THERMAL ANALYSIS OF WASTE PACKAGE PRELIMINARY RELIABILITY ASSESSMENT

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ABSTRACT

A thermal analysis has been performed for the Basalt Waste Isolation Project waste package designs in the postemplacement period. This analysis is an integral part of the preliminary reliablility assessment of the first phase of the waste package advanced conceptual design. A three-dimensional integrated model was used to simulate and predict thermal conditions for the waste package and its environment. These predicted temperature histories of the waste package container are employed, in turn, to assess the container lifetimes. The temperature profiles and histories of the packing material and host rock are used to assess their behaviors and to guide future material test plans. It is found that all components of waste package are within the current BWIP temperature limits of concern to safety. Axial temperature gradients in the waste form and container also have been predicted. An analysis of the uncertainty of material properties on the temperature predictions is also described.

INTRODUCTION

The Basalt Waste Isolation Project (BWIP), conducted for the U.S. Department of Energy by Rockwell Hanford Operations, has completed a preliminary reliability assessment of the waste package designs. The thermal analysis is an important element of the waste package reliability assessment. The thermal responses of the waste package and the designs environment in the postemplacement period are reported in this paper. The current BWIP waste package design consist of three main components: the waste form, the container, and the packing (Fig. 1). The container is required to provide substantially complete containment of radionuclides for 300 to 1,000 yr after repository closure. Presently, the container lifetime model is empirically correlated as a function of temperature only. Thus, thermal analysis has a key role in the determination of the container lifetime in the repository. Furthermore, the thermal analysis provides the temperature profiles and histories of the waste package and its surrounding host rock. This information is essential for testing programs to determine the geochemical conditions, permeability, and other properties of packing materials, and to determine thermal stress and hydraulic behavior of host rock. A realistic approach is taken to perform the thermal analysis.

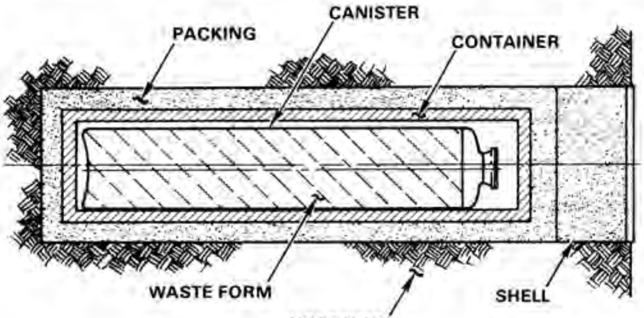

Fig. 1. Diagram Illustrating Waste Package Terminology.

MODELING EFFORT

Currently, the Cohassett flow of Columbia River Basalt Group is the candidate horizon for the BWIP repository, which is 970 m below the ground surface. A sketch of the current repository layout is presented in Fig. 2. The repository layout consists of four storage panels. Each storage panel consists of 10 emplacement panels. Each emplacement panel has four emplacement rooms or drifts, which are long tunnels. In both sides of the emplacement rooms, there are more than 120 short horizontal boreholes. Each horizontal borehole contains one waste package (to facilitate emplacement and retrieval).

The widely accepted thermal analysis code in the nuclear community, HEATING5[1] is used in the present analysis. A three-dimensional model was constructed to simulate the waste package and its environment as shown in Fig. 3 and 4. This model is constructed based on the following assumptions.

- The model, including the repository and its environment, is in a homogeneous basalt flow and extends vertically (i.e., from ground surface to 1,030 m below the repository) to the boundaries of the problems investigated.
- All waste packages are simultaneously emplaced in the basalt repository. With this assumption, the geometrical symmetry consideration can be employed. A single slab, symetrically cut through a waste package, represents the typical waste package and its environment.
- All components of the waste package (i.e., waste form, container, and packing) are made of isotropic and homogeneous materials.
- Material properties remain constant in each computer run.
- The heat of the vaporization and condensation of groundwater in the host rock and convective transport of heat are not considered.

