)
PROP FRIC=23.5 ; (degrees)
*
*--- Rock Joints:
PROP JCOH=0.1 ; (MPa)
PROP JFRIC=28.4 JANG=90. ; (degrees)
*
*--- THERMAL PROPERTIES OF THE ROCK ...
*   (Ref: SCP-CDR Chap. 2, Sec. 2.3.1.9, Table 2-9)
PROP CON=2.29 ; (W/mK)
PROP SPE=931. ; (J/kgK)
PROP THEX=8.8E-6 ; (1/K)
*
```



```

*--- 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. Note that the null zones
*   previously introduced affects the specified range of J,
*   thus, using 4 to 30 instead of 1 to 33.)
*
FIX Y I=1,26 J=4
FIX X I=1 J=4,30
FIX X I=26 J=4,30
*
*--- 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 x SYY.)
INI SXX=-3.5 ;(MPa)
INI SYY=-7.0 ;(MPa)
APPLY PRES=7.0 I=1,26 J=30 ;(MPa)
*
*--- SET THE INITIAL TEMPERATURE TO 26 DEG. CELSIUS ...
INI TEMP=26. ;(Degree Celsius)
*
*--- SET THERMAL BOUNDARY CONDITIONS ...
*--- THE BOUNDARIES ARE BY DEFAULT ADIABATIC (thermally insulated)
*
*--- SET THE CRITERIA FOR AUTOMATIC TERMINATION OF EXECUTION ...
SET F=1E-2 ;Out-of-balance force (Mega Newton)
SET CLOCK=120 ;Maximum execution time (minutes)
SET STEP=5000 ;Maximum number of time steps
*
*--- EXCAVATE THE DISPOSAL ROOM (save results) ...
MOD NULL I=1,5 J=15,18
TIT
    Time is After Initial Excavation, Horiz. Empl. (NRC-F)
SOLVE
SAVE NRCH_M0.SAV
*

```

```

*--- THERMAL PROPERTIES OF THE DISPOSAL ROOM FROM 0 TO 50 YEARS.
*   (The maximum thermal time step in FLAC is determined from
*   the element size and associated thermal diffusivity. Using
*   air in the disposal room with an "equivalent" conductivity
*   results in a maximum time step of insufficient length to
*   complete the analysis within a reasonable time period.
*   Therefore, the room is given thermal properties of TSw2 tuff,
*   but with the thermal conductivity increased about 22 times
*   to 50 W/mK. The size of the room elements are also increased.
*
*--- CHANGE THE ELEMENT SIZES IN THE ROOM SO THAT AS LARGE A TIME STEP
*--- AS POSSIBLE MAY BE USED ...
*   (This is done by restoring a thermal region in the room, and
*   surrounding it by null zones, and then "stretching" the thermal
*   region to fit the entire room.)
*
THMOD ISO I=2,3 J=17
*
*--- Fit the restored thermal region to the entire room ...
*
ini x=0.00 y=0.00 i=2 j=17
ini x=0.00 y=3.96 i=2 j=18
ini x=1.629 y=0.00 i=3 j=17
ini x=1.630 y=3.60 i=3 j=18
ini x=3.51 y=0.00 i=4 j=17
ini x=3.51 y=2.00 i=4 j=18
*
*--- Assign thermal properties to the restored thermal region ...
*
PROP CON=50. I=2,3 J=17 ; (W/mK)
PROP SPE=931. I=2,3 J=17 ; (J/kgK)
PROP DENS=2320. I=2,3 J=17 ; (kg/m^3)
PROP THEX=0. I=2,3 J=17 ; (1/K)
*
*--- DEFINE INTERFACES BETWEEN THE THERMAL REGION AND THE
*--- DISPOSAL ROOM SURFACE ...
*
INTER 1 ASIDE 1,15 2,15 3,15 4,15 5,15 6,15 6,16 6,17 6,18 6,19
INTER 1 ASIDE 5,19 4,19 3,19 2,19 1,19
INTER 1 BSIDE 2,18 3,18 4,18 4,17 3,17 2,17
*

```

