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PARAMETRIC THERMAL ANALYSIS FOR CODISPOSAL WASTE PACKAGE CANISTER

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ABSTRACT

The engineering viability of disposal of aluminum-clad, aluminum-based spent nuclear fuel (Al-SNF) in a geologic repository requires a thermal analysis to provide the temperature history of the waste form. Calculated temperatures are used to demonstrate compliance with criteria for waste acceptance into the Mined Geologic Disposal System and as input to assess the chemical and physical behavior of the waste form within the waste package (WP).

A thermal analysis methodology was developed to calculate peak temperatures and temperature profiles of Al-SNF in the DOE spent nuclear fuel canister within a codisposal WP. A two-dimensional baseline model with conduction and radiation coupled heat transport was developed to evaluate the thermal performance of Al-SNF directly stored in a canister in a codisposal WP over the range of possible heat loads and boundary conditions. In addition, a conduction model and a detailed model which includes convection were developed to identify the dominant cooling mechanism under the present WP configuration, to investigate physical cooling mechanism in detail, and to estimate the conservatism imbedded in the baseline model.

The results of the baseline model showed that the direct disposal configuration with a helium-filled WP satisfied the present waste acceptance criteria (WAC) for the WP design in terms of the peak temperature criterion, $T_{max} \leq 350$ °C, under the reference boundary conditions. A period of 10 years' cooling time for the decay heat loads of the SNF and the High-level Waste Glass Log (HWGL) regions was used as one of the reference design conditions.

1. INTRODUCTION

A thermal analysis is made to calculate peak temperatures and profiles of the codisposal waste package (WP). The leading codisposal WP design proposes that a central DOE spent nuclear fuel (SNF) canister be surrounded by five defense waste process facility (DWPF) glass log canisters, that is, High-level Waste Glass Logs (HWGL's), in a WP. The codisposal WP will be laid down horizontally in a drift tunnel repository. The present model for the WP thermal performance analysis is shown in Fig. 1.

There are two waste form options for Al-SNF disposition using the codisposal WP design configuration. They are the

- direct Al-SNF form and the
- melt-dilute Al-SNF form.

For the direct form option, a total of up to 64 standard-sized Material Test Reactor (MTR) type Al-SNF fuel assemblies, some with highly-enriched U, are to be packed in a DOE SNF canister. For the melt-dilute form option, a number of Al-SNF assemblies are melted and diluted to be emplaced in the central DOE SNF stainless steel canister, which result in a SNF canister containing uranium-aluminum alloy ingots. The present results are for the direct Al-SNF form. Thermal analysis of the melt-dilute Al-SNF form is in progress.

The transient decay heat loads were recently developed for this analysis [1]. The heat loads included the Al-SNF assemblies in the direct form and the HWGL. The Al-SNF heat loads were computed by the ORIGEN code under SCALE 4.2 system.

Thermal performance analysis of the codisposal WP for licensing would be performed for the specific design conditions and thermal history of a geological repository. This information is not available at this time. Therefore, reference design conditions were assumed to perform the analyses. The assumed reference conditions are shown in Table 1. In addition, sensitivity analyses for key design parameters of the codisposal WP were performed over a range of boundary conditions.

The objective of this study is to develop a thermal analysis methodology and to perform analyses of codisposal storage configurations to estimate the SNF, HWGL, and WP temperatures in a geological repository for various boundary conditions. The present paper addresses thermal performance internal to the codisposal WP (see Fig. 1 for the computational domain of the present model).

Three thermal models were developed to assess the thermal performance of the codisposal WP design using intact prototypic geometry created under the body-fitted coordinate system in the computational fluid dynamics (CFD) preprocessing environment. They are the conduction model, the conduction-radiation coupled model referred to as baseline model in this paper, and the detailed model. The present baseline analysis uses the baseline model based on a parametric approach to evaluate thermal performance for each WP design option since the baseline model is the most efficient one among them in terms of computational time and reasonable accuracy. The detailed model is considering the convection and radiation as well as conduction cooling processes to estimate the conservatism of the baseline model for a typical design condition and to understand the physical cooling mechanism in full detail for the present codisposal WP design.

