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Variation of Heat Loading for a Repository at Yucca Mountain

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ABSTRACT

This report presents the results of numerical analyses to determine the range in container pitch (i.e., the spacing between vertically emplaced containers), disposal room extraction ratio, and waste stand-off distance that will satisfy design criteria expressed for a repository at Yucca Mountain. Effects are investigated for a range in thermal properties of the rock represented by the "saturated" and "dry" conditions expressed in Chapter 2 of the SCPCDR. A number of heat transfer analyses were performed for a time period of 50 years after initial waste emplacement. Within this period, temperatures have peaked in the vicinity of the waste containers. The analyses included three-dimensional heat transfer models that account for the explicit interaction of single waste containers emplaced in a repository panel. Vertical and horizontal waste emplacement concepts of commingled SF and DHLW were investigated.

The analyses indicate that the configuration of container boreholes and extraction ratio, as well as the stand-off distance to waste proposed in the SCPCDR, Chapter 4, could result in the development of temperatures that exceed design goals currently expressed in the SCP and the SCPCDR.

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1.0 INTRODUCTION

This report addresses the subject of varying the initial thermal loading in a nuclear waste repository and its consequence for current design criteria. The report also outlines a configuration range of waste disposal rooms and container boreholes that would meet current repository design criteria as expressed in the Site Characterization Plan Conceptual Design Report (SCPCDR) (MacDougall et al., 1987).

1.1 Background

Much of the concern and study regarding the geologic disposal of nuclear waste is associated with the behavior of the host rock when subjected to heat released from the waste. Federal Regulations that deal specifically with such concerns and are related to the design of a repository have been issued by the U.S. Nuclear Regulatory Commission (NRC) in 10 CFR Part 60.

Although the rate of heat generation by the nuclear waste [spent fuel (SF) and defense high level waste (DHLW) are considered] decreases continuously with time, heat from the waste will be generated for thousands of years after initially being emplaced in a repository. Temperatures throughout the repository and host rock environment will increase and reach a maximum at various times. High temperatures may contribute to degrading the waste isolation capabilities of the waste package and the host rock. Sustained, high temperatures could cause changes to the porewater chemistry and result in an increase in the corrosion rate of the waste containers. High temperatures and thermal gradients can induce fractures in the rock as well as initiating movement along pre-existing fractures. This behavior could modify the structural integrity of the host rock and also result in an increased fracture permeability in case of potential flow. Therefore, the ability of a geologic site to permanently isolate the waste is strongly affected by the amount of heat being released into the host rock. The thermal loading capacity is probably the single most important parameter to determine for a repository.

The candidate repository site is located at Yucca Mountain, Nevada, where the proposed repository horizon is a densely welded tuff. The site is being evaluated by the Yucca Mountain Project (YMP) as potentially the first geologic repository for high level waste in the United States. The importance of limiting the temperature rise of the host rock is recognized by the YMP, and reflected in several repository design criteria which have been formulated into "design goals". These design goals are discussed in the SCPCDR, and are based on considerations of limiting the degradation of the waste isolation capability of the container and host rock, to preserve the option for waste retrieval if such retrieval should become necessary, and to limit impact on the surface environment.

Design goals associated with the repository thermal loading are as follows.

1. Maximum borehole wall temperature of:

   (a) 275°C (refer to SCP, p. 6-35);

   (b) 235°C (refer to SCP, p. 6-193); and

   (c) 220°C (refer to SCPCDR, Appendix P, p. P-533).

2. Maximum temperature 1 m from borehole wall of 200°C (refer to SCP, p. 6-35).

3. For vertical emplacement, maximum temperature of 50°C in access drifts after 50 years (refer to SCPCDR, Section 2.4.4.3).

4. For horizontal emplacement, maximum temperature of 50°C in disposal rooms after 50 years (refer to SCPCDR, Section 2.4.4.3).

5. Maximum waste temperature of 350°C (refer to SCP, p. 8.3.2.5-17).

6. Maximum ground surface temperature rise of less than 6°C (refer to SCP, p. 8.3.2.2-17).

7. Maximum temperature of the Calico Hills thermomechanical unit of 115°C (refer to SCP, p. 8.3.2.2-17).

8. Maximum temperature of the Vitrophyre thermomechanical unit 115°C (refer to SCP, p. 8.3.2.2-17).

Of these criteria, only the first four are investigated in this study. Note that three temperature criteria can be found in the SCP and the SCPCDR for the maximum temperature at the borehole wall.

1.2 Thermal Loading

The thermal loading of a repository [also called areal power density (APD)] is the amount of power emitted by the nuclear waste stored in the repository, divided by the plan area occupied by the repository. It is expressed in W/m^2 or kW/acre. The repository plan area includes non-waste emplacement areas such as access drifts, service shops, and support facilities. The thermal loading, therefore, will be different if the scale of the plan area changes. An example would be to consider only the area within an emplacement panel or part of an emplacement panel. The design criteria investigated are with respect to the locations of the waste containers and the close vicinity of the containers. Therefore, the thermal loading is expressed in terms of a plan area represented by part of an emplacement panel.

1.3 Objective

The objective of this report is to provide an estimate of the range of the combined parameters of container pitch, extraction ratio, and waste stand-off distance that will satisfy design criteria expressed for a repository at Yucca Mountain.

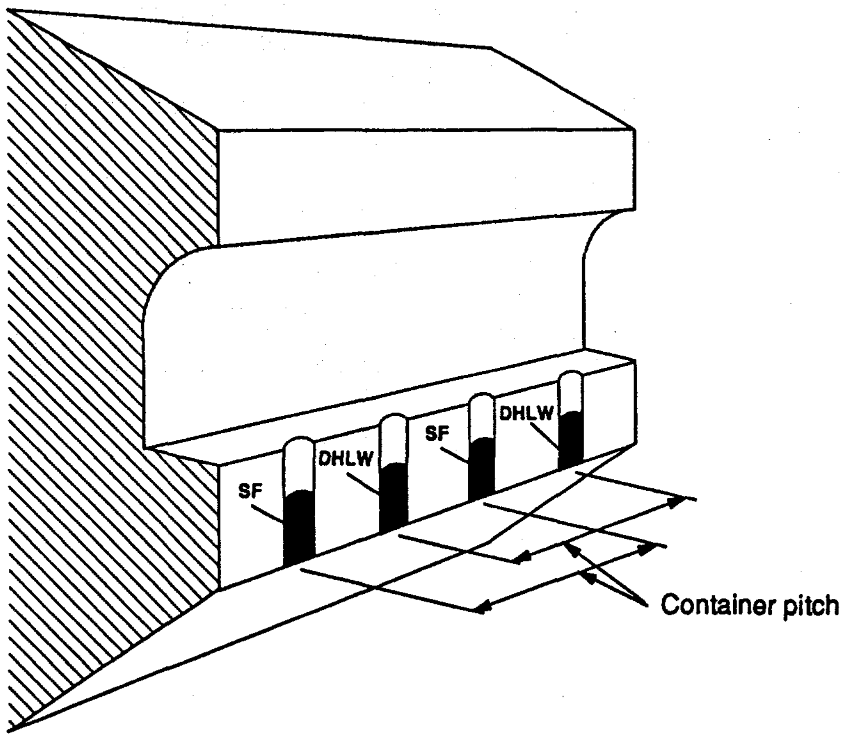
1.4 Scope

The variation of heat load was investigated in this study by a combination of changes to the container pitch (i.e., the spacing between vertically emplaced containers) and disposal room extraction ratio (refer to Fig. 1), and changes to the stand-off distance from the waste location to the emplacement room (for horizontal emplacement only). Effects were investigated for a range in thermal properties of the rock represented by the "saturated" and "dry" conditions expressed in Chapter 2 of the SCPCDR. The evaluation of these effects required that a number of heat transfer analyses be performed. These analyses included three-dimensional heat transfer models that account for the explicit interaction of single waste containers emplaced in a repository panel.

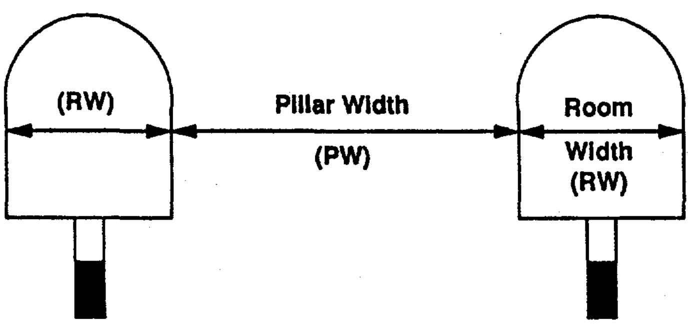
The present study included both vertical and horizontal waste emplacement concepts of commingled SF and DHLW as described in the SCPCDR, Chapter 4. This means that single waste containers are placed in a row of vertical boreholes along the disposal room floor, or that multiple waste containers are placed in a row of long horizontal boreholes perpendicular to the room walls. The effect of heat transfer in the host rock was investigated for a maximum time period of 50 years. Within this period, temperatures have peaked in the vicinity of the waste containers.

The analyses indicate that the configuration of container boreholes and extraction ratio, as well as the stand-off distance to waste proposed in the SCPCDR, Chapter 4, could result in the development of temperatures that exceed design goals currently expressed in the SCP and the SCPCDR.

a) Container Pitch "P"



b) Extraction Ratio "ER"



$$ER = \frac{RW}{RW + PW} \times 100\%$$

Fig. 1 Illustration of Container Pitch and Extraction Ratio

2.0 APPROACH

2.1 Numerical Model

The semi-analytical model STRES3D (St.John and Christianson, 1980) has been used to simulate the three-dimensional heat transfer effects in the container/borehole vicinity. The model allows for the evaluation of transient temperatures and thermally induced stresses by superposition of analytical solutions to constant and/or exponentially-decaying point heat sources in an infinite or semi-infinite medium. The presence of a single, planar, traction free surface, such as the ground surface above a repository, may be included in the analysis. However, boreholes and arbitrary shaped excavations cannot be explicitly incorporated in the model. The material modeled is assumed to be elastic, isotropic, and homogeneous. Note that in this study STRES3D is used to evaluate temperatures only.

2.2 Assumptions and Idealizations

The effective use of STRES3D to predict the transient temperatures in the container/borehole vicinity requires a number of idealizations and simplifying assumptions regarding the presence of disposal rooms and boreholes, sequence and timing of waste emplacement, and the physical state of the rock mass.

The assumptions and idealizations made in this study, and their effects on calculated rock mass response, are as follow:

- 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. The reason for this is that more energy (in the form of heat generating waste) is immediately available to elevate the rock temperature.

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

  Selecting a disposal room cross-section or container/borehole location close to the center of a waste panel ensures that maximum temperatures will be predicted with minimum effect from the stand-off distance between emplacement panels. 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. (Refer to Fig. 2, and Appendix A for the calculation).

- Boiling of porewater is not included.

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

- Repository ventilation is not included.

  Ventilation of access drifts or disposal rooms during the preclosure period of the repository will remove heat from the repository and, therefore, result in lower rock temperatures than if the repository is unventilated.

- Access drifts, disposal rooms, and boreholes are considered to be back-filled.

  There are no provisions in STRES3D to include multiple material types, for example air and rock, to account for excavation of rooms or construction of boreholes. Thus, the mode of heat transfer in the rooms and boreholes remains identical to that of the rock, i.e., thermal conduction in a medium with rock properties as opposed to free convection and radiant heat transfer taking place in air-filled voids. The effect of this limitation, therefore, becomes that of the difference between conductive heat transfer and free convection and radiant heat transfer. These effects are not expected to be substantial regarding the predicted temperatures in this study.