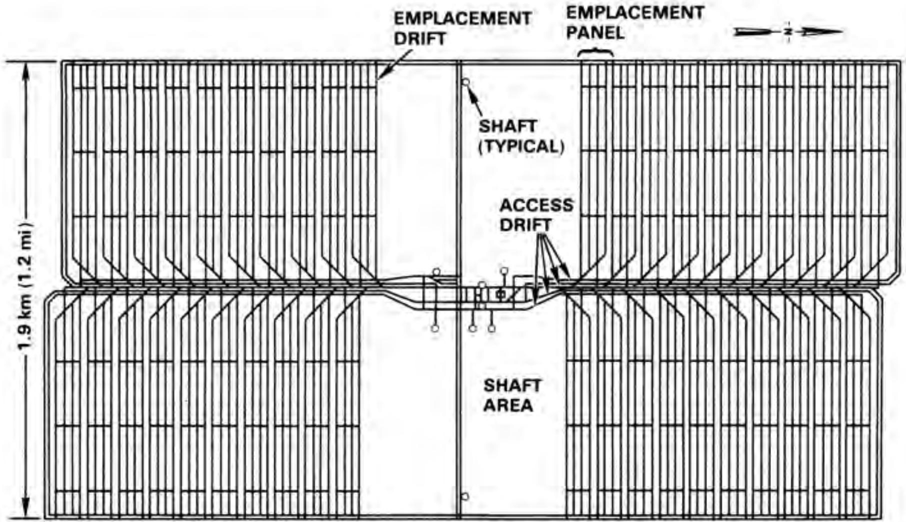

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Fig. 2. Underground Repository Layout.

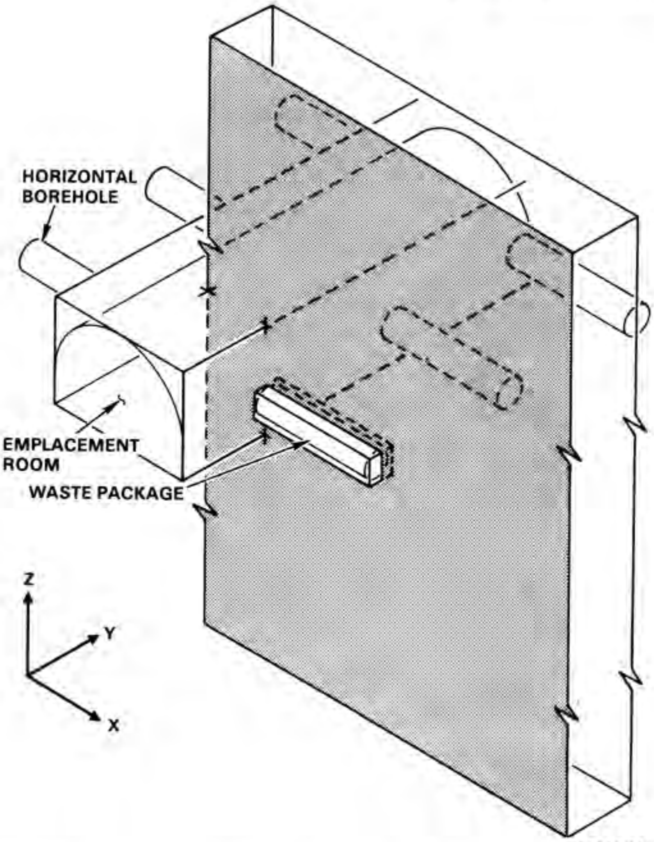

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Fig. 3. Integrated Three-Dimensional Thermal Model Based on Assumptions of Geometric Symmetry and Waste Package Simulataneous Emplacement.

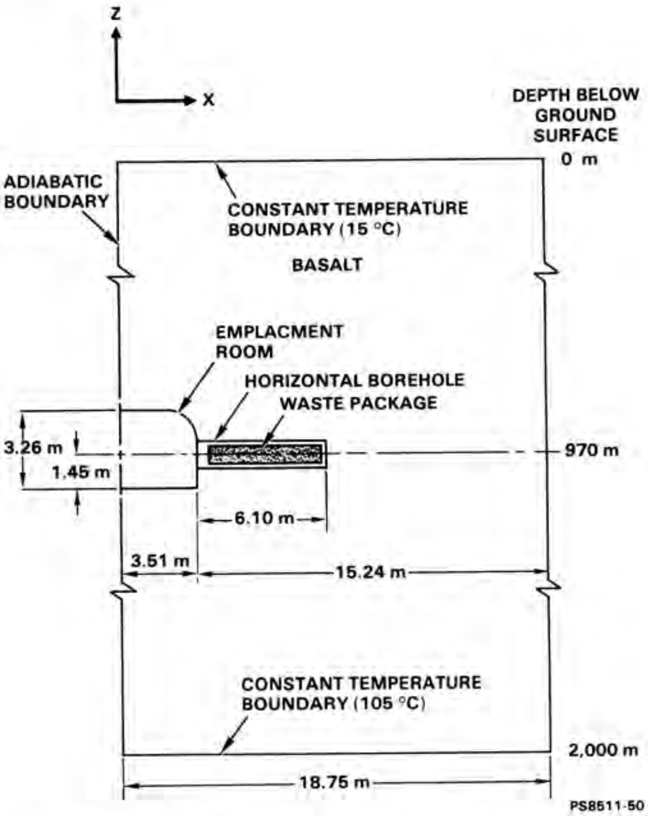

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Fig. 4. Detailed XZ Plane Dimensions of the Integrated Three-Dimensional Model.