The thermal analysis results will be used to demonstrate compliance with the waste acceptance criteria (WAC) for the MGDS and as input to assess the chemical and physical behavior of the Al-SNF forms within the WP.

2. DESCRIPTION OF THE PRESENT APPROACH

A codisposal waste package contains High-Level Waste Glass Logs (HWGL) and a DOE Spent Nuclear Fuel (SNF) canister. The codisposal WP is emplaced horizontally at the center of a geological drift tunnel. The single DOE SNF canister will be surrounded by five HWGL canisters inside the codisposal WP as schematically shown in Fig. 1. Both the canister and the WP will be filled with air or helium depending on the design.

A general energy balance equation on a control volume of the WP is given in a vector form as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \beta T \frac{DP}{Dt} + \nabla \cdot \left(k \nabla T - q_r \right) + q''' \qquad (1)$$

Energy terms within a control volume of the package include convection, $(\vec{v} \cdot \nabla T)$ conduction ($k \nabla T$), radiation heat transfer (q_r), internal heat sources (q'''), compression work of back-filled gas ($\beta T\,(DP/Dt)$), and energy storage due to transients ($\rho C_p\, \partial T/\partial t$). A steady state temperature distribution was assumed for a selected time since the waste package transient temperatures will reach equilibrium in a few days. When a convection term is not included in a transparent gas medium, the heat conducted into a wall surface is balanced by the radiant heat lost from the wall surface as seen by Eq. (1).

For the present baseline model, a two-dimensional, steady state, a conduction-radiation coupled model was developed using uniformly-distributed heat generation sources within HWGL and SNF canisters to predict the package thermal performance within a geological repository. It is assumed to have no solid conduction paths among the SNF and HLWG canisters such that the HLWG canisters, the SNF canister, and the codisposal waste package inner wall do not touch each other since final geometrical configuration for the codisposal WP is neither confirmed nor available yet. A half-cylinder model of the codisposal waste package was used as a computational domain for computational efficiency by imposing symmetrical boundary conditions along the centerline of the WP as shown in Fig. 1.

The ambient temperature around the package was assumed to be uniform. A typical natural convective heat transfer coefficient of 1.5 $W/m^2\,°C$ was used as an external wall boundary condition of the WP for the present analysis. The present value of the heat transfer coefficient was computed on a conservative basis from the literature data [2]. An effective thermal conductivity for the fuel assembly region of the direct Al-SNF canister was obtained from the SRS separate-effect test using a volumetric-averaging technique [3]. The CFD approach has been taken to model and simulate the thermal performance for the direct and melt-dilute codisposal WP's in a geological drift tunnel repository. The CFX code had been previously used to simulate and benchmark the test data for the interim dry spent nuclear fuel storage canister with reasonable accuracy [4].

The main design parameters involved in the thermal performance analysis of the WP are:

- Different combinations of back-filled gases in the SNF canister and the WP container (e.g., helium-helium, air-air)
- Various sets of combinations of SNF and HWGL decay heat sources
- Repository temperature history since emplacement of waste package in a geologic repository

The thermal performance analysis for the codisposal WP requires known values for the design parameters listed above to study design options for a codisposal waste package. Some of them are not available at this time. For the present work, initial reference time was assumed to be 10 years' cooling time since the discharge from reactor and production of HWGL. Thus, reference conditions were used to perform the baseline analysis for each design option of the direct and the melt-dilute codisposal waste packages as shown in Table 1. Sensitivity analyses for some of the main design parameters were performed with respect to the reference conditions.