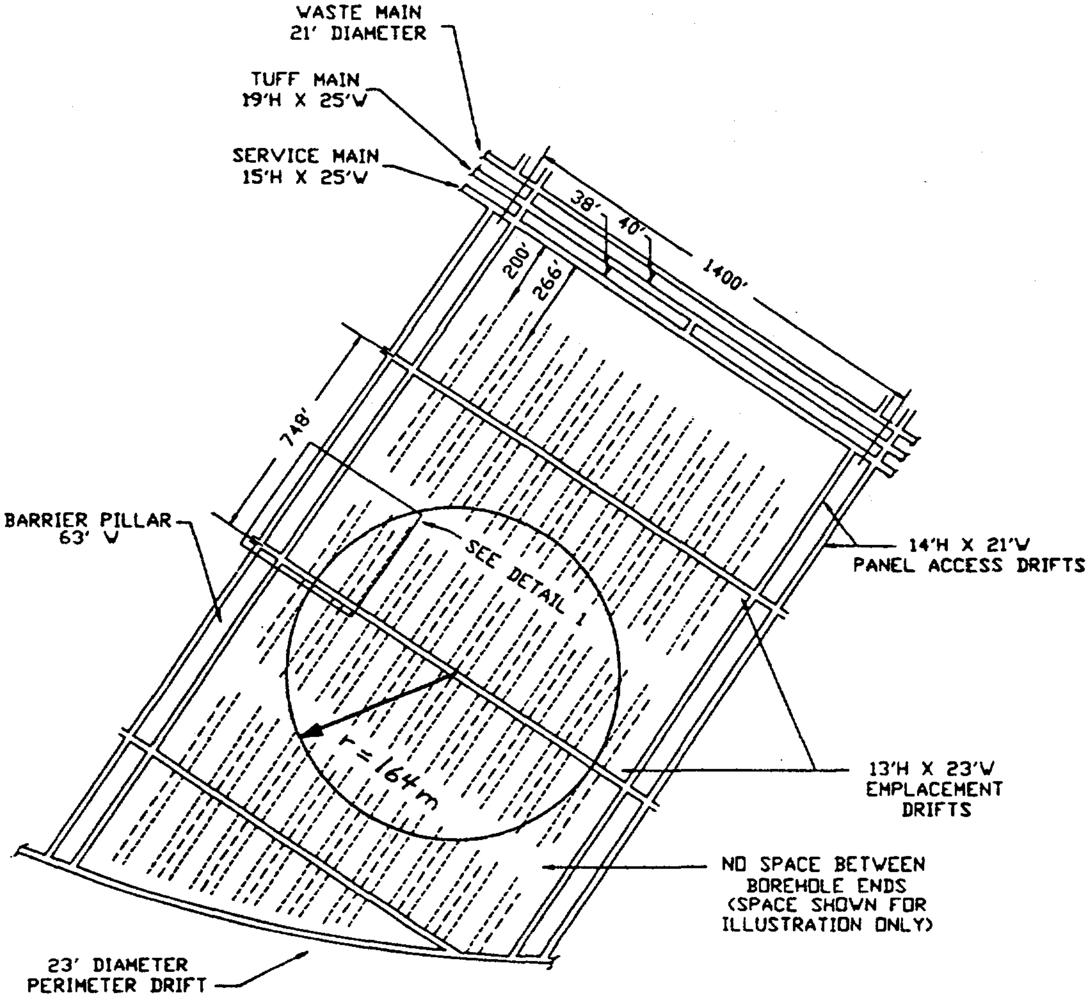


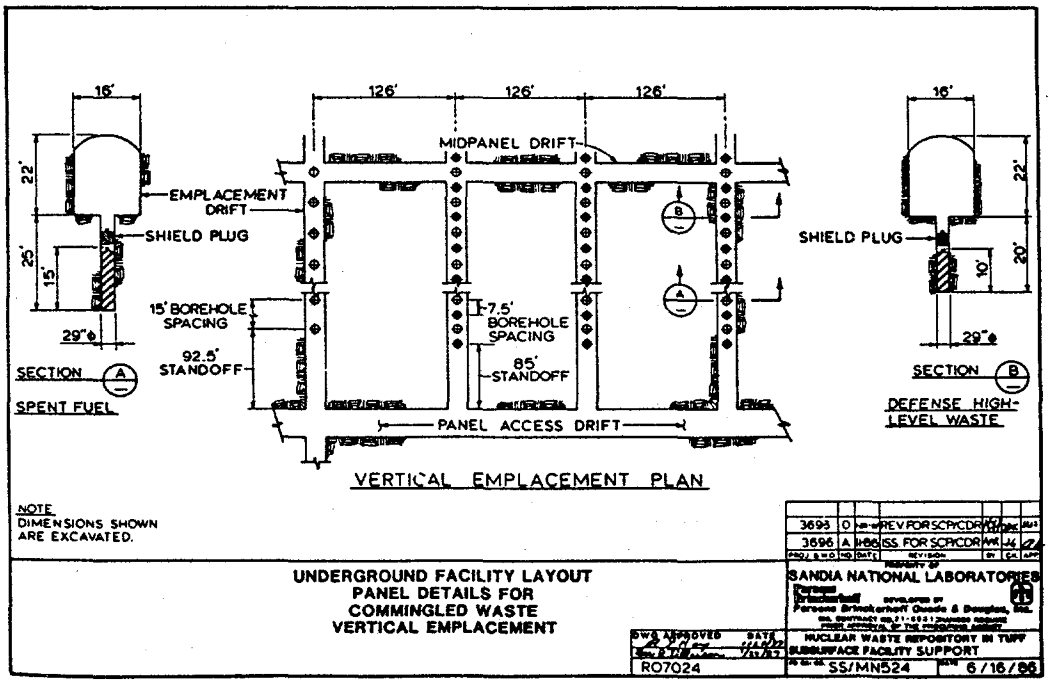
Fig. 2 Range of Thermal Influence at Waste Panel Center After 50 Years

2.3 Conceptual Considerations

Vertical or horizontal boreholes for waste emplacement are the alternatives considered in the SCPCDR for Yucca Mountain. Therefore, both these concepts are included in this study. Figures 3 and 4 illustrate the vertical and horizontal emplacement concepts, respectively.

Because a three-dimensional model is used, the explicit effect of individual containers can be evaluated. The containers can be represented by one or several heat sources. Using several heat sources provides a more accurate representation of the waste container, and is used where the temperatures are investigated in the close vicinity of the container borehole. Geometric details of the containers are of less importance to the prediction of temperatures at distances of several meters beyond the containers. Therefore, at these distances, waste containers can be represented by a single heat source without affecting the accuracy of the predictions. In these analyses, the SF and DHLW containers in the particular region of interest have been modeled with ten heat sources per container, while beyond this region the containers are each represented by one source. Figures 5, 6 and 7 illustrate the STRES3D conceptual model for the current design configurations of vertical and horizontal emplacement (SCPCDR, Chapter 4) and plan views of container locations for vertical and horizontal emplacement investigated with STRES3D.

Determination of the initial areal power density (APD) for the current design configuration is described in detail in Appendix B. Variations in the container pitch and extraction ratio will change the initial APD.



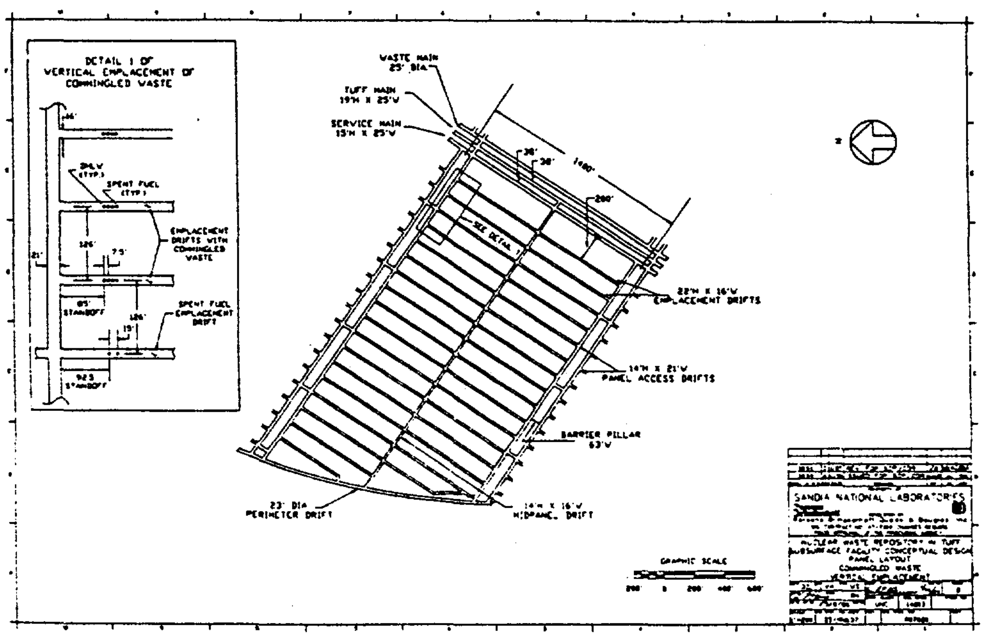


Fig. 3 Plan and Cross-Sectional Views of the Vertical Commingled SF and DHLW Emplacement Configuration [MacDougall et al., 1987, Chapter 4]

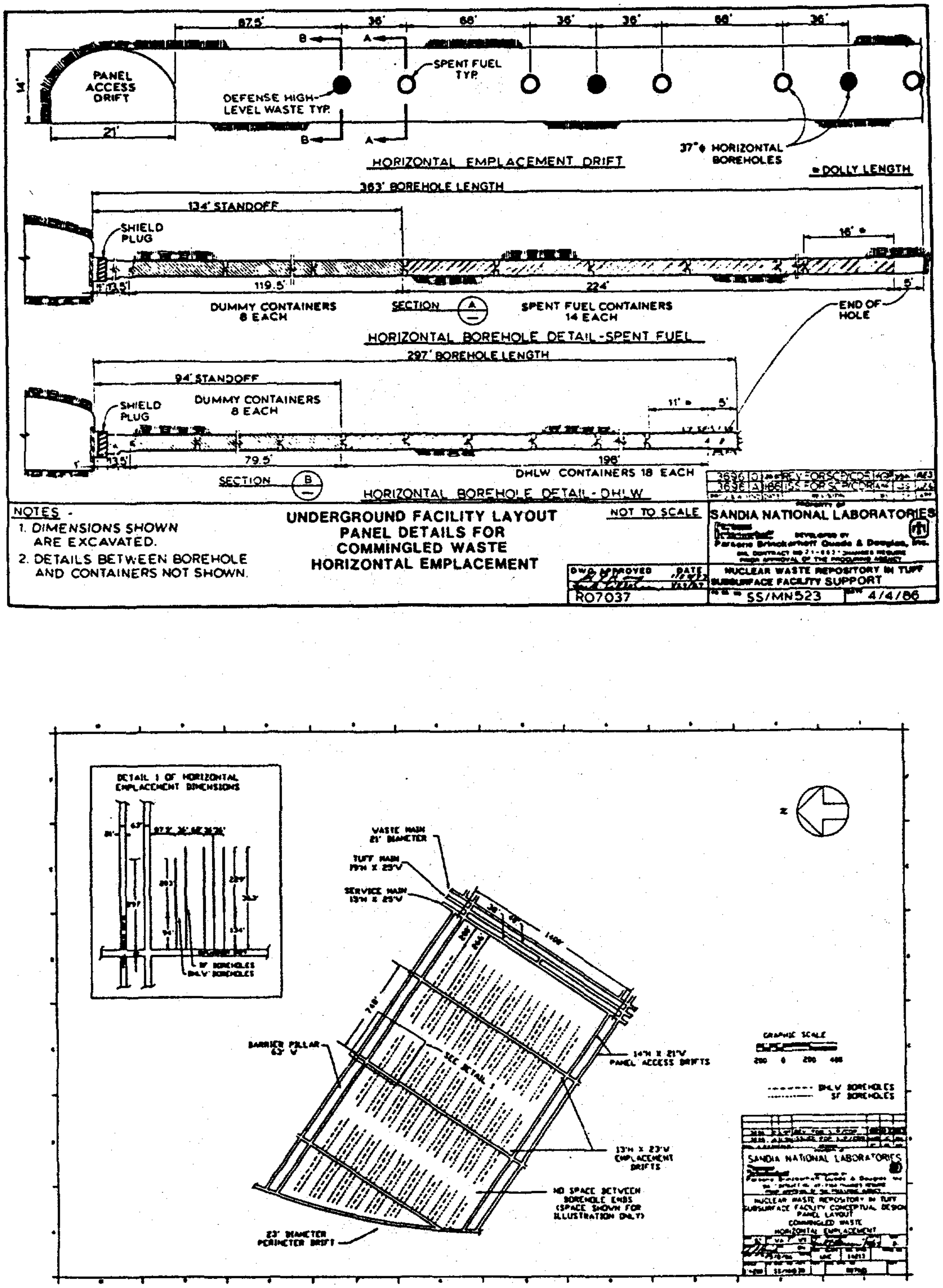


Fig. 4 Plan and Cross-Sectional Views of the Horizontal Commingled SF and DHLW Emplacement Configuration [MacDougall et al., 1987, Chapter 4]

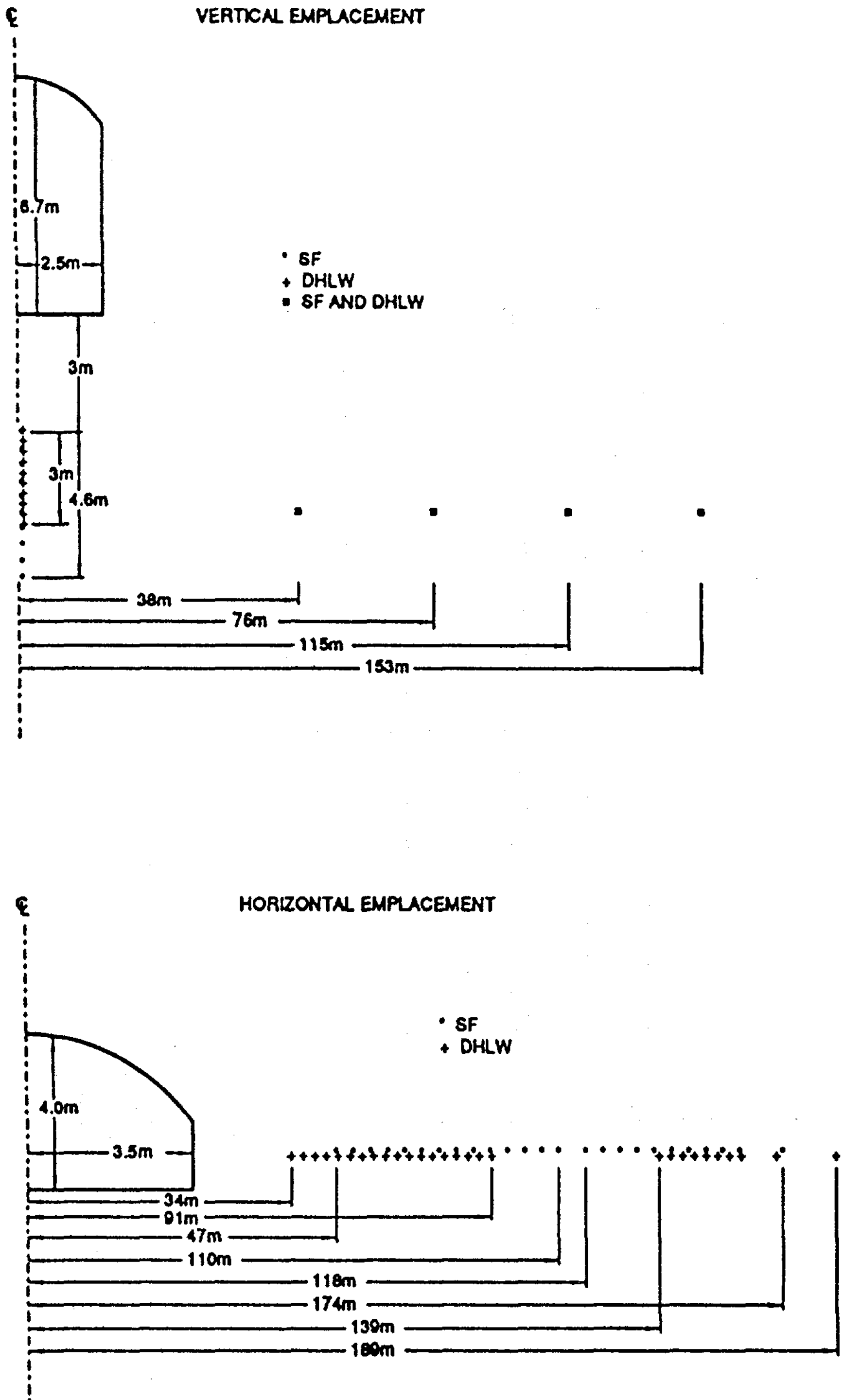


Fig. 5 Conceptual Models of Vertical and Horizontal Waste Emplacement (Note that rooms are not modeled.)