A very fine grid size is used within the waste package to provide accurate temperature predictions. As the distance from the waste package increases, the grid sizes gradually increase. This approach is based on the fact that the thermal gradient diminishes as the distance from the heat source increases.

The significance of this modeling approach is that it simultaneously provides both the thermal fields of the waste package and its near-field and far-field environment. This is in contrast with previous work (e.g., Ref. 2). For most earlier analyses, the domain of the investigation was usually divided into three regions: the waste package, the near field and the far field. For each of these divided regions, a computational model was constructed. To ensure consistency among these models, they were linked artificially at the boundaries between the regional models. The contribution of the present modeling effort is the elimination of the mathematical discontinuities on the boundaries between regions. Furthermore, the in situ (natural) temperature gradient of the basalt site has been imposed in the present model to obtain realistic assessment for the waste package temperature profile with inherent temperature effects.

RESULTS

The waste package designs considered three different waste forms: consolidated spent fuel (CSF), intact spent fuel assembly (SFA), and West Valley high-level waste (WVHLW). These three designs were investigated separately in the reliability study. In this paper, the CSF waste package is used to illustrate the basic characteristics of the temperature profiles, which are similar for all three cases.

The temperature histories of the waste package design for CSF and its immediate vicinity are plotted in Fig. 5. The initial decay power of the waste form is 2,069 W. The temperature at the center of the spent fuel increases rapidly and reaches its peak at 263 °C about 10 yr after the waste package is emplaced in the horizontal borehole. Beyond 10 yr, the spent fuel temperature decreases more or less exponentially for 1,000 yr. The temperatures at midplane and at the ends of the container exhibit a noticeable difference in the first 100 yr after emplacement. Hence, to show their difference, two curves were plotted: at the center portion of the container (curve B) and at one of its ends (curve B'). At the first year after emplacement, there is a difference as high as 30 °C.

The temperature histories of the container, curve B and curve B', follow a pattern similar to the waste form (spent fuel) and peak approximately 10 yr after emplacement with temperatures of 221 °C and 198 °C, respectively. Similarly, packing temperature (inner surface of the horizontal borehole, curve C) peaks at 12 yr with a temperature of 186 °C. Curve D represents the host rock temperature history at the vicinity of the waste package (1.6 m from the center of the waste package). The temperature history has a considerable component temperature. It peaks at about 24 yr after emplacement, stays in the plateau for some 20 yr, then slowly moves downward.

The prediction of the temperature difference within a container has not been reported previously. The difference is the direct result of the axial temperature gradient along the spent fuel inside the container. The axial temperature gradient of the container cannot be totally diminished due to the rather long length of the container in relation to its thickness (even though the conductivity of the container is very high). The current model for waste form heat generation is assumed uniform. In reality, however, both ends lack heat-generating materials. Therefore, it is anticipated that in reality both ends of the container will be cooler.

To clarify the observation of temperature difference in a container, plots to illustrate the axial temperature profiles in the waste form and its container for 1, 5, 10, 25, and 50 yr after emplacement are shown in Fig. 6 and 7, respectively.

The temperature profiles of the near field as functions of distance from the waste package center in planes A-A' and B-B' along the Z direction are shown in Fig. 8(a) and Fig. 8(b), respectively. From these figures, the temperature gradients as functions of distance can be seen; and these gradients could be used to estimate the thermally induced stress of the host rock. Steeper temperature gradients exist out to ~5 m along the B-B' plane, whereas the gradients within ~5 m along the A-A' plane are more benign. It is clear that the thermally induced stress is three-dimensional and certain cautions should be exercised. Since the in situ stresses in the basalt flow are not isotropic, a given temperature gradient in different directions will produce different results. As time passes, the temperature gradient gradually decreases as can be seen in the thermal contour plots in Fig. 9(a) through 9(d) for 1, 5, 25, and 50 yr, respectively.