3. RESULTS AND DISCUSSIONS

Based on the approach methodology and the assumptions, the two-dimensional conduction model, conduction-radiation coupled model, and conduction-convection-radiation conjugated or detailed model were developed to investigate key design parameters and to find sensitivities to the changes of the design parameters with respect to the reference conditions in relation to the thermal performance assessment of the codisposal WP. The CFD code CFX 4.1 was used as a tool to create the geometry file under a non-orthogonal mesh environment and body-fitted coordinate system and to solve the non-linear conjugate equations. Buoyancy-driven natural convective cooling and discrete radiation transport were applied for the detailed model.

The thermal performance analyses were made based on the decay heat sources for the reference conditions shown in Table 2. The direct WP temperatures were then computed for selected times during the first 2000 years after emplacement in the repository. Figure 2 shows radial temperature distributions of the codisposal WP under the reference conditions as a function of storage time using the baseline model. Maximum temperature for the baseline model is about 304 °C at the initial storage time (0 years of storage time). The conduction model predicts maximum temperature by 121 °C higher than the baseline model, that is, conduction-radiation coupled model, does. The detailed model considering all the three modes of thermal energy transport predicts about 303 °C for the maximum temperature of the codisposal WP at 0 years of storage time under the same reference conditions. The radial temperature profiles performed by the two models are shown in Fig. 3.

The present work was also conducted over a wide range of possible repository temperature conditions. Figure 4 presents peak temperatures with respect to repository temperatures for two different WP designs. It was also noted that the peak temperature location of the WP is moved from the central edge of the HWGL region to the SNF region as the heat load of the SNF canister increases.

4. CONCLUSIONS

Three thermal models were developed to assess the thermal performance of the codisposal WP design using intact prototypic geometry created under the body-fitted coordinate system in the CFD preprocessing environment. They are the conduction model, the baseline model considering conduction-radiation coupled heat transfer mechanisms, and the detailed model including all three possible modes such as conduction, convection, and radiation energy transport processes.

The present analysis used well-defined decay heat loads for the SNF canister and HWGL regions. Reference model boundary conditions were provided by the WP performance requirements of a drift tunnel repository. In this report, the direct spent fuel disposal was considered for the alternative SNF treatment program using the codisposal WP configuration. The thermal performance analyses for various design options of the present codisposal WP configuration were performed mainly using the baseline model because of the computational efficiency. The analysis of the melt-dilute Al-SNF form is in progress.

The results of the detailed model provided quantitative estimation of the conservatism imbedded in the baseline model. The detailed model gave highly non-uniform package wall surface temperature such that top surface temperature of the WP is about 10 °C higher than that of the bottom surface. On the other hand, as shown in Fig. 3, the baseline model results showed that top temperature is slightly lower than the bottom surface of the WP due to the neglect of internal buoyancy-driven gas circulation although the baseline model predicts the peak temperature similar to that of the detailed model. The detailed model results also showed that temperature gradients across the HWGL regions are much smaller compared to the baseline model results for a given elevation height from the bottom of the WP in a horizontal storage position. This is one of the evidences of the buoyancy-driven circulation internal to the codisposal WP. This phenomenon may be important in relation to the movement of water moisture around the WP surface inside a drift tunnel since the moisture directly affects corrosion of the WP materials. Peak temperatures with the detailed model are about 1 °C lower than those of the baseline model under the reference conditions. From the results of the conduction model, the radiative cooling mechanism is shown to be the most dominant cooling mode among the three possible cooling modes for higher than 130 °C of the peak package temperature although detailed cooling mechanisms are quite different each other.

Table 1. Reference design conditions for the present thermal analysis.

Design Parameters	Design Conditions
• Back-filled Gas Inside / Outside of SNF Canister in Codisposal WP	• Helium gas inside and outside of SNF canister
• Transient Decay Heat Loads for SNF and HWGL	• Bounding decay hjeat source and DWPF canister design basis (See Table 2)
• Initial Reference Time (Storage Time: "Year 0")	• 10 year cooling time since discharge from reactor and production of HWGL
• Internal Structure of the WP Container	• Intact codisposal geometry
• Repository Ambient Temperature	• 100 °C
• WP Location in a Repository Tunnel	• Center of a drift tunnel

Table 2. Bounding decay heat source in SNF canister and HWGL regions for direct codisposal WP.