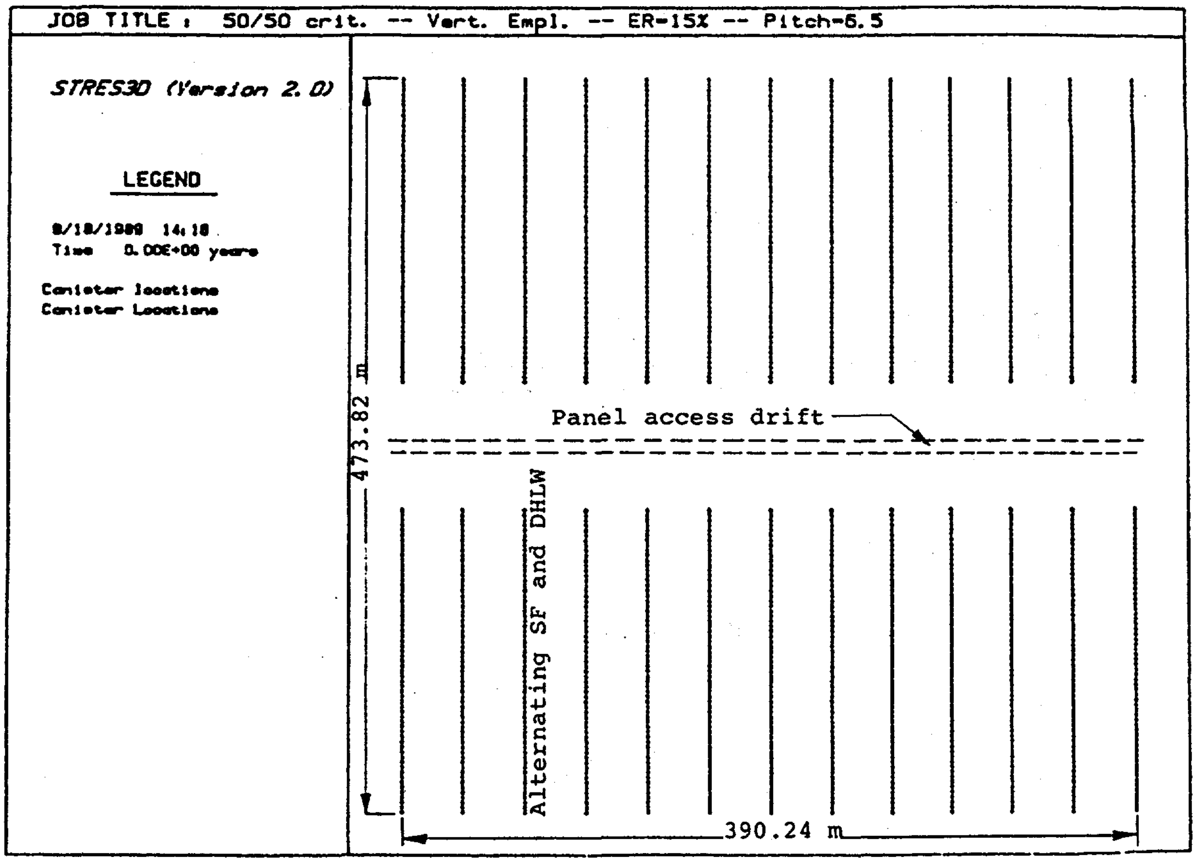


Fig. 6 Plan View of Point Heat Sources Simulating Vertical Emplacement of Commingled SF and DHLW

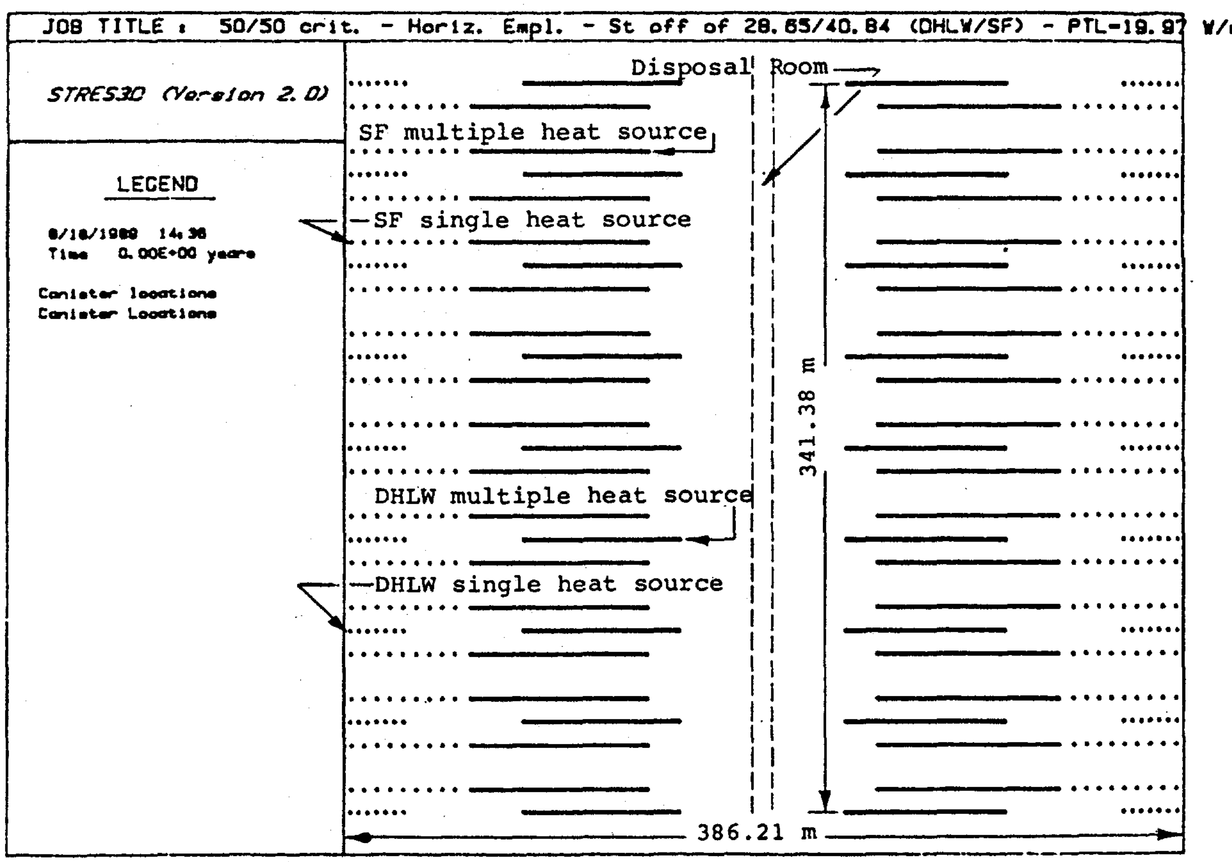


Fig. 7 Plan View of Point Heat Sources Simulating Vertical Emplacement of Commingled SF and DHLW

3.0 MODEL INPUT PARAMETERS

3.1 Material Properties

The material properties used in this study have been taken from the SCPCDR, Chapter 2, Tables 2-4 and 2-9, and are specific to the rock at the repository horizon (designated as thermal/mechanical unit TSw2). Properties for "saturated" and "dry" rock as listed in the SCPCDR are noted. Although porewater boiling is not considered in this study, using "saturated" and "dry" properties permits a partial evaluation of the effect of boiling on the predicted temperatures. (Of course, no account is taken of latent heat changes due to evaporation of porewater.) In addition, it allows for an evaluation of the effect of uncertainty in rock properties on the predicted temperatures, since the "saturated" thermal diffusivity (α) is about 21 percent higher than that calculated from the "dry" properties. Table 1 gives the property values used.

Table 1

ROCK PROPERTIES
(MacDougall et al., 1987)

PROPERTY	"SATURATED"	"DRY"
Thermal Conductivity, k (W/m-K)	2.29	1.88
Specific Heat Cap., C_p (J/kg-K)	931	935
Bulk Density, ρ (kg/m^3)	2320	2240
Thermal Diffusivity[1], α (m^2/year)	33.44	27.69

1) Determined as $\alpha = k/\rho C_p$

3.2 Waste Form Characteristics

The thermal loading in a repository will depend on the age (i.e., the thermal decay) of the waste, the type of waste being disposed of (SF and/or DHLW), and the initial power of the waste containers at time of emplacement. In this work commingled SF and

DHLW are considered for the emplacement configurations given in the SCPCDR, Chapter 4. The initial power of a SF container at the time of emplacement may range from 2.3 kW to 3.4 kW (O'Brien, 1985). The initial power was set conservatively to 3.2 kW in this study. The initial power of DHLW containers was chosen as 0.42 kW after Peters (1983).

The waste is assumed to have been in interim storage for ten years prior to emplacement in the repository. The thermal decay characteristics of the SF and DHLW are given by Peters (1983) for ten year old waste:

Spent Fuel $$P(t) = 0.54 \exp(\ln(0.5)t/89.3) + 0.44 \exp(\ln(0.5)t/12/8)$$

DHLW $$P(t) = 0.86 \exp(\ln(0.5)t/34.2) + 0.14 \exp(\ln(0.5)t/15.2)$$

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

t = time in years.

The normalized power as a function of time, described by the above expressions and that given by Mansure (1985) for SF, are shown in Fig. 8. The two approximations shown for SF are observed to be very similar.

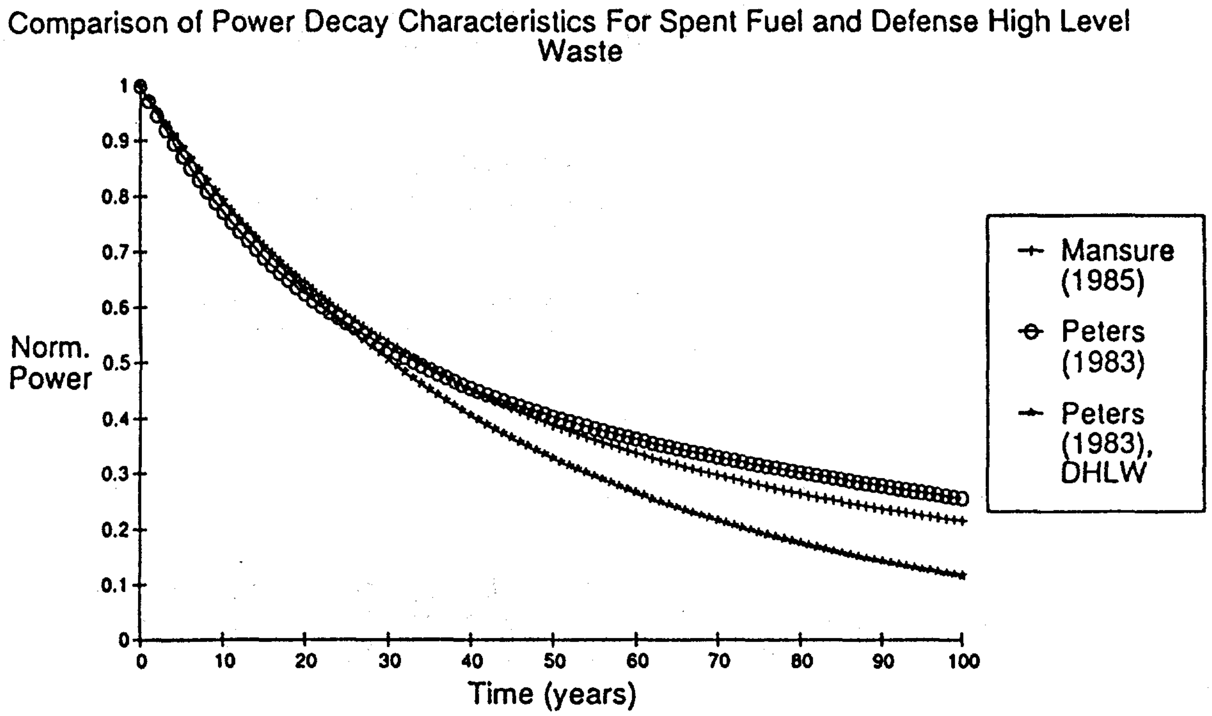


Fig. 8 Waste Form Power Decay

4.0 DISCUSSION OF RESULTS

The parameters varied in this study were container pitch, extraction ratio, waste stand-off distance, and rock properties. The extraction ratio and container pitch were investigated in the model for vertical emplacement, while the stand-off distance was only considered for horizontal emplacement. Rock properties used correspond to "saturated" and "dry" conditions. The effect of these variations on the predicted temperature at specific locations was investigated. The specific locations are the container borehole wall for SF containers, 1 m from the borehole wall, the midheight of access drift walls (i.e., access drifts for vertical emplacement), and the midheight of the disposal room walls for horizontal emplacement. A summary of the various cases evaluated, the temperatures predicted and the times of their maxima are listed in Appendix C.

Note that in these analyses the initial power was assumed to be 3200 W for all SF containers, and 420 W for all DHLW containers. Because of the much higher initial power of the SF container compared to the DHLW, temperatures in the package and in the vicinity of the borehole will be higher for the SF than for the DHLW. Therefore, the design goals evaluated in this study and applied to the vicinity of the container borehole are with respect to SF.

In the following discussion, the "50/50 design goal" refers to the criterion of limiting the temperature of access drifts for vertical emplacement, and the disposal rooms for horizontal emplacement to 50°C, 50 years after waste emplacement.

4.1 Vertical Emplacement

For design purposes, control of temperatures in and around the vertically emplaced waste can be accomplished by altering the spacing between the containers (i.e., the pitch), the spacing between disposal rooms (i.e., the extraction ratio), or a combination of the two. It is desirable to seek a combination of pitch and extraction ratio that results in temperatures which comply with design goals, and at the same time provides a configuration that requires a minimum amount of excavation.

4.1.1 Temperatures 1 m from the Borehole Wall

Figure 9 illustrates the relation between the container pitch and the maximum temperature 1 m from the borehole wall for a SF container for various choices of extraction ratio. The results are for saturated rock conditions. The design goal of 200°C suggested by the Yucca Mountain Project (YMP) for this location is indicated in the figure. Each symbol in the figure represents a separate numerical analysis. The curves fit to the symbols are polynomial functions. As seen, there are many combinations of extraction ratio and container pitch that satisfy the current YMP design goal. The single asterisk shown in the figure represents the current YMP design configuration. This configuration results in a maximum temperature well below the design goal. As the container pitch decreases and extraction ratio increases, temperatures will increase. Note, however, that the temperature in the rock 1 m from the borehole wall is hardly affected by increasing the extraction ratio from 5 to 10 percent.

Figure 10, which is a transformation of the previous figure, shows the relation between the container pitch, the extraction ratio and the thermal loading [designated as panel thermal loading (PTL) in the figure]. The dashed line represents the 200°C maximum temperature design goal for the location 1 m from the borehole wall. The shaded area in this figure indicates the combinations of container pitch and extraction ratio and the resulting thermal loading that will satisfy the YMP design goal. The figure also shows that only extraction ratios greater than 10 percent will affect the current design goal. The current YMP design configuration is represented by the asterisk in Fig. 10.

The effect of using "saturated" and "dry" thermal properties on the predicted maximum temperatures can be evaluated by comparing Figs. 9 and 11. For the same pitch and extraction ratio, predicted temperatures are higher when "dry" properties are used. The thermal diffusivity (defined in Table 1) for dry properties is lower than for saturated properties. Therefore, the rate of heat transfer is less for "dry" rock than for "saturated" rock. All other conditions being equal, this must result in higher temperatures.