The temperature profiles for the far field up to 1,000 yr are plotted in Fig. 10 in the Y-Z plane through the center of the waste package. It can be seen that in the earlier years after emplacement, considerable temperature gradients exist. When the time after emplacement becomes large, the temperature gradient decreases.

The far-field thermal profiles were obtained by the present integrated thermal analysis without any additional effort when the boundary conditions were properly set. Even though the focus of the present study is on the waste package and its immediate environment, this far-field information is useful for overall assessment of repository performance. This is one of the advantages of the integrated-model approach.

In the uncertainty analysis, the decay power and the thermal conductivity of the waste form and packing have been varied in their estimated ranges. It is found that the conductivities of the waste form, as well as of the packing, are the most influential parameters affecting the temperature profiles. The ranges considered in the study showed that a temperature difference of more than 70 °C may result from the uncertainty of the conductivities.

Important temperatures from the thermal analysis for the three designs (i.e., CSF, SFA, and WVHLW) are summarized in Table I. Two values are listed as calculated peak temperatures: one is from the nominal case, and the other is the highest temperature from the uncertainty analysis. As can be seen, all predicted temperatures are well within current BWIP temperature limits.

CONCLUSIONS

Based on the thermal analysis results of the preliminary reliability assessment for the post-emplacement period under anticipated conditions, the following conclusions may be drawn.

- The predicted temperatures of the waste package design are all within the current BWIP temperature limits that affect the waste form, container, packing, and host rock.

- The present investigation points out that three-dimensional modeling is warranted since the axial temperature gradient in the container is significant. This temperature gradient may be a concern with respect to the corrosion behavior of the container.

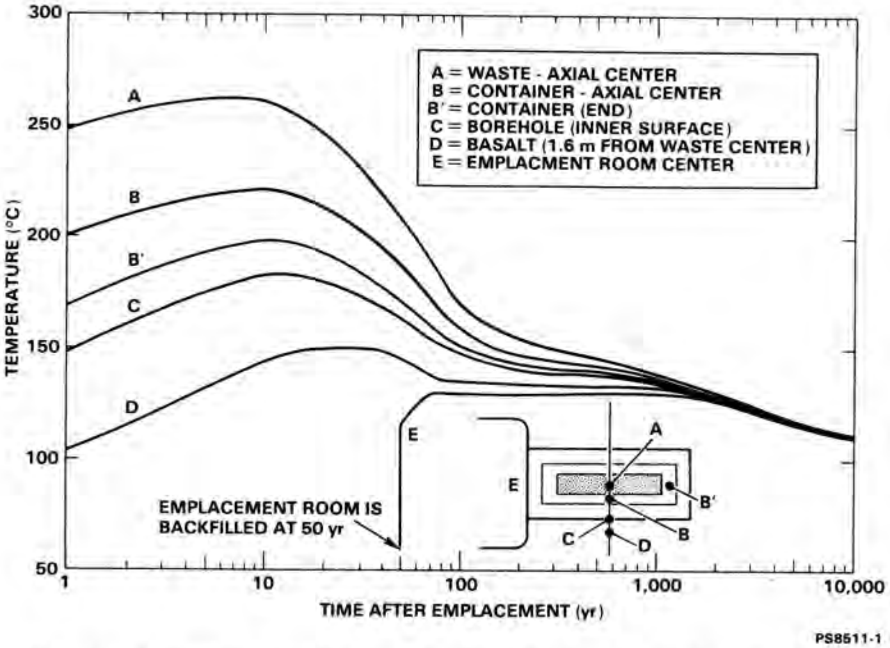

Fig. 5. Temperature Histories in and Near Consolidated Spent Fuel Waste Package in the Nominal Case, Calculated by the Integrated Thermal Model.

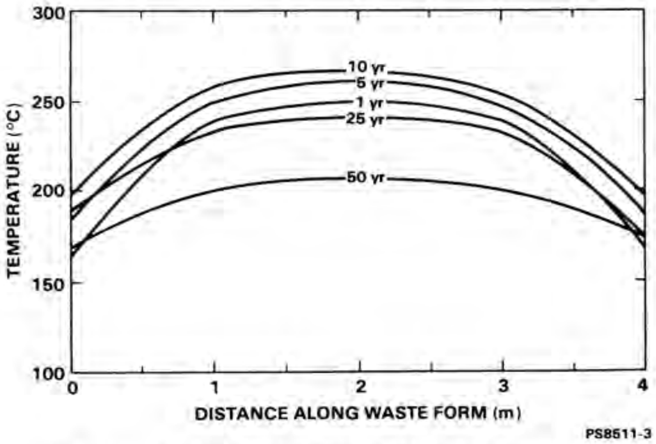

Fig. 6. Axial Temperature Profiles in Consolidated Spent Fuel Waste Form Midplane.