Storage Time (yrs)	Assembly Power (W/assembly)	Power per HWGL (W)	Total Power for SNF Can. (W)	Volumetric SNF Power (W/m3)	Volumetric HWGL Power (W/m3)
0	8.58	472.3	549.12	2735.752	530.913
10	6.53	375.99	417.92	2082.105	422.651
20	5.243	301.35	335.552	1671.742	338.748
50	2.83	159.5	181.12	902.352	179.294
90	1.382	73.1	88.448	440.654	82.1718
190	0.487	16.81	31.168	155.281	18.896
290	0.3442	7.09	22.0288	109.749	7.9699
590	0.2218	1.98	14.1952	70.721	2.2257
990	0.1468	1.14	9.3952	46.808	1.2815
1990	0.0794	0.72	5.0816	25.317	0.8094
2990	0.063	0.62	4.032	20.088	0.6969
5990	0.0505	0.52	3.232	16.102	0.5845
9990	0.041	0.43	2.624	13.073	0.4834
19990	0.0265	0.3	1.696	8.4496	0.3372
49990	0.0103	0.16	0.6592	3.2842	0.1799
99990	0.0034	0.11	0.2176	1.0841	0.1237

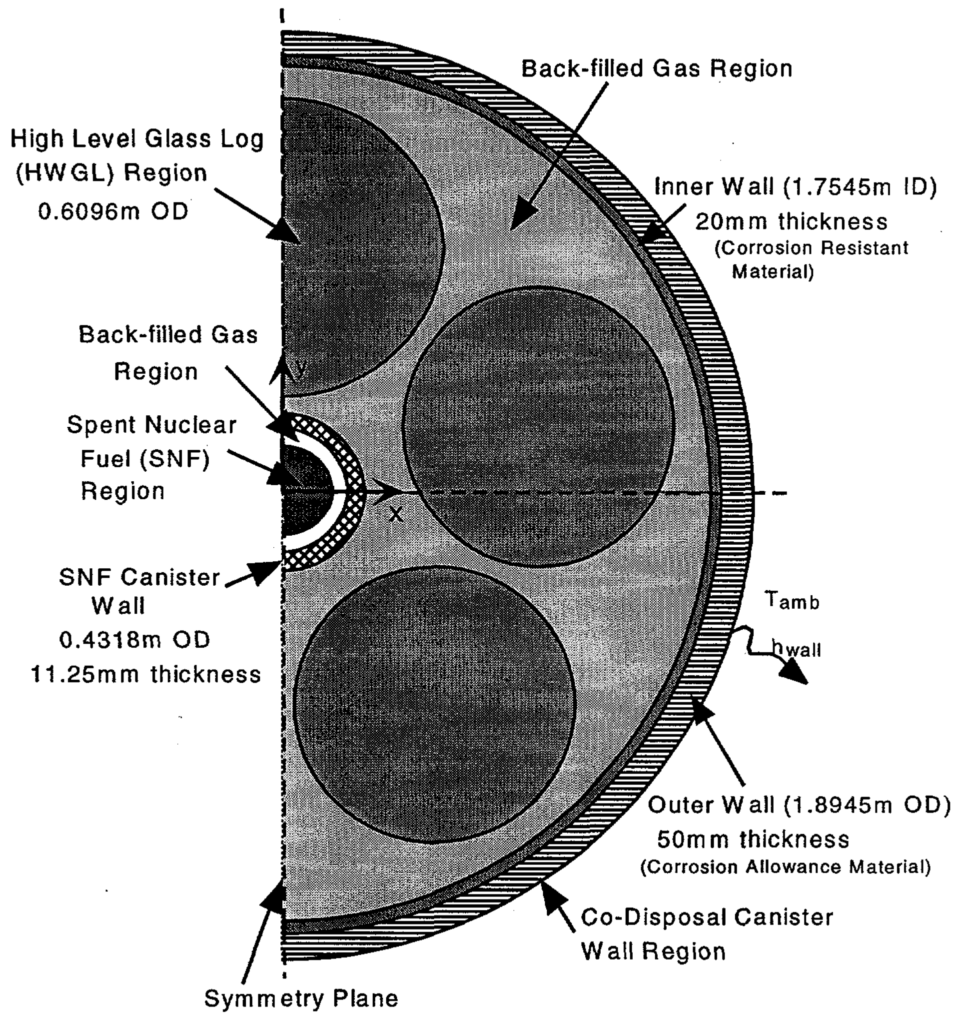
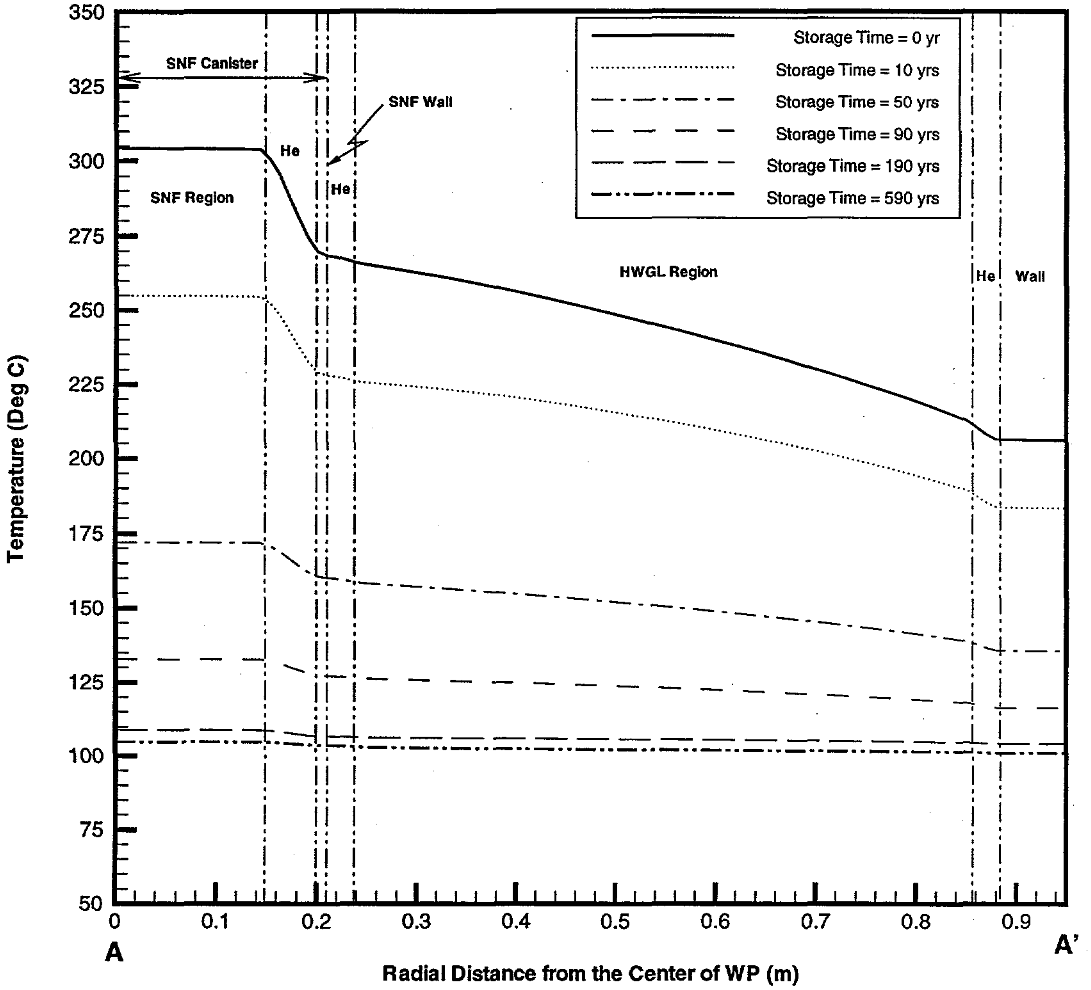


Figure 1. Thermal Modeling of codisposal SNF waste package in a geological repository.