If porewater boiling were to take place, energy would be expended in the boiling process as heat of vaporization, and thus be unavailable to increase the rock temperatures. However, within the portion of dehydrated rock (i.e., dry rock as a result of porewater boiling) the rate of heat transfer would be decreased, with the effect that heat would accumulate in the rock at a higher rate than for saturated conditions. If the rate of heat transfer is sufficiently low in the dehydrated rock, enough heat could accumulate to generate temperatures exceeding those predicted for saturated conditions. If it is not, temperatures would be lower than those predicted for saturated conditions. This scenario does not account for the heat transfer associated with the complex phenomenon of vapor transport. However, under no circumstance would temperatures exceed those predicted for dry conditions.

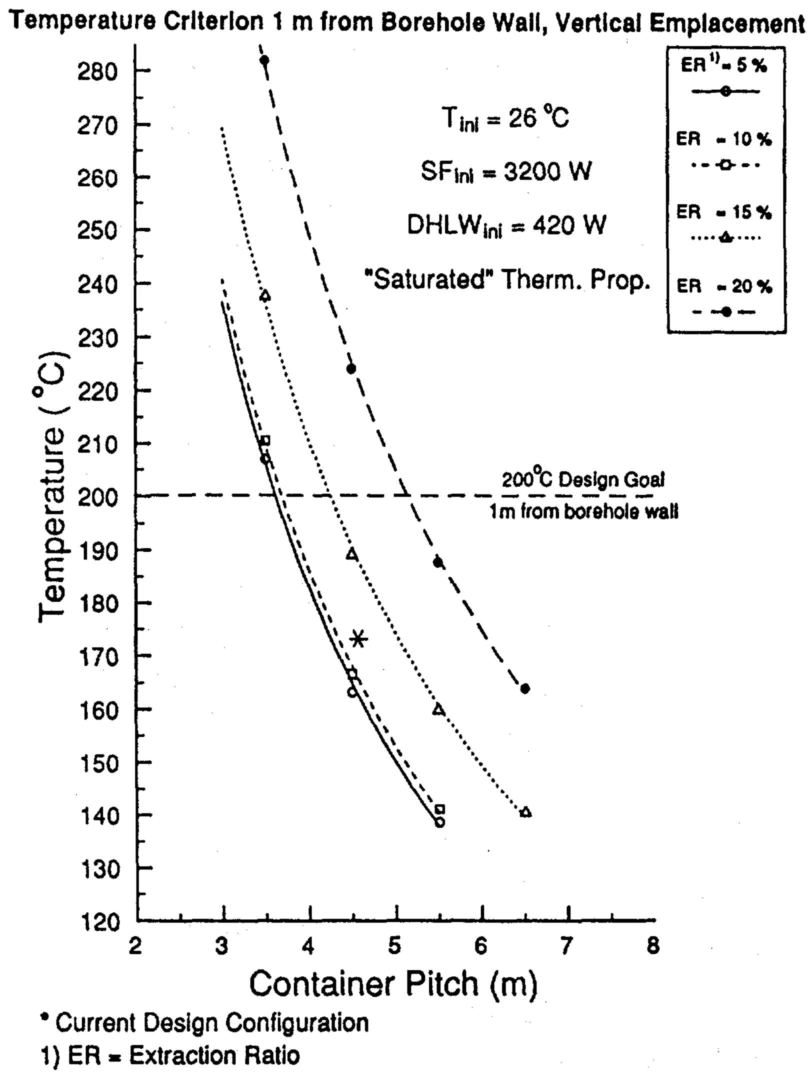
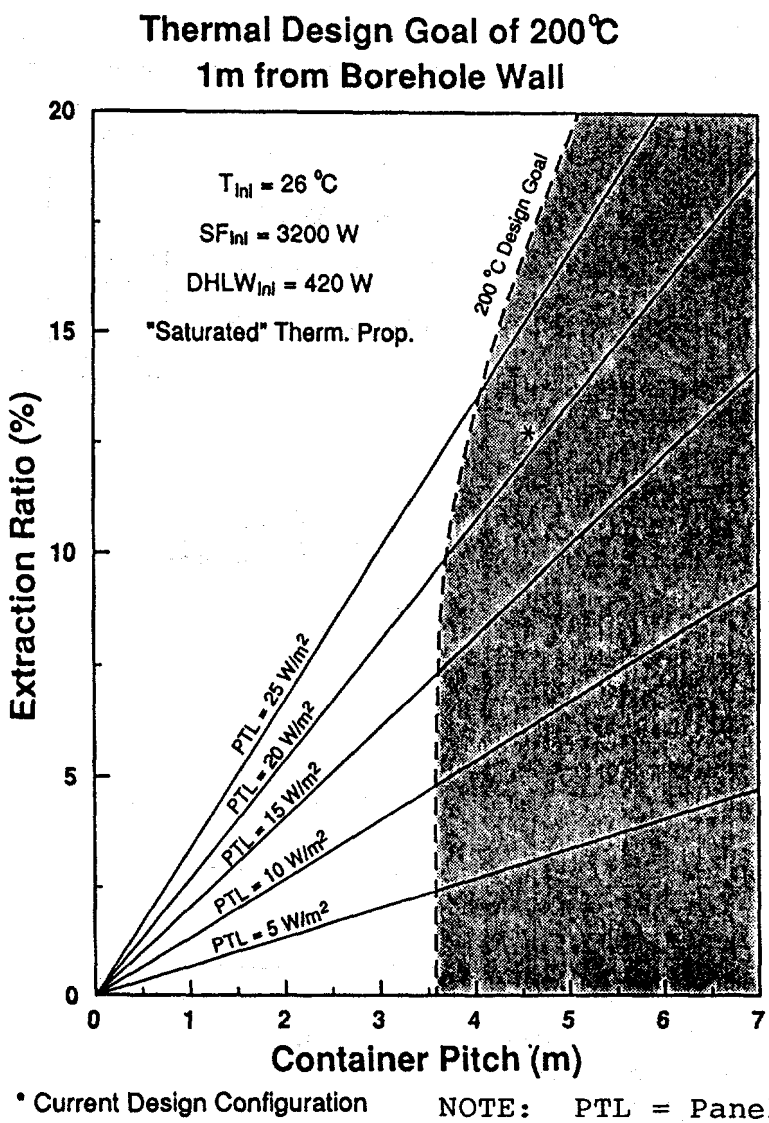


Fig. 9 Predicted Maximum Temperature 1 Meter from the Borehole Wall as a Function of Container Pitch, for Various Extraction Ratios (saturated rock properties)



NOTE: PTL = Panel Thermal Load

Fig. 10 Combinations of Extraction Ratio and Container Pitch that Comply With the YMP Design Goal of 200°C, 1 Meter from the Borehole Wall (saturated rock properties) [Note: PTL = Panel Thermal Load]

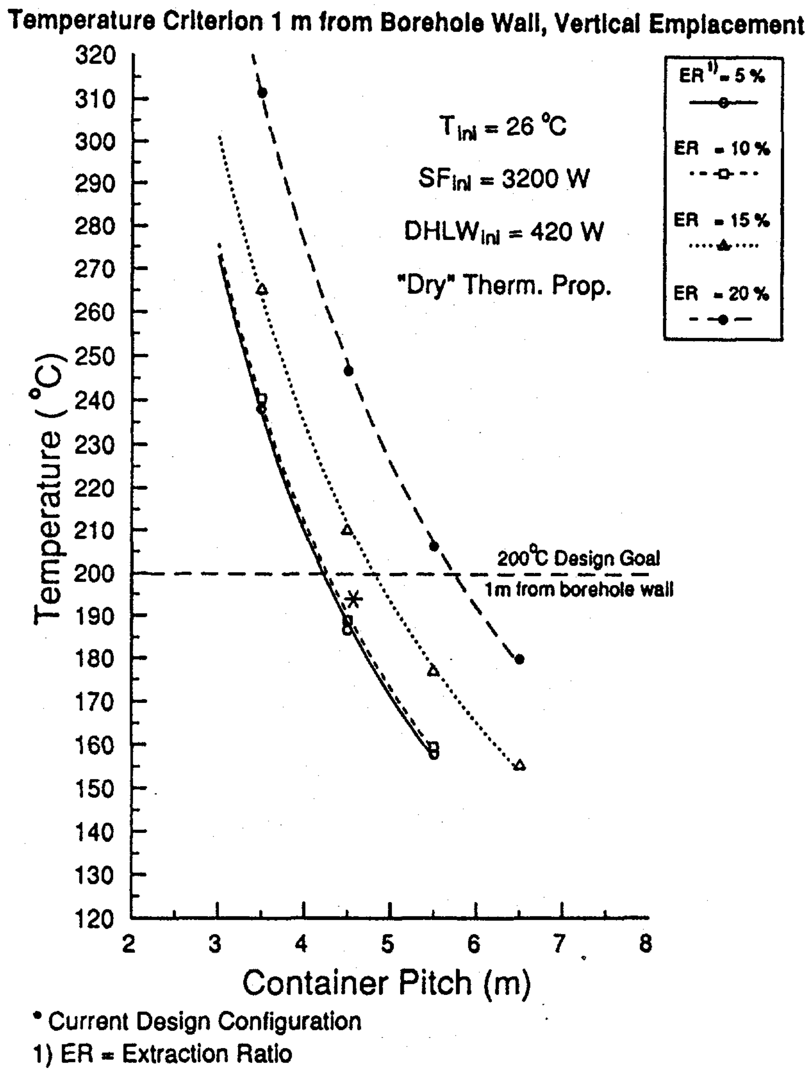


Fig. 11 Predicted Maximum Temperature 1 Meter from the Borehole Wall as a Function of Container Pitch, for Various Extraction Ratios (dry rock properties)

It is worth noticing from Figs. 9 and 11 that the 21 percent difference in thermal diffusivity between dry and saturated rock results in about 12 to 15 percent difference in predicted temperatures 1 m from the borehole wall, depending on the container pitch and extraction ratio selected. Using saturated and dry thermal properties, therefore, allows an evaluation of the effect of uncertainty in rock properties on the predicted temperatures. Considering the inhomogeniety of rock, it is not unreasonable to expect the uncertainty in thermal properties to be as much as 20 percent. Lappin and Nimick (1985) have reported that test methods for thermal conductivity of tuff, are accurate to ± 10 percent of the measured value.

Figure 12 illustrates the results of saturated and dry conditions superimposed. In this case, the effect of a 21 percent uncertainty in the thermal diffusivity relates to a difference of about 0.6 m in the container pitch for any extraction ratio, or a difference of about 5 percent for extraction ratios greater than 10 percent (e.g., an extraction ratio of 10 percent versus 15 percent).

To further illustrate the effect of uncertainty in the thermal diffusivity, Fig. 13 shows the predicted temperature at the borehole wall for the current YMP design configuration as a function of thermal diffusivity. A range in thermal diffusivity from 20 m^2/year to 50 m^2/year results in a predicted temperature difference of 143°C.

The effect of uncertainty can also be expressed in terms of a sensitivity coefficient (e.g., $\Delta T/\Delta\alpha$). Figure 14 illustrates the sensitivity of temperatures at the borehole wall for various uncertainties in thermal diffusivity. As expressed, the sensitivity function must necessarily be discontinuous.

4.1.2 Temperatures at the Borehole Wall

The effect of varying pitch and extraction ratio for the maximum temperature at the borehole wall for a SF container are illustrated in Fig. 15 for saturated properties. The three design goals expressed in the SCP and SCPCDR are included in the figure. As mentioned earlier, each symbol in the figure represents a separate numerical analysis, and the curves fit to the symbols are polynomial functions. There are many combinations of extraction ratio and container pitch that would satisfy the YMP design goals. The single asterisk shown in the figure represents the current YMP design configuration. This configuration results in a maximum borehole wall temperature well below even the strictest design goal of 220°C. As the container pitch decreases and extraction ratio increases, temperatures will increase. Note, however, that the maximum borehole wall temperature is hardly affected by increasing the extraction ratio from 5 to 10 percent.

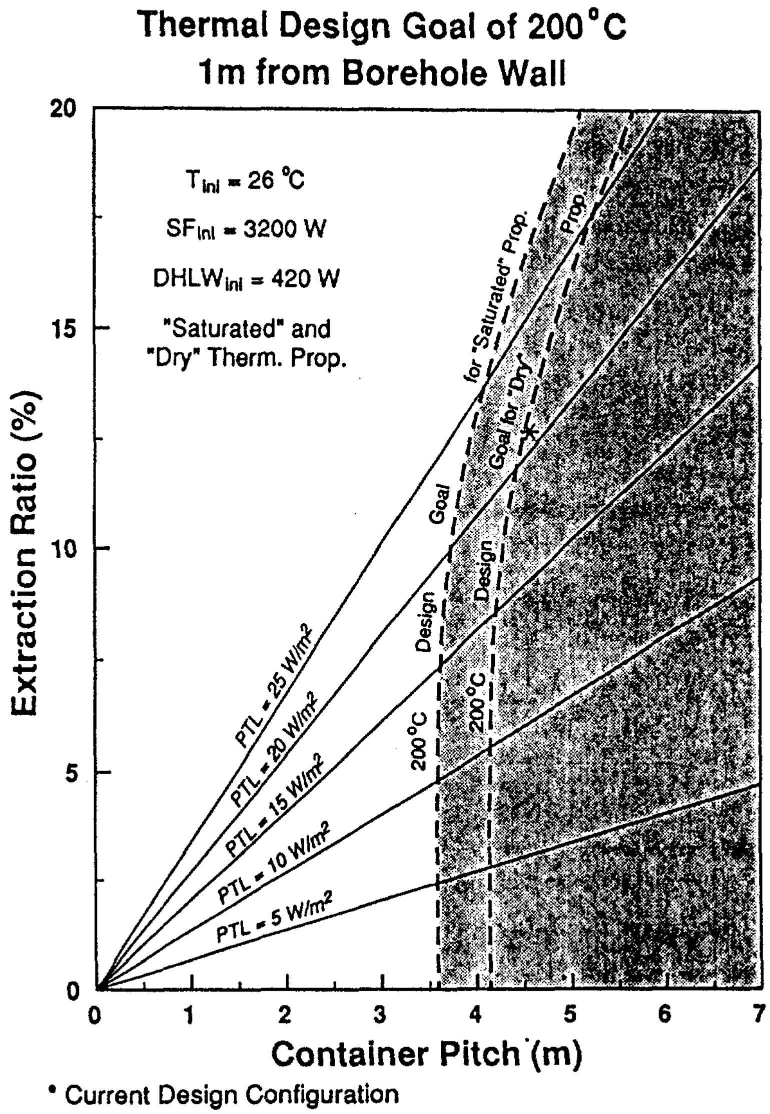


Fig. 12 Combinations of Extraction Ratio and Container Pitch that Comply With the YMP Design Goal of 200°C, 1 Meter from the Borehole Wall (saturated and dry rock properties)