```

*--- Assign properties to the interfaces ...
*   (Make sure the stiffness and strength properties are
*   small so that no interaction with the mechanical behavior
*   of the room occurs.)
*
INTER 1 KS=1.E-6 KN=1.E-6 TB=0. COH=0. FRIC=0. UNGLUED
*
*--- 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 792 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 ...
*
THAPP FLUX 16.6 -2.46E-10 I=17,26 J=17 ;(SPENT FUEL FIRST TERM)
THAPP FLUX 13.5 -1.72E-9 I=17,26 J=17 ;(SPENT FUEL SECOND TERM)
THAPP FLUX 2.5 -6.43E-10 I=15,23 J=17 ;(DHLW FIRST TERM)
THAPP FLUX 0.4 -1.45E-9 I=15,23 J=17 ;(DHLW SECOND TERM)
*
*--- DEFINE NODAL POINTS FOR WHICH TEMP. HISTORIES ARE RECORDED ...
*
THIS NSTEP=10 ;Record results every 10 time steps ...
THIS TEMP I=1 J=15 ;Location at the floor center ...
THIS TEMP I=6 J=17 ;Location at the rib center ...
THIS TEMP I=1 J=19 ;Location at the crown center ...
THIS TEMP I=20 J=17 ;Location at the borehole center ...
*
*--- START THE HEAT TRANSFER SOLUTION USING THE EXPLICIT SCHEME ...
THSOLVE CLOCK=6.e3 TEMP=5.E2 STEP=100000 AGE=7
*
SET THDT=14400. ; Time step of 4 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=30 IMPLICIT ; 1 month
*
SET THDT=28800. ; Time step of 8 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=60 IMPLICIT ; 2 months
*
SET THDT=43200. ; Time step of 12 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=365 IMPLICIT ; 1 year
TIT
    Predicted temperatures after 1 year, Horiz. Empl. (NRC-F)
SAVE NRCH_T1.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 1 YEAR OF HEATING ...

SOLVE

TIT

Predicted T/M response after 1 year. Horiz. Empl. (NRC-F)

SAVE NRCH_M1.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 2.5 YEARS ...

SET THDT=64800. ; Time step of 18 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=912.5 IMPLICIT ; 2.5 years

TIT

Predicted temperatures after 2.5 years, Horiz. Empl. (NRC-F)

SAVE NRCH_T2.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 2.5 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 2.5 years. Horiz. Empl. (NRC-F)

SAVE NRCH_M2.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 5 YEARS ...

SET THDT=86400. ; Time step of 24 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=1825 IMPLICIT ; 5 years

TIT

Predicted temperatures after 5 years, Horiz. Empl. (NRC-F)

SAVE NRCH_T5.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 5 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 5 years. Horiz. Empl. (NRC-F)

SAVE NRCH_M5.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 7.5 YEARS ...

SET THDT=86400. ; Time step of 24 hrs.

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=2737.5 IMPLICIT ; 7.5 years

TIT

Predicted temperatures after 7.5 years, Horiz. Empl. (NRC-F)

SAVE NRCH_T7.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 7.5 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 7.5 years. Horiz. Empl. (NRC-F)