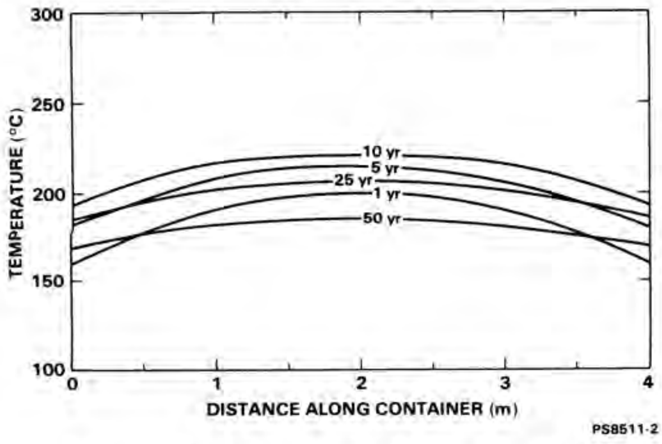

Fig. 7. Axial Temperature Profiles in Container for Consolidated Spent Fuel Waste Form.

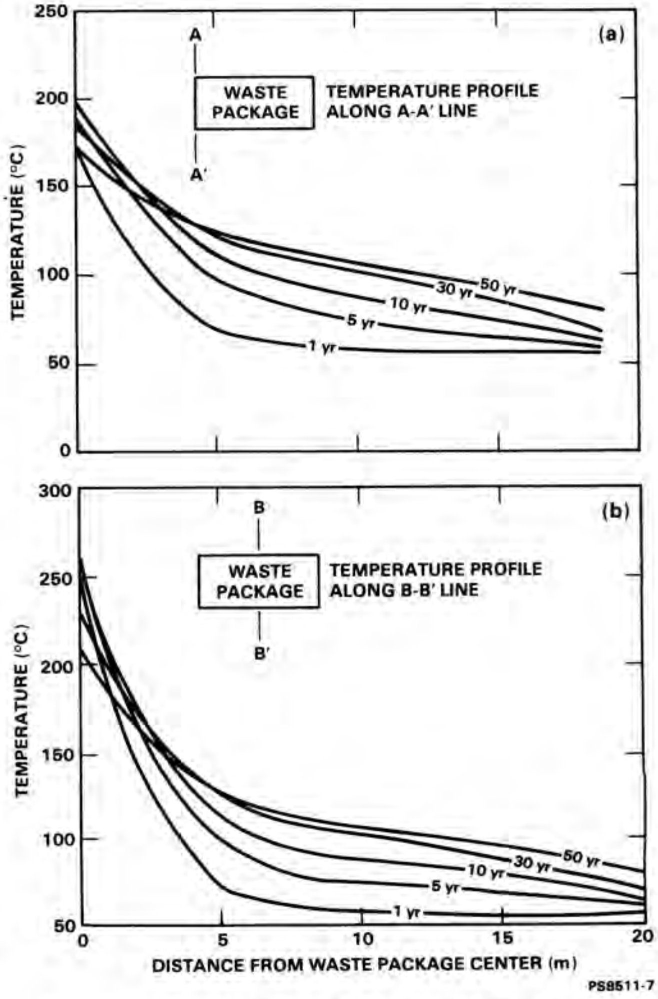

Fig. 8. Temperature Profiles in the Near Field of the Consolidated Spent Fuel Waste Package.