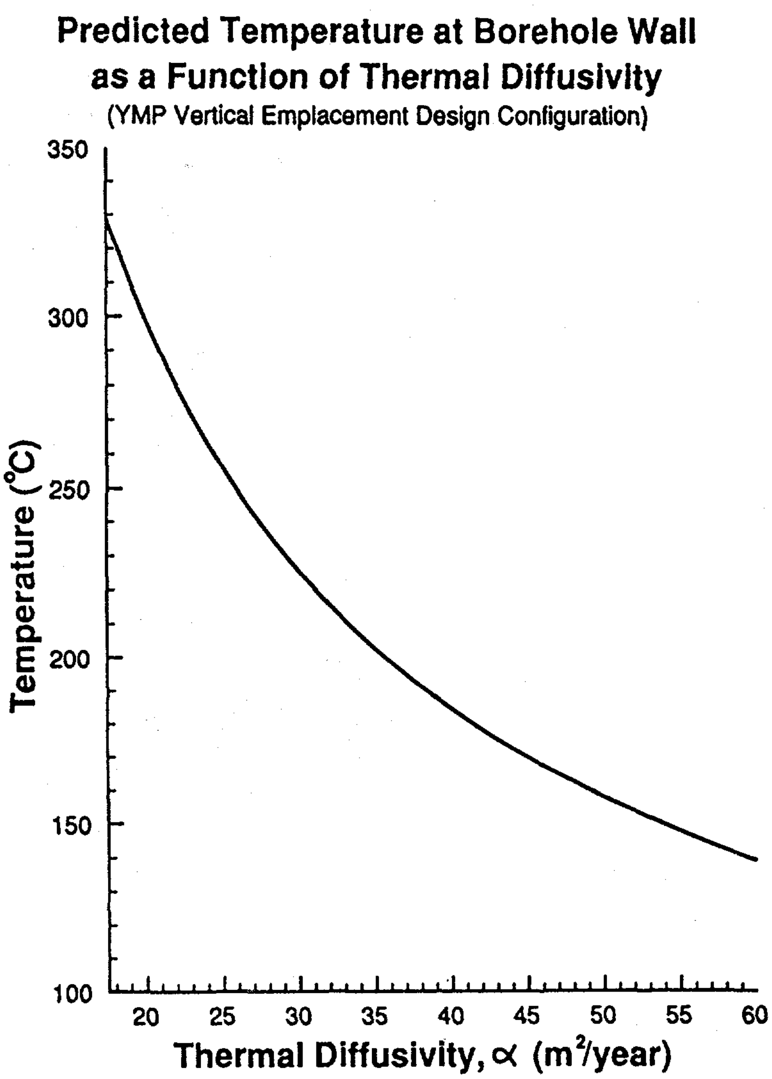


Fig. 13 Effect of Uncertainty in Thermal Diffusivity on Predicted Temperatures at the Borehole Wall (YMP vertical emplacement design configuration)

Figure 16, is Fig. 15 transformed to show the relation between the container pitch, the extraction ratio and the thermal loading [designated as panel thermal loading (PTL) in the figure]. The dashed lines represent the various thermal design goals applied to the SF borehole wall. The shaded area in this figure indicates the combinations of container pitch and extraction ratio and the resulting thermal loading that will satisfy the various YMP design goals. The current YMP design configuration is represented by the asterisk in Fig. 16.

The effect of using "saturated" and "dry" thermal properties on the predicted maximum borehole wall temperature is evaluated by comparing Figs. 15 and 17. For the same pitch and extraction ratio, predicted temperatures are higher when "dry" properties are used. The current YMP design configuration identified by the asterisk in Fig. 17, is now located above the design goal of 235°C for the borehole wall.

Comparing the results of Fig. 18, which are for dry thermal properties, to those in Fig. 16 for saturated properties, the effect of a 21 percent uncertainty in thermal diffusivity can be evaluated. For a design goal of 275°C the evaluation relates to a difference in container pitch of about 0.6 m. For the design goals of 235°C and 220°C the evaluation relates to a difference of about 1 m. The reason for the different effects on the container pitch in these cases is related to the distances between the containers in order to comply with the different design goals and the effect of heat transfer across these distances.

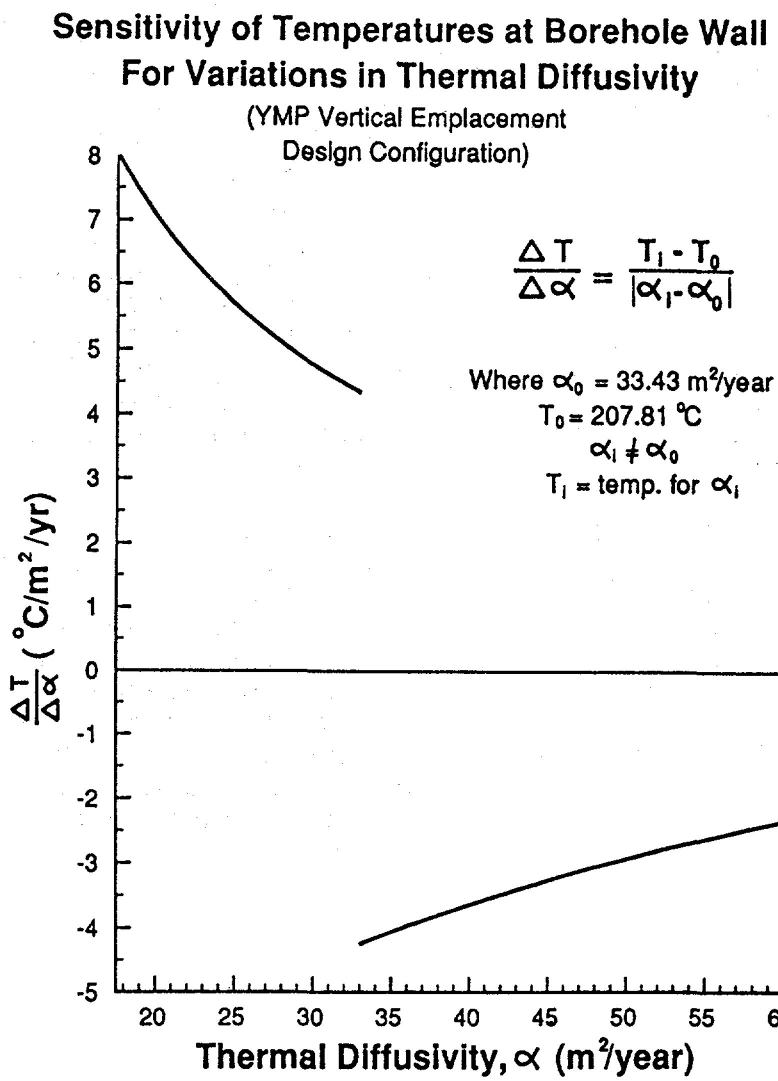


Fig. 14 Sensitivity of Predicted Temperatures at the Borehole Wall to Variations in Thermal Diffusivity (YMP vertical emplacement design configuration)

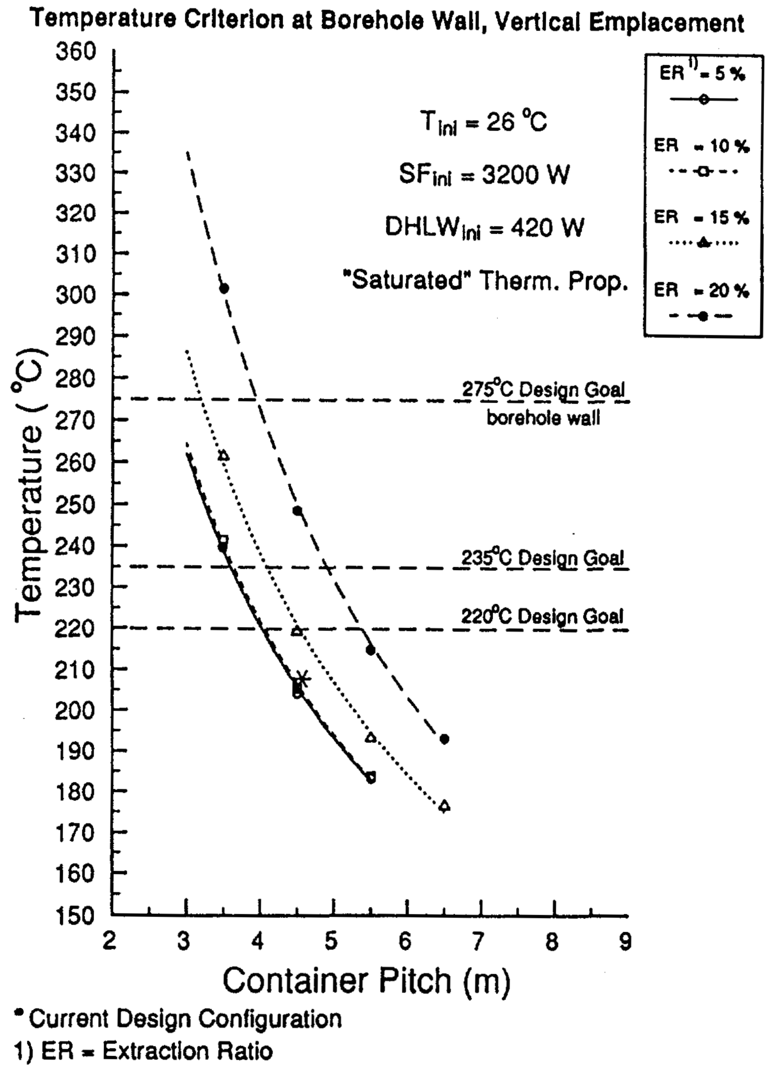


Fig. 15 Predicted Maximum Temperature at the Borehole Wall as a Function of Container Pitch for Various Extraction Ratios (saturated rock properties)

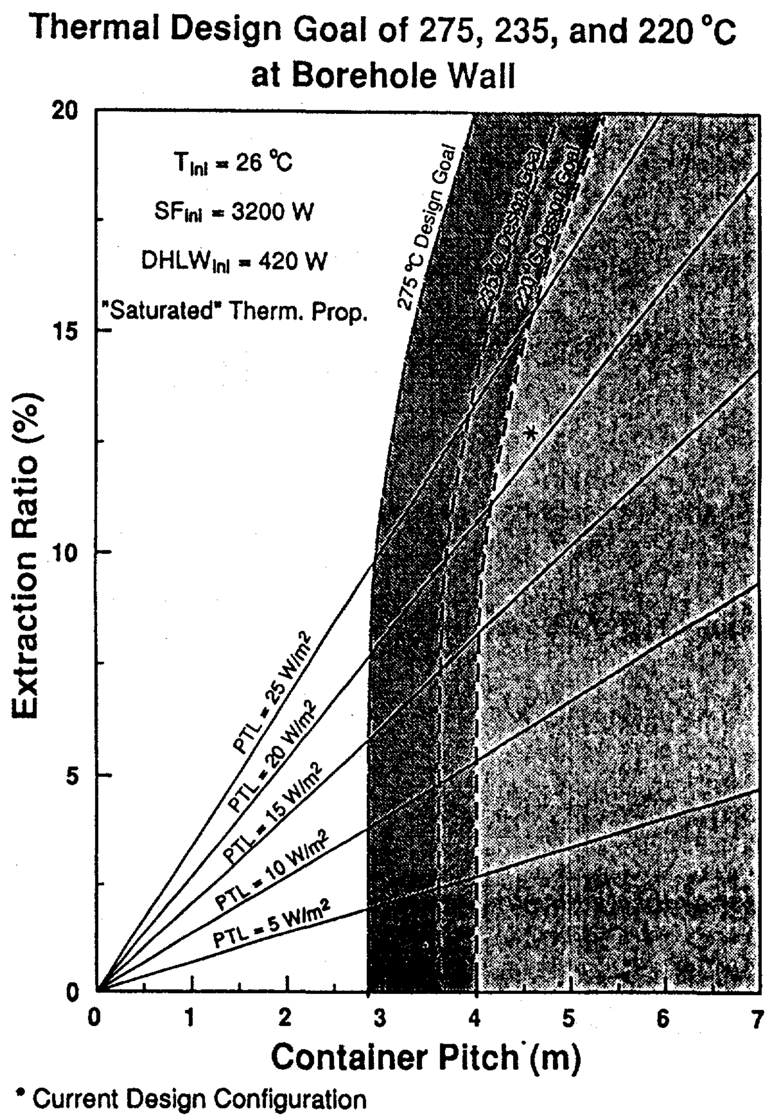
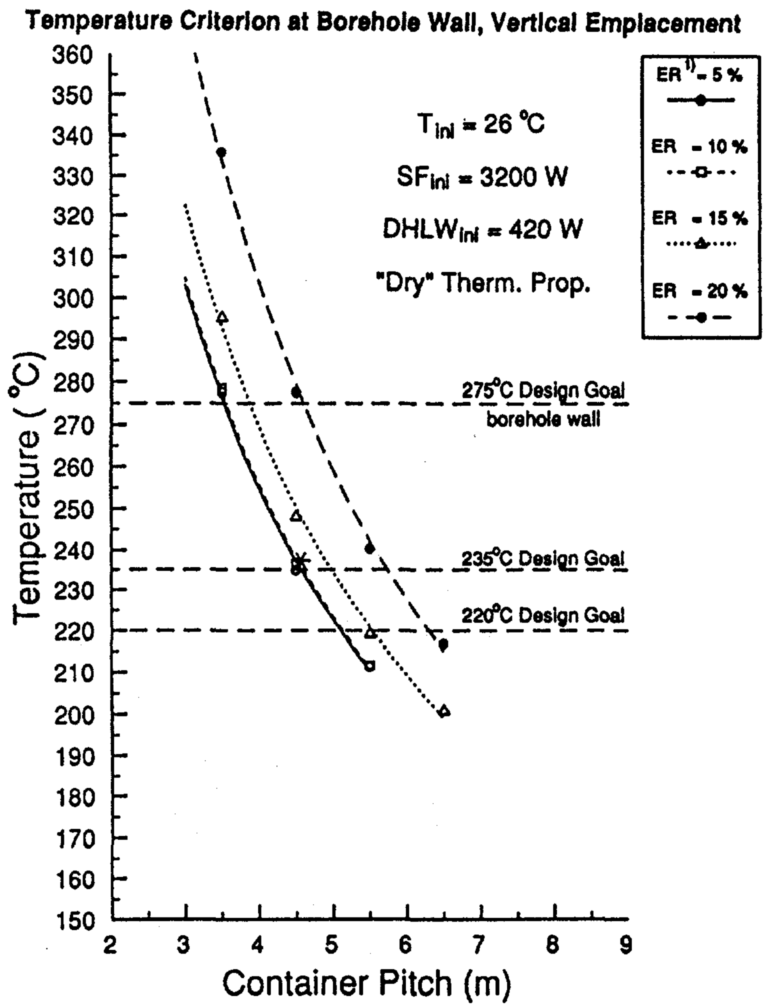