SAVE NRCH_M7.SAV

*

```

*--- CONTINUE HEAT TRANSFER SOLUTION TO 10 YEARS ...
SET THDT=86400. ; Time step of 24 hrs.
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=3650 IMPLICIT ; 10 years
TIT
    Predicted temperatures after 10 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T10.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 10 YEARS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 10 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M10.SAV
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 15 YEARS ...
SET THDT=172800. ; Time step of 2 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=5475 IMPLICIT ; 15 years
TIT
    Predicted temperatures after 15 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T15.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 15 YEARS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 15 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M15.SAV
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 20 YEARS ...
SET THDT=259200. ; Time step of 3 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=7300 IMPLICIT ; 20 years
TIT
    Predicted temperatures after 20 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T20.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 20 YEARS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 20 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M20.SAV
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 25 YEARS ...
SET THDT=258200. ; Time step of 3 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=9125 IMPLICIT ; 25 years
TIT
    Predicted temperatures after 25 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T25.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 25 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 25 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M25.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 30 YEARS ...

SET THDT=345600. ; Time step of 4 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=10950 IMPLICIT ; 30 years

TIT

Predicted temperatures after 30 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T30.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 30 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 30 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M30.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 35 YEARS ...

SET THDT=345600. ; Time step of 4 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=12775 IMPLICIT ; 35 years

TIT

Predicted temperatures after 35 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T35.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 35 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 35 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M35.SAV

*

*--- CONTINUE HEAT TRANSFER SOLUTION TO 40 YEARS ...

SET THDT=345600. ; Time step of 4 days ...

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=14600 IMPLICIT ; 40 years

TIT

Predicted temperatures after 40 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T40.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 40 YEARS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 40 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M40.SAV

*

```
*--- CONTINUE HEAT TRANSFER SOLUTION TO 45 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=16425 IMPLICIT ; 45 years
TIT
    Predicted temperatures after 45 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T45.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 45 YEARS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 45 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M45.SAV
*
*--- CONTINUE HEAT TRANSFER SOLUTION TO 50 YEARS ...
SET THDT=345600. ; Time step of 4 days ...
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18250 IMPLICIT ; 50 years
TIT
    Predicted temperatures after 50 years, Horiz. Empl. (NRC-F)
SAVE NRCH_T50.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YEARS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 years. Horiz. Empl. (NRC-F)
SAVE NRCH_M50.SAV
*
```

```

*****
*
*   S T A R T   C O N V E C T I V E   C O O L I N G   T O
*
*   P R E P A R E   F O R   W A S T E   R E T R I E V A L
*
*   ( V E N T I L A T I O N   A I R   T E M P   O F   2 0 ° C )
*
*****
*
*--- APPLY THE CONVECTIVE HEAT TRANSFER COEFFICIENT (h=2.78 W/mmK)
*--- TO THE ROOM PERIPHERY, AND ASSIGN THE TEMPERATURE OF THE COOLING
*--- AIR (20 degrees C) AT THE TIME OF WASTE RETRIEVAL (50 YEARS) ...
*
THMOD NULL I=2,3 J=17
THAPP CONV 2.78 20. I=1,6 J=15
THAPP CONV 2.78 20. I=6 J=15,19
THAPP CONV 2.78 20. I=1,6 J=19
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18255
TIT
    Predicted temperatures after 50 yrs & 5 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T51.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 5 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 5 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M51.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18260
TIT
    Predicted temperatures after 50 yrs & 10 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T52.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 10 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 10 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M52.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18270
TIT
    Predicted temperatures after 50 yrs & 20 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T53.SAV
*

```


*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 20 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 20 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M53.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18290

TIT

Predicted temperatures after 50 yrs & 40 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T54.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 40 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 40 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M54.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18310

TIT

Predicted temperatures after 50 yrs & 60 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T55.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 60 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 60 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M55.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18330

TIT

Predicted temperatures after 50 yrs & 80 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T56.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 80 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 80 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M56.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18350

TIT

Predicted temperatures after 50 yrs & 100 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T57.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 100 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 100 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M57.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18370

TIT

Predicted temperatures after 50 yrs & 120 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_T58.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 120 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 120 ds. Horiz. Empl. (NRC-F)
SAVE NRCH_M58.SAV

*