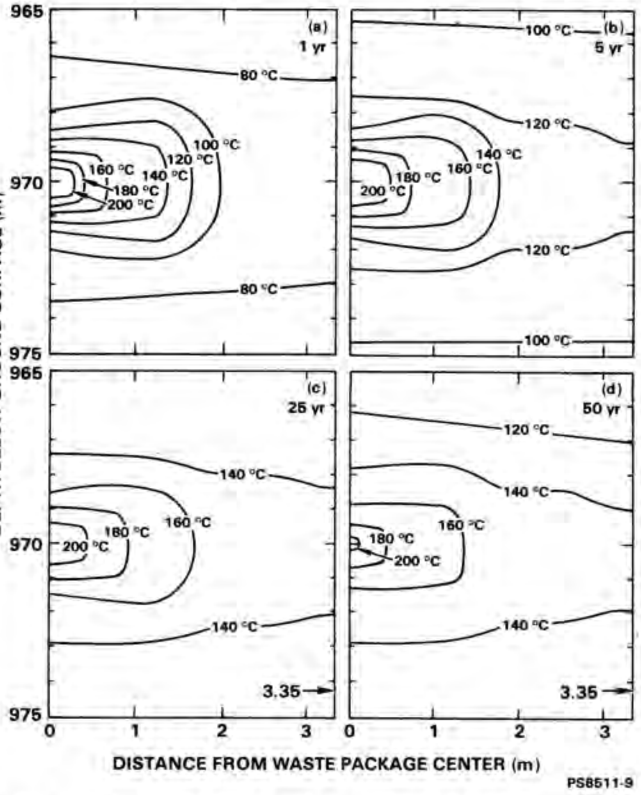

Fig. 9. Isotherms in the XZ Plane Through Consolidated Spent Fuel Waste Package Center 1, 5, 25, 50 Yr after Emplacement.

- The integrated model provides a completed and integrated profile for the waste package, its near field, and far field in a single computation and is recommended for detail design thermal analysis.

In the uncertainty analysis, the decay power and the thermal conductivity of the waste form and packing have been varied in their estimated ranges. It is found that the conductivities of the waste, as well as of the packing, are the most influential parameters affecting the temperature profiles. The ranges considered in the study showed that a temperature difference of more than 70 °C may result from the uncertainty of the conductivities.

Important temperatures from the thermal analysis for the three designs (i.e., CSF, SFA, and WVHLW) are summarized in Table I. Two values are listed as calculated peak temperatures: one is temperature from the uncertainty analysis. As can be seen, all predicted temperatures are will within current BWIP temperature limits.

REFERENCES

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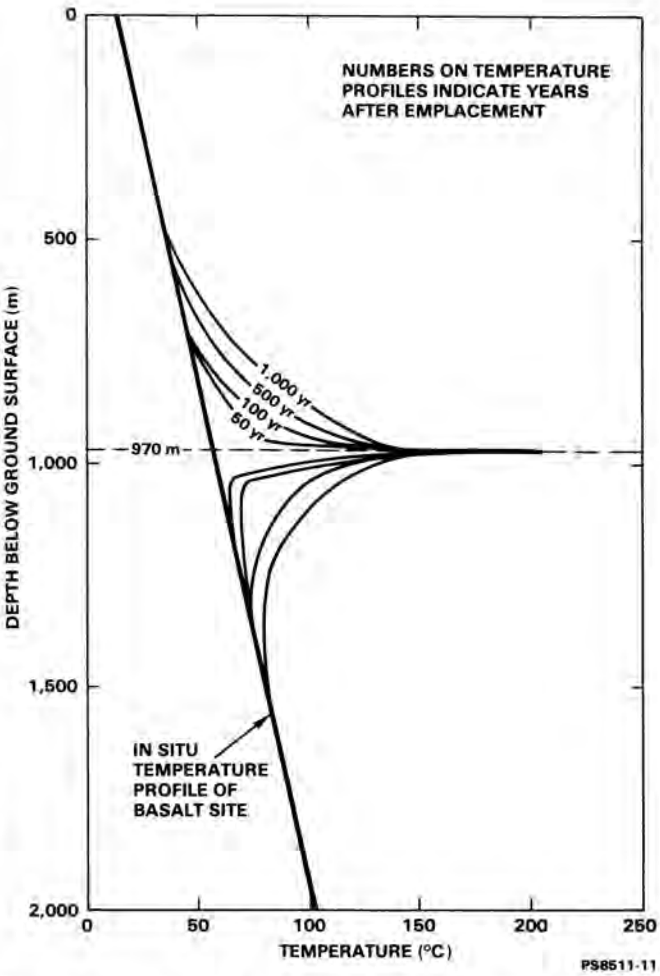

Fig. 10. Far-Field Temperature Profiles in YZ Plane Through Center of Consolidated Spent Fuel Waste Package.

TABLE I

Important Temperatures from HEATING5 Computation Results.

Components	Design allowable temperature, °C	Peak calculated temperature, °C	
		Nominal	Uncertainty
Consolidated Spent Fuel			
Waste Form	400	263	304
Container	430	221	250
Packing	370	221	250
Basalt	450	183	195
Spent Fuel Assembly			
Waste Form	400	213	280
Container	430	204	235
Packing	370	204	235
Basalt	450	167	167
West Valley High-Level Waste			
Waste Form	500	81	86
Container	430	75	79
Packing	370	75	79
Basalt	450	71	72