Fig. 16 Combinations of Extraction Ratio and Container Pitch that Comply with Various YMP Design Goals at the Borehole Wall (saturated rock properties)



* Current Design Configuration
1) ER = Extraction Ratio

Fig. 17 Predicted Maximum Temperature at the Borehole Wall as a Function of Container Pitch for Various Extraction Ratios (dry rock properties)

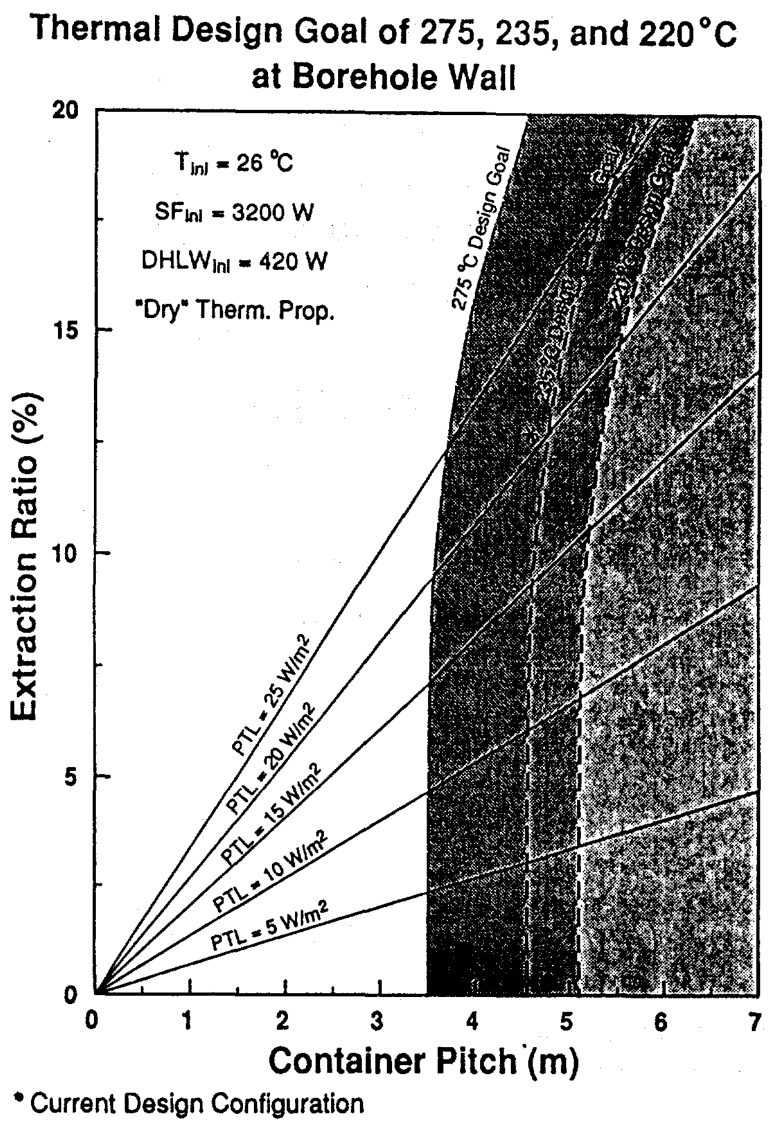


Fig. 18 Combinations of Extraction Ratio and Container Pitch that Comply with Various YMP Design Goals at the Borehole Wall (dry rock properties)

4.1.3 Temperature of Access Drifts

The YMP thermal design goal of access drifts for vertical emplacement is based on establishing an acceptable environment to accommodate the potential event of waste retrieval. The goal is that rock temperatures of the drift surface shall not exceed 50°C, 50 years after the beginning of waste emplacement. Figure 19 illustrates the combinations of container pitch and extraction ratio that will satisfy this goal for saturated thermal properties. The current YMP design configuration is indicated by the single asterisk in the figure. It is evident from these analyses that this configuration does not comply with the current design goal. The access drift temperature could be brought into compliance by increasing the container pitch, or by decreasing the disposal room extraction ratio. A third option would be to increase the distance between the access drifts and the waste. This option has not been evaluated in this study.

Figure 20 shows the access drift thermal design goal in relation to container pitch, extraction ratio, and panel thermal loading (PTL). Note that the dashed line representing the design goal has been discontinued for a container pitch of less than 3 m. This is a limitation adopted only in this study, and is based on the assumption that practical and safe operation of waste emplacement/retrieval equipment could not be conducted for a container pitch less than 3 m. The limitation is not associated with any design goal set by the YMP.

The difference between saturated and dry thermal properties is not reflected in the predicted temperatures of the access drifts at 50 years.

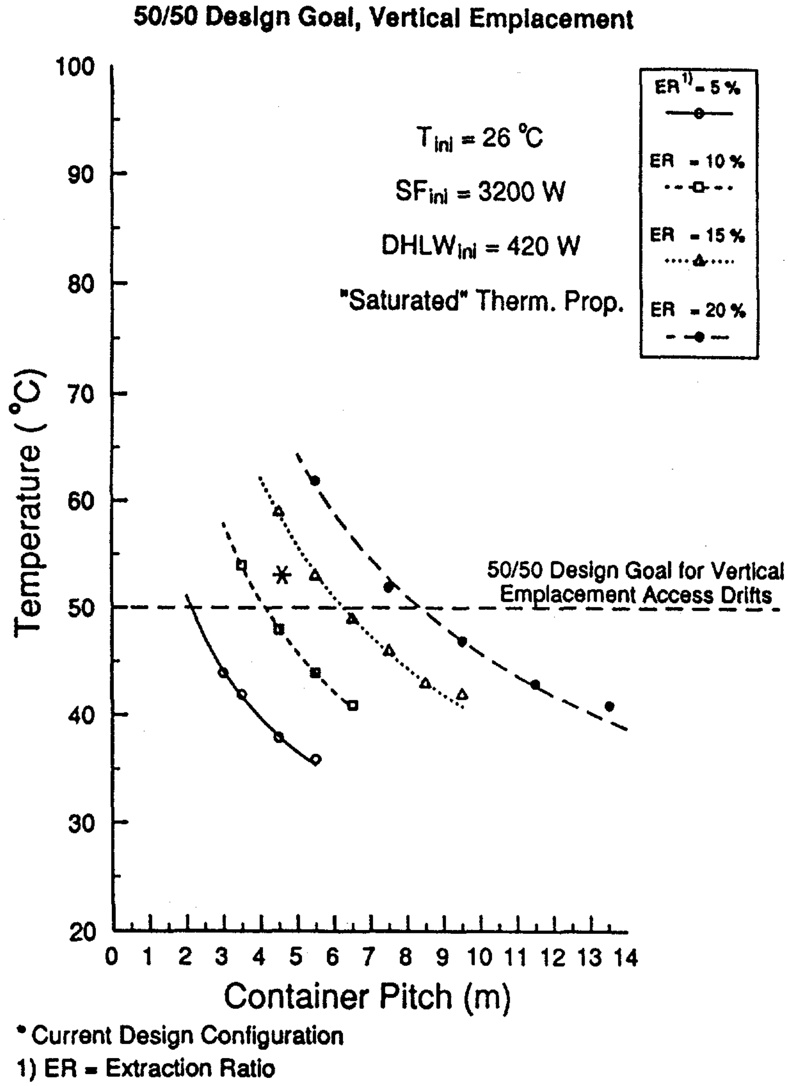
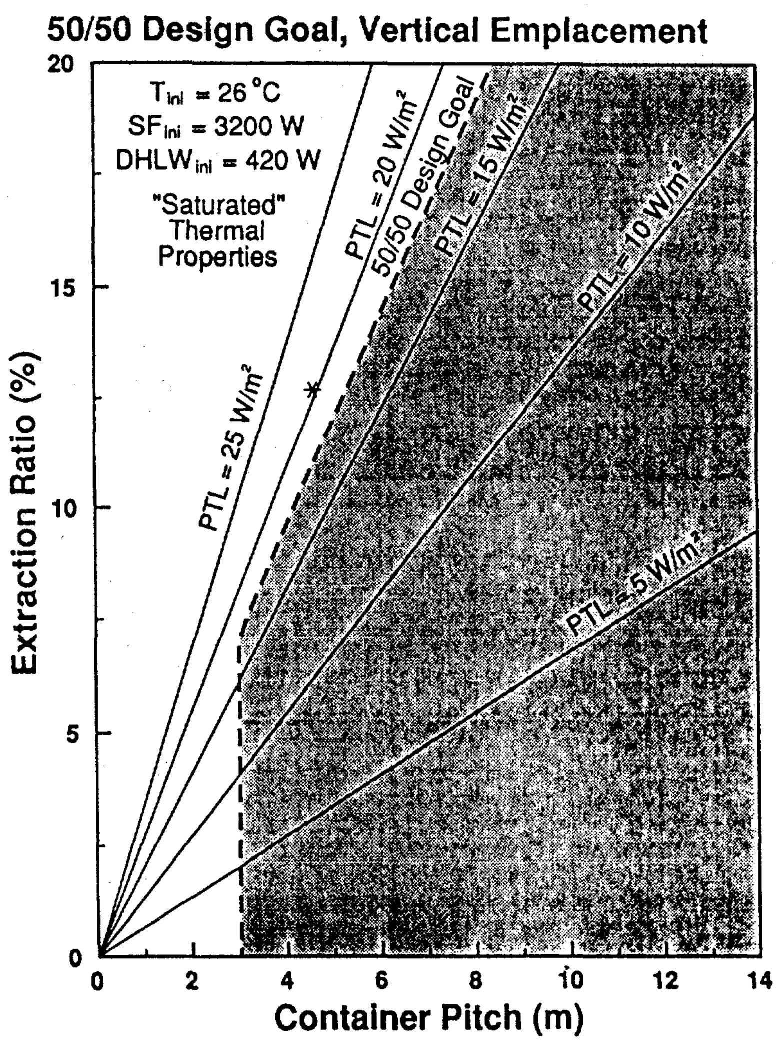


Fig. 19 Predicted Temperature of Vertical Emplacement Access Drifts at 50 Years for Variations in Container Pitch and Extraction Ratio (saturated rock properties)



* Current Design Configuration

Fig. 20 Combinations of Extraction Ratio and Container Pitch that Comply With the 50/50 Design Goal of Access Drifts (saturated rock properties)

4.2 Horizontal Emplacement

Varying the container pitch or extraction ratio to control temperatures in the waste package vicinity is not meaningful in the horizontal emplacement concept. Although temperatures could be controlled by varying the container power, or the horizontal spacing between containers along the horizontal boreholes, these options have not been evaluated in this study.

The design goal evaluated for horizontal emplacement is related to the limitation of 50°C in the disposal room, 50 years after initial waste emplacement. The goal is associated with establishing an acceptable environment to accommodate the potential event of waste retrieval, and is evaluated by changing the stand-off distance between the waste and the disposal room. Figure 21 illustrates the predicted temperature of the disposal room wall as a function of the percentage increase in the stand-off distance. The results are shown for both saturated and dry thermal properties. Notice, however, that the results for saturated and dry properties are only different by about 2°C. The results show temperatures for the case of saturated thermal properties to be higher than for dry properties. This is the opposite to the results previously shown in the vicinity of the waste package, and is caused by the lower rate of heat transfer within the "dry" rock. The YMP design configuration for horizontal emplacement is indicated by an asterisk in the figure. The results show that the current configuration does not comply with this design goal. However, increasing the stand-off distance by about 30 percent would bring the design into compliance.

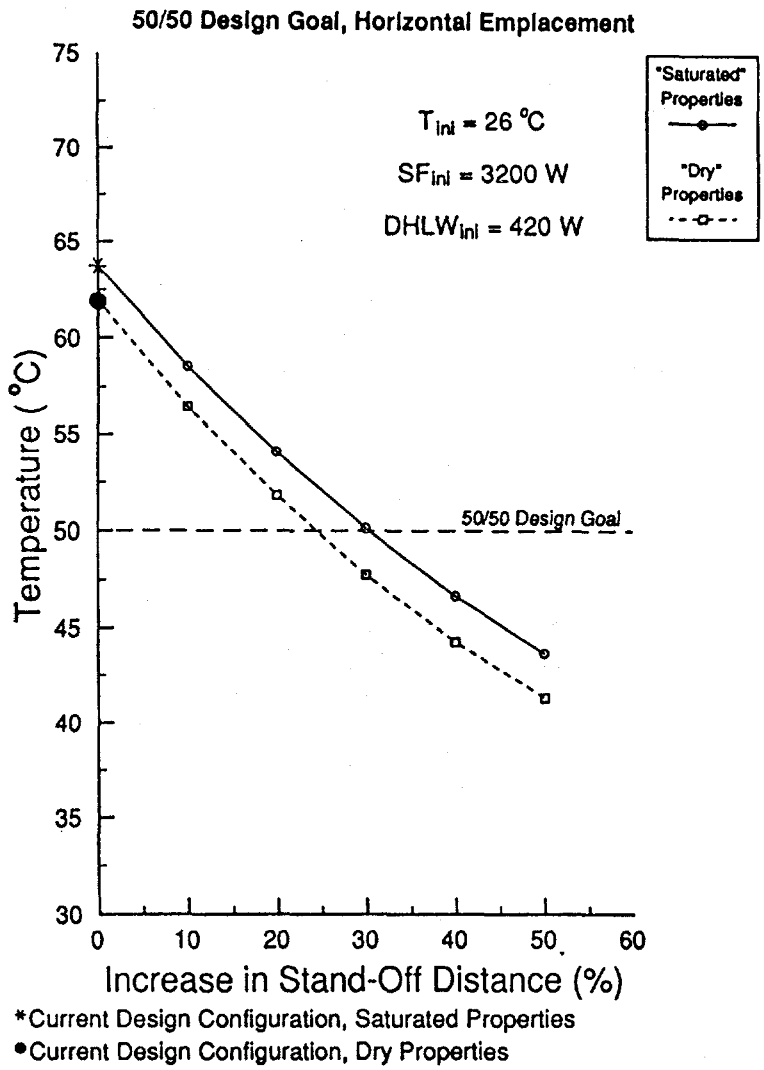


Fig. 21 Predicted Temperature of Horizontal Emplacement Rooms at 50 Years for Variations in Container Pitch

5.0 CONCLUSIONS

The issue of controlling the temperatures in the repository and surrounding host rock is one that requires understanding of the many parameters affecting the heat transfer. Besides the phenomenon of heat transfer itself in saturated, unsaturated, or dehydrated rock, including the heat transfer associated with vapor transport, important parameters include waste age and initial power of the waste package, geometric parameters such as container pitch, disposal room extraction ratio, and waste standoff distance, as well as the thermal properties of the rock. Additional means of controlling temperatures, at least in the preclosure period of the repository, are the use of forced ventilation.