*

```

*****
*
*   S T A R T   C O N V E C T I V E   C O O L I N G   T O
*
*   P R E P A R E   F O R   W A S T E   R E T R I E V A L
*
*   ( V E N T I L A T I O N   A I R   T E M P   O F   10 °C)
*
*****
*
RES NRCH_M50.SAV
*
*--- APPLY THE CONVECTIVE HEAT TRANSFER COEFFICIENT (h=2.88 W/mmK)
*--- TO THE ROOM PERIPHERY, AND ASSIGN THE TEMPERATURE OF THE COOLING
*--- AIR (10 degrees C) AT THE TIME OF WASTE RETRIEVAL (50 YEARS) ...
*--- Note that the convective heat transfer coefficient is different
*--- for different air temperatures and different room geometries ...
*
THMOD NULL I=2,3 J=17
THAPP CONV 2.88 10. I=1,6 J=15
THAPP CONV 2.88 10. I=6 J=15,19
THAPP CONV 2.88 10. I=1,6 J=19
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18255
TIT
    Predicted temperatures after 50 yrs & 5 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_T61.SAV
*
*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 5 DAYS OF HEATING ...
SOLVE
TIT
    Predicted T/M response after 50 yrs 5 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_M61.SAV
*
THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18260
TIT
    Predicted temperatures after 50 yrs & 10 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_T62.SAV
*

```

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 10 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 10 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_M62.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18270

TIT

Predicted temperatures after 50 yrs & 20 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_T63.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 20 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 20 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_M63.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18290

TIT

Predicted temperatures after 50 yrs & 40 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_T64.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 40 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 40 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_M64.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18310

TIT

Predicted temperatures after 50 yrs & 60 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_T65.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 60 DAYS OF HEATING ...

SOLVE

TIT

Predicted T/M response after 50 yrs 60 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_M65.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18330

TIT

Predicted temperatures after 50 yrs & 80 ds. 10°C Horiz. Empl. (NRC-F)

SAVE NRCH_T66.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 80 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 80 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_M66.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18350

TIT

Predicted temperatures after 50 yrs & 100 ds. 10' Horiz. Empl. (NRC-F)
SAVE NRCH_T67.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 100 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 100 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_M67.SAV

*

THSOLVE CLOCK=6.E3 TEMP=5.E2 STEP=100000 AGE=18370

TIT

Predicted temperatures after 50 yrs & 120 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_T68.SAV

*

*--- PREDICT THE MECHANICAL RESPONSE OF 50 YRS & 120 DAYS OF HEATING ...
SOLVE

TIT

Predicted T/M response after 50 yrs 120 ds. 10°C Horiz. Empl. (NRC-F)
SAVE NRCH_M68.SAV

NRC FORM 335 (8-87) NRCM 1102, 3201, 3202 BIBLIOGRAPHIC DATA SHEET SEE INSTRUCTIONS ON THE REVERSE		U.S. NUCLEAR REGULATORY COMMISSION 1. REPORT NUMBER (Assigned by PPMB: DPS, add Vol. No., if any) NUREG/CR-5335					
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13. ABSTRACT (200 words or less) <p>This report presents the results of a numerical analysis to determine the stability of waste disposal rooms for vertical and horizontal emplacement during the period of waste retrieval. It is assumed that waste retrieval starts 50 years after the initial emplacement of the waste, and that access to and retrieval of the waste containers take place through the disposal rooms. It is further assumed that the disposal rooms are not backfilled. Convective cooling of the disposal rooms in preparation for waste retrieval is included in the analysis. Conditions and parameters used were taken from the Nevada Nuclear Waste Storage Investigation (NNWSI) Project Site Characterization Plan Conceptual Design Report (MacDougall et al., 1987).</p> <p>Thermal results are presented which illustrate the heat transfer response of the rock adjacent to the disposal rooms. Mechanical results are presented which illustrate the predicted distribution of stress, joint slip and room deformations for the period of time investigated.</p> <p>Under the assumption that the host rock can be classified as "fair to good" using the Geomechanics Classification system (Bieniawski, 1974), only light ground support would appear to be necessary for the disposal rooms to remain stable.</p>							
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