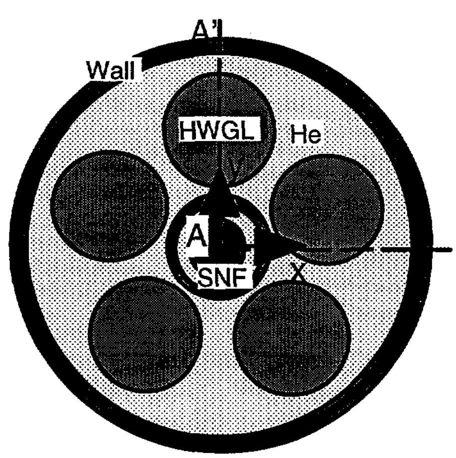


Figure 2. He-cooled direct codisposal WP temperature distribution for various storage times based on the baseline model with bounding SNF decay heat source.

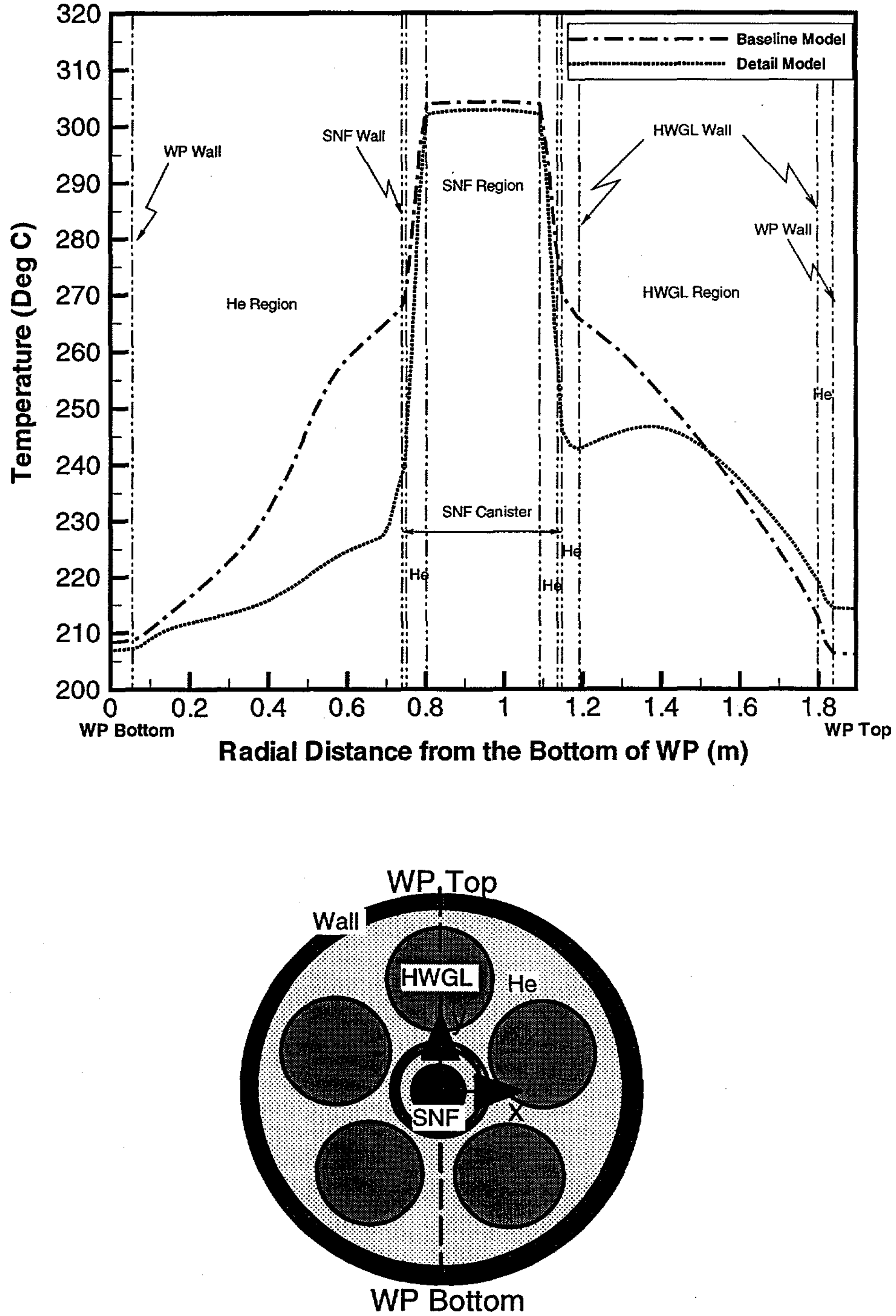


Figure 3. Comparison of centerline temperature distributions based on the baseline model and the detailed