The parameters evaluated in this work were container pitch, disposal room extraction ratio, waste stand-off distance (for horizontal emplacement only), and rock properties. The age and power of the waste packages at initial emplacement were kept constant in this study. The effect of porewater boiling and heat transfer associated with the potential vapor transport were not considered, and ventilation was not included.

The results of the many configurations evaluated have been compiled to provide a perspective and understanding of how each parameter affects the predicted temperatures in relation to design goals. For vertical emplacement, Figs. 22 and 23 summarize the results for "saturated" and "dry" thermal properties, respectively. The shaded areas in these figures, bounded by the 50/50 design goal and the 220°C design goal for the borehole wall, define the acceptable combinations of container pitch, extraction ratio, and thermal loading of the waste panel.

From Fig. 22, for saturated rock properties, the following is concluded.

- The minimum container pitch is 4 m for a maximum extraction ratio of 9.5 percent.
- For each percentage increase in the extraction ratio above 9.5 percent, the container pitch would have to be increased by 0.5 m to maintain compliance with the design goals.

- The current YMP design configuration for vertical emplaced waste does not comply with the 50/50 design goal. However, compliance could be achieved by reducing the extraction ratio to 10.5 percent.

- The maximum panel thermal loading that would satisfy the design goals is 17.8 W/m^2.

From Fig. 23, for dry rock properties, the following is concluded.

- The minimum container pitch is 5.1 m for a maximum extraction ratio of about 13 percent.

- An uncertainty of 21 percent in the thermal diffusivity of the rock results in a difference in container pitch of about 1 m.

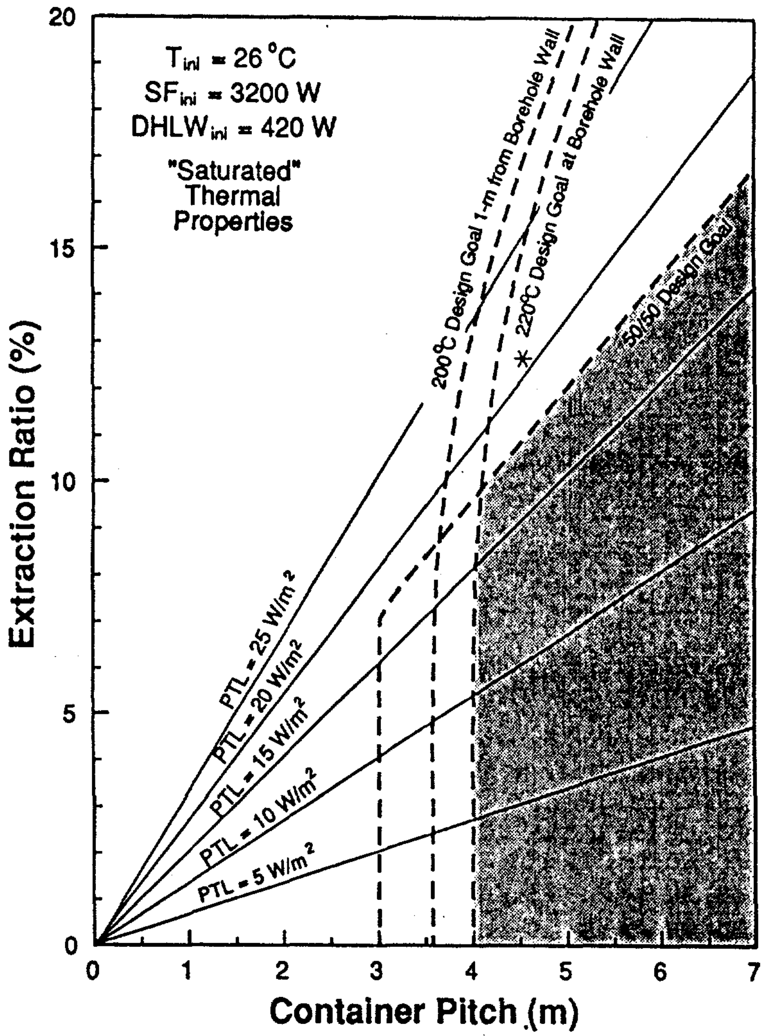
Additional conclusions from Fig. 23 remain the same as from Fig. 22, because rock temperatures associated the 50/50 design goal are unaffected by the difference in saturated and dry rock properties during the first 50 years after waste emplacement.

From the results associated with the horizontal emplacement concept, the following is concluded.

- The current YMP design configuration for horizontally emplaced waste does not comply with the 50/50 design goal. However, compliance could be achieved by increasing the waste stand-off distance by 30 percent.

It is important to keep in mind that the conclusions are specific to the conditions of 10 year old SF and DHLW, with initial container powers of 3200 W and 420 W, respectively. The set of conclusions would change should the waste age and initial container power change. The results, however, could easily be updated to also include variations in these two parameters.

Listings of typical computer input for STRES3D used in this study are included in Appendix D.



* Current Design Configuration

Fig. 22 Combination of Extraction Ratio and Container Pitch that Comply With Current YMP Design Goals (saturated rock properties)

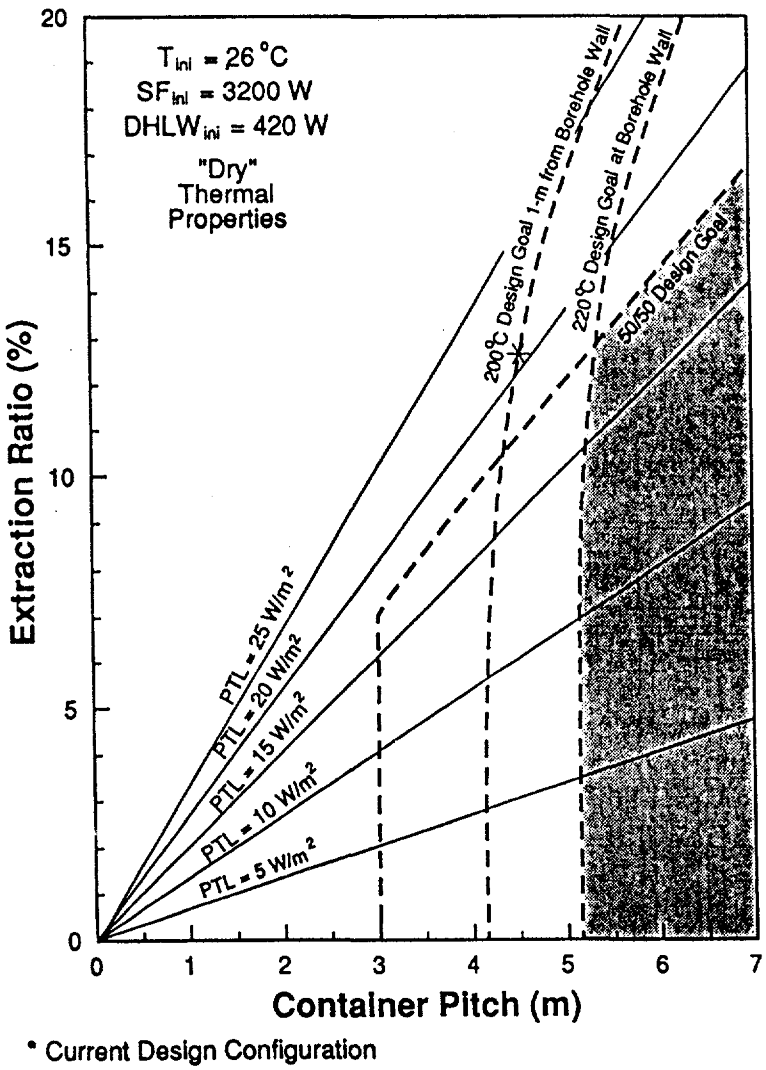


Fig. 23 Combination of Extraction Ratio and Container Pitch that Comply With Current YMP Design Goals (dry rock properties)

6.0 RECOMMENDATIONS

Uncertainties will be present in all the parameters affecting the predictions of temperatures in the repository and host rock. It is important to determine these uncertainties and their effects on compliance with the design goals for the repository. In this work, the effect of uncertainty in the thermal diffusivity of the rock has been evaluated. Variations in other parameters, in particular waste age and container power, need to be evaluated, since the repository will store waste of different age and different container power.

The design goals evaluated in this study are all related to the temperatures in access drifts, the horizontal disposal room, and the vicinity of the waste packages. Additional design goals listed in Section 1.1 remain to be evaluated, for which the numerical model, STRES3D, is not well suited. Evaluation of these design goals requires attention to great detail with respect to the spent fuel waste package, and to the thermomechanical structure at Yucca mountain. Models should be applied to evaluate the effects of parameter uncertainties on the temperatures at these locations, and to assure compliance with design goals.

7.0 REFERENCES

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

St. John, Christopher, and Mark Christianson. "STRES3D: A Computer Program for Determining Temperatures, Stresses, and Displacements Around Single or Arrays of Constant or Decaying Heat Sources — User's Guide and Manual," University of Minnesota Report to Rockwell Hanford Operations, RHO-BWI-C-78, September 1980.

U.S. Nuclear Regulatory Commission (NRC). Code of Federal Regulations: Title 10, Parts 0 to 199 (Energy); 10 CFR Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories." January 1988.

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):

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

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

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

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

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

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 33.43 m^2/year, the radius of thermal influence, R, is determined to be approximately 164 m.

REFERENCES

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.

St. John, C. M. "Thermal Analysis of Spent Fuel Disposal in Vertical Displacement Boreholes in a Welded Tuff Repository," Sandia National Laboratories, SAND84-7207, November 1985.

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.

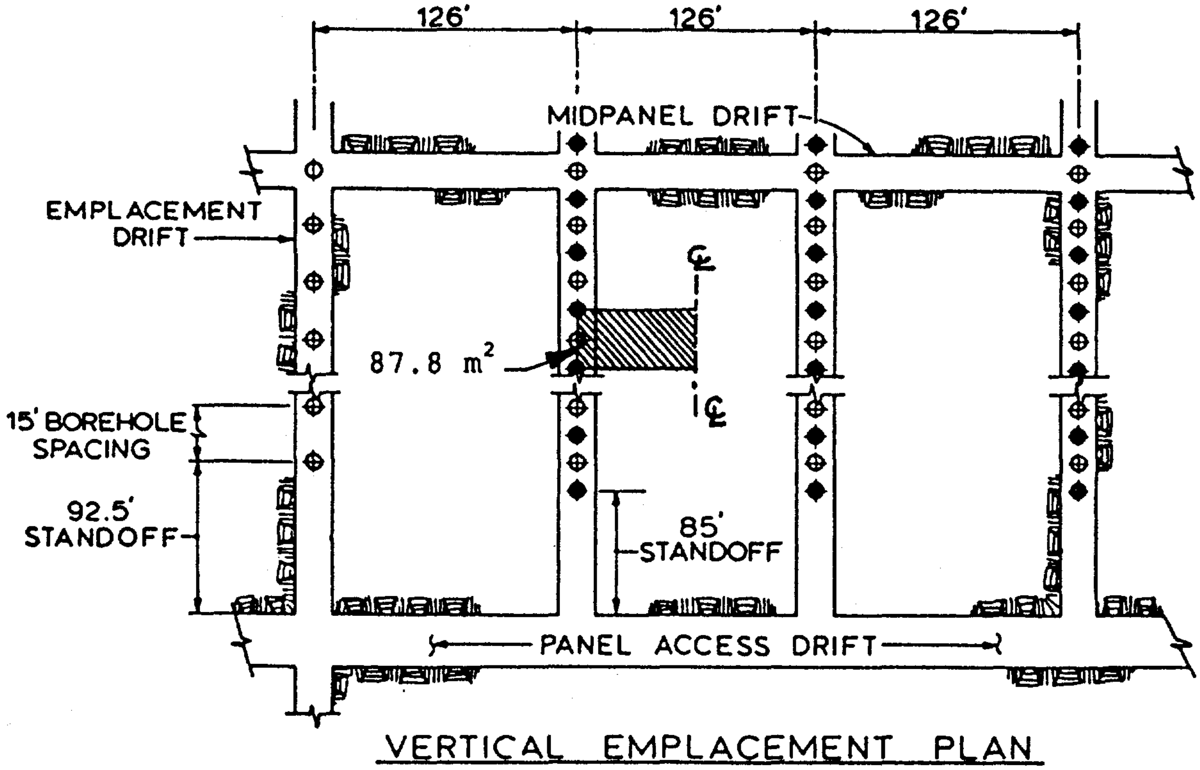

Fig. B-1 Layout of Waste Containers for Vertical Emplacement [after MacDougall et al., 1987, Chapter 4]

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 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 W/m^2 or 80.8 kW/acre.

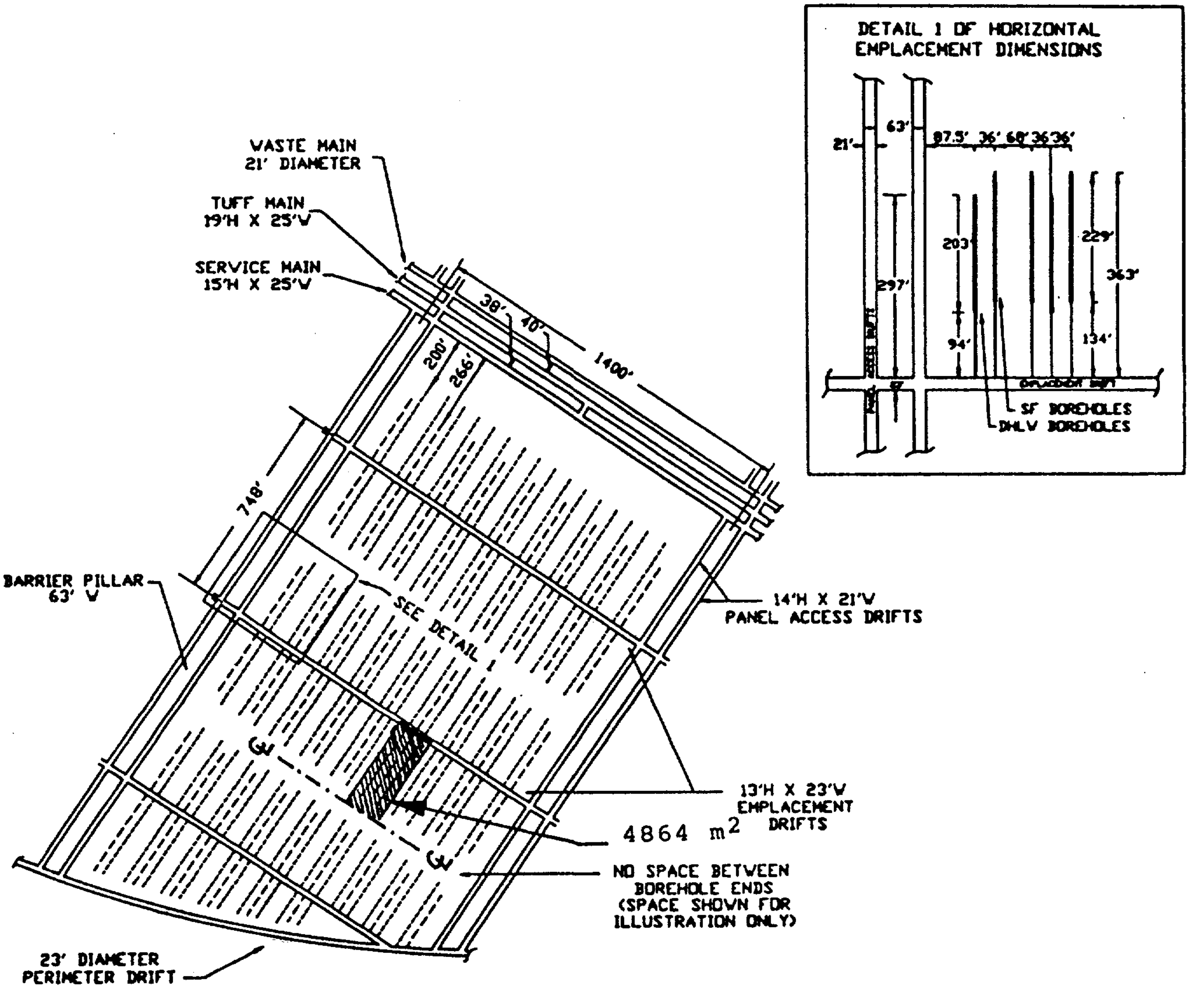

Fig. B-2 Layout of Waste Containers for Horizontal Emplacement [after MacDougall et al., 1987, Chapter 4]

REFERENCE

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

APPENDIX C

SUMMARY OF PARAMETERS AND RESULTS

Table C-1 : Summary of Parameter Values and Results for the Vertical Emplacement Concept

ER (%)	Pitch (m)	Th. Load* (W/m²)	Borehole Wall				1m from Borehole Wall				Access Drifts
			"Saturated"		"Dry"		"Saturated"		"Dry"		
			Max. Temp. (°C)	Time (yrs)	Max. Temp. (°C)	Time (yrs)	Max. Temp. (°C)	Time (yrs)	Max. Temp. (°C)	Time (yrs)	Temp. at 50 years
5	3.0	12.37									44
	3.5	10.60	240	7	277	7	207	8	238	8	42
	4.5	8.25	204	6	236	6	163	8	187	8	38
	5.5	6.75	183	6	211	6	139	8	158	8	36
10	3.5	21.21	242	8	278	8	211	12	240	10	54
	4.5	16.50	205	7	237	7	167	12	189	11	48
	5.5	13.50	184	6	212	6	141	12	160	11	44
	6.5	11.42									41
15	3.5	31.81	261	19	295	16	238	27	265	24	
	4.5	24.24	219	16	248	14	189	29	210	26	59
	5.5	20.24	193	14	219	12	160	29	177	26	53
	6.5	17.13	177	11	201	10	140	28	155	25	49
	7.5	14.85									46
	8.5	13.10									43
	9.5	11.72									42
20	3.5	42.41	302	32	336	29	282	41	312	38	
	4.5	32.99	249	28	278	25	224	42	247	40	
	5.5	26.99	215	24	240	21	188	44	206	42	62
	6.5	22.84	193	21	217	18	164	43	180	41	
	7.5	19.79									52
	9.5	15.62									47
	11.5	12.91									43
	13.5	11.00									41
YMP Design Config.	4.6	20.62	208	11	237	9	173	21	194	18	53

* To convert to kW/acre, multiply values by 4.04686

Table C-2 : Summary of Parameter Values and Results for the Horizontal Emplacement Concept

Increase in Stand-Off Distance [1] (%)	Disposal Room Temp (°C) at 50 Years	
	"Saturated"	"Dry"
10	59	57
20	54	52
30	50	48
40	47	44
50	44	41

1) Distance between the closest waste and the disposal room for the current YMP design configuration

APPENDIX D

STRES3D INPUT FILES

D-1 INPUT FILE FOR VERTICAL WASTE EMPLACEMENT

```
***************************************************************
*                                                             *
*   V E R T I C A L   W A S T E   E M P L A C E M E N T       *
*                                                             *
*  Data file for evaluating the maximum temperature criteria  *
*  at the borehole wall (275, 235, and 220 °C), and 1 m from  *
*  the borehole wall (200 °C) for vertical emplacement        *
*  Disposal Room Width = 4.88 m, Pillar Width = 27.64 m       *
*  Extraction Ratio = 15%                                     *
*  Pitch = 6.5 m                                              *
*  PTL = 17.13 W/m2                                           *
*  1397 individual containers are included in this model      *
*                                                             *
***************************************************************
log on
head
 Max temp. crit. -- Vert. Empl. -- ER=15% -- Pitch=6.5 m
can 1 4.6 1 300
can 2 3.0 1 300
can 3 4.6 10 300
can 4 3.0 10 300

*--- SF containers ...
qline 28 1 -195.10,0. -195.10,175.5 0
qline 28 1 -130.07,0. -130.07,175.5 0
qline 28 1 -97.55,0. -97.55,175.5 0
qline 28 1 -65.03,0. -65.03,175.5 0
qline 28 1 -32.52,0. -32.52,175.5 0
qline  4 3 0.,0. 0.,19.5 0
qline 24 1 0.,26. 0.,175.5 0
qline 28 1 32.52,0. 32.52,175.5 0
qline 28 1 65.03,0. 65.03,175.5 0
qline 28 1 97.55,0. 97.55,175.5 0
qline 28 1 130.07,0. 130.07,175.5 0
qline 28 1 195.10,0. 195.10,175.5 0

qline 27 1 -195.10,-6.5 -195.10,-175.5 0
qline 27 1 -130.07,-6.5 -130.07,-175.5 0
qline 27 1 -97.55,-6.5 -97.55,-175.5 0
qline 27 1 -65.03,-6.5 -65.03,-175.5 0
```

```
qline 27 1 -32.52,-6.5 -32.52,-175.5 0
qline  3 3 0.,-6.5 0.,-19.5 0
qline 24 1 0.,-26. 0.,-175.5 0
qline 27 1 32.52,-6.5 32.52,-175.5 0
qline 27 1 65.03,-6.5 65.03,-175.5 0
qline 27 1 97.55,-6.5 97.55,-175.5 0
qline 27 1 130.07,-6.5 130.07,-175.5 0
qline 27 1 195.10,-6.5 195.10,-175.5 0

*--- DHLW containers ...
qline 28 2 -195.10,3.25 -195.10,178.75 0
qline 28 2 -130.07,3.25 -130.07,178.75 0
qline 28 2 -97.55,3.25 -97.55,178.75 0
qline 28 2 -65.03,3.25 -65.03,178.75 0
qline 28 2 -32.52,3.25 -32.52,178.75 0
qline  3 4 0.,3.25 0.,16.25 0
qline 25 2 0.,22.75 0.,178.75 0
qline 28 2 32.52,3.25 32.52,178.75 0
qline 28 2 65.03,3.25 65.03,178.75 0
qline 28 2 97.55,3.25 97.55,178.75 0
qline 28 2 130.07,3.25 130.07,178.75 0
qline 28 2 195.10,3.25 195.10,178.75 0

qline 28 2 -195.10,-3.25 -195.10,-178.75 0
qline 28 2 -130.07,-3.25 -130.07,-178.75 0
qline 28 2 -97.55,-3.25 -97.55,-178.75 0
qline 28 2 -65.03,-3.25 -65.03,-178.75 0
qline 28 2 -32.52,-3.25 -32.52,-178.75 0
qline  3 4 0.,-3.25 0.,-16.25 0
qline 25 2 0.,-22.75 0.,-178.75 0
qline 28 2 32.52,-3.25 32.52,-178.75 0
qline 28 2 65.03,-3.25 65.03,-178.75 0
qline 28 2 97.55,-3.25 97.55,-178.75 0
qline 28 2 130.07,-3.25 130.07,-178.75 0
qline 28 2 195.10,-3.25 195.10,-178.75 0

*--- Thermal decay characteristics (Peters, 1983) ...
decay 1 1 0 25229.0 .00777
decay 1 2 0 20557.0 .0541
decay 2 1 0 5274.0 .0202
decay 2 2 0 858.0 .0456
decay 3 1 0 25229.0 .00777
decay 3 2 0 20557.0 .0541
decay 4 1 0 5274.0 .0202
decay 4 2 0 858.0 .0456
mod inf
*
* rock mass properties 'recommended' values from chapter 2 SCPCDR
```

```
*
rmp 15.2e9  .22  22736.0
rtp 33.43, 26., 0., 8.8e-6

* print temperatures at borehole wall and 1 m away ...
line 2 0.,.37,300. 0.,1.37,300.

time 0
pri tem
time 5.
pri tem
time 6.
pri tem
time 7.
pri tem
time 8.
pri tem
time 9.
pri tem
time 10.
pri tem
time 11.
pri tem
time 12.
pri tem
time 13.
pri tem
time 14.
pri tem
time 15.
pri tem
time 16.
pri tem
time 17.
pri tem
time 18.
pri tem
time 19.
pri tem
time 20.
pri tem
time 21.
pri tem
time 22.
pri tem
time 23.
pri tem
time 24.
```

```
pri tem
time 25.
pri tem
time 26.
pri tem
time 27.
pri tem
time 28.
pri tem
time 29.
pri tem
time 30.
pri tem
time 31.
pri tem
time 32.
pri tem
time 33.
pri tem
time 34.
pri tem
time 35.
pri tem
stop
```

D-2 INPUT FILE FOR HORIZONTAL WASTE EMPLACEMENT

```
*****************************************************************
*                                                               *
*  C U R R E N T   D E S I G N   H O R I Z.   E M P L M.       *
*                                                               *
*  Data file for evaluating the 50/50 criterion in the empl.    *
*  drifts for horizontal  emplacement                           *
*  Stand-off distance = 28.65 m for DHLW                        *
*  Stand-off distance = 40.84 m for SF                          *
*                                                               *
*  PTL = 19.97 w/m2                                             *
*  2316 individual containers are included in this model        *
*                                                               *
*****************************************************************
log on
head
 50/50 crit. - Horiz. Empl. - St off of 28.65/40.84 (DHLW/SF)
can 1 4.6 1 300
can 2 3.0 1 300
can 3 4.6 1 300
can 4 3.0 1 300

*--- Panel #1 -- each container represented by 5 heat sources
qgrid 90 9 4 31.85,0.     92.20,341.38 0
qgrid 70 8 3 44.04,10.97 112.32,309.68 0
qgrid 70 8 3 44.04,31.70 112.32,330.40 0

*--- Panel #2 -- each container represented by 5 heat sources
qgrid 90 9 4 -31.85,0.     -92.20,341.38 0
qgrid 70 8 3 -44.04,10.97 -112.32,309.68 0
qgrid 70 8 3 -44.04,31.70 -112.32,330.40 0

*--- Panel #3 -- each container represented by 1 heat source
qgrid 18 9 2 137.46,0.    194.46,341.38 0
qgrid 14 8 1 118.11,10.97 181.51,309.68 0
qgrid 14 8 1 118.11,31.70 181.51,330.40 0

*--- Panel #4 -- each container represented by 1 heat source
qgrid 18 9 2 -137.46,0.    -194.46,341.38 0
qgrid 14 8 1 -118.11,10.97 -181.51,309.68 0
qgrid 14 8 1 -118.11,31.70 -181.51,330.40 0

*--- Thermal decay characteristics (Peters, 1983)
decay 1 1 0 25229.0 .00777    ; SF thermal decay ...
decay 1 2 0 20557.0 .0541     ; SF thermal decay ...
decay 2 1 0 5274.0 .0202      ; DHLW thermal decay ...
```

```
decay 2 2 0 858.0 .0456        ; DHLW thermal decay ...

*--- Reduce the init. power per source for multiple sources
decay 3 1 0 5045.8 .00777     ; SF thermal decay ...
decay 3 2 0 4111.4 .0541      ; SF thermal decay ...
decay 4 1 0 1054.8 .0202      ; DHLW thermal decay ...
decay 4 2 0 171.6 .0456       ; DHLW thermal decay ...

mod inf

*--- Rock mass properties 'recommended' values from Chap. 2 SCPCDR
rmp 15.2e9  .22  22736.0
rtp 33.43, 26., 0., 8.8e-6   ; mean thermal properties ...

*--- Determine temp. at three locations along the disp. room wall
line 3 3.20,149.35,300. 3.20,192.03,300.

time 0
pri tem
time 25.
pri tem
time 30.
pri tem
time 35.
pri tem
time 40.
pri tem
time 45.
pri tem
time 50.
pri tem

stop
```

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

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(See instructions on the reverse)

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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents the results of numerical analyses to determine the range in container pitch (i.e., the spacing between vertically emplaced containers), disposal room extraction ratio, and waste stand-off distance that will satisfy design criteria expressed for a repository at Yucca Mountain. Effects are investigated for a range in thermal properties of the rock represented by the "saturated" and "dry" conditions expressed in Chapter 2 of the SCPCDR. A number of heat transfer analyses were performed for a time period of 50 years after initial waste emplacement. Within this period, temperatures have peaked in the vicinity of the waste containers. The analyses included three-dimensional heat transfer models that account for the explicit interaction of single waste containers emplaced in a repository panel. Vertical and horizontal waste emplacement concepts of commingled SF and DHLW were investigated. The analyses indicate that the configuration of container boreholes and extraction ratio, as well as the stand-off distance to waste proposed in the SCPCDR, Chapter 4, could result in the development of temperatures that exceed design goals currently expressed in the SCP and the SCPCDR.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Nuclear Waste
Geologic Disposal
Heat Transfer
Repository Design
Thermal Loading
Site Characterization Plan Conceptual Design Report (SCPCDR)

13. AVAILABILITY STATEMENT

14. SECURITY CLASSIFICATION

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