model for helium-cooled direct codisposal WP with bounding decay heat source.

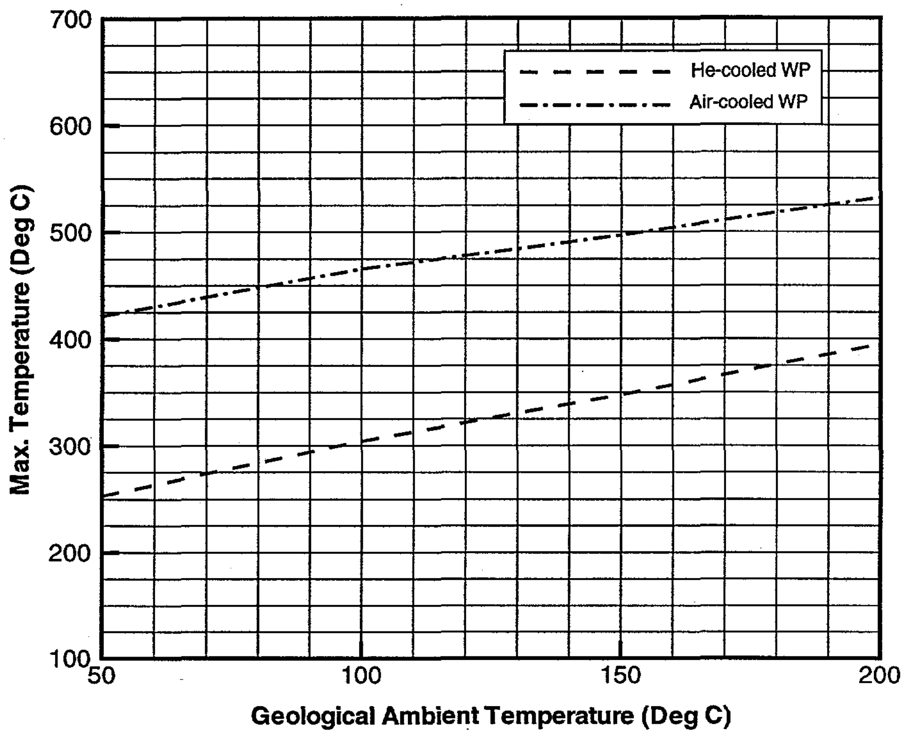


Figure 4. Maximum temperatures of air-cooled and helium-cooled direct codisposal waste packages with bounding SNF decay heat loads for various geological ambient temperatures.

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