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THERMAL PERFORMANCE OF A DEPLETED URANIUM SHIELDED STORAGE, TRANSPORTATION, AND DISPOSAL PACKAGE[a]

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I. INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for management and disposal of large quantities of depleted uranium (DU) in the DOE complex. Viable economic options for the use and eventual disposal of the material are needed. One possible option is the use of DU as shielding material for vitrified Defense High-Level Waste (DHLW) storage, transportation, and disposal packages. Use of DU as a shielding material provides the potential benefit of disposing of significant quantities of DU during the DHLW storage and disposal process.

Two DU package concepts have been developed by Sandia National Laboratories.[1] The first concept is the Storage/Disposal plus Transportation (S/D+T) package. The S/D+T package consists of two major components: a storage/disposal (S/D) container and a transportation overpack. The second concept is the S/D/T package which is an integral storage, transportation, and disposal package. The package concept considered in this analysis is the S/D+T package with seven DHLW waste canisters.

The S/D+T package provides shielding and containment for the DHLW waste canisters. The S/D container is intended to be used as an on-site storage and repository disposal container. In this analysis, the S/D container is constructed from a combination of stainless steel and DU. Other material combinations, such as mild steel and DU, are potential candidates. The transportation overpack is used to transport the S/D containers to a final geological repository and is not included in this analysis.

The scope of this effort is to calculate the thermal performance of the S/D container of the S/D+T package in storage and in an underground repository. The results of the thermal calculations can allow design changes in the S/D container and the transportation overpack which will allow heat dissipation in a more efficient manner.

II. DESCRIPTION

The S/D container and repository were modeled using PATRAN[2] as a pre- and post-processor and P/THERMAL[3] as the thermal solver. Calculations of the S/D container and repository thermal response were made and results from the calculations are presented.

A. Thermal Model

The thermal model is a two-dimensional representation of the S/D container and the repository. The thermal model was used to calculate the thermal response of the S/D container in on-site storage and in final disposal at the repository. Axes of symmetry were used to simplify the thermal model. Details of the S/D container are included in the model. The thermal model consists of 7179 nodes and 8781 elements. Figure 1 presents the overall thermal model geometry.

1. On-site storage thermal model. The on-site storage thermal model assumes storage occurs outdoors in a hot climate. A steady-state analysis was performed to calculate the maximum S/D container on-site storage temperatures. Instead of developing a separate on-site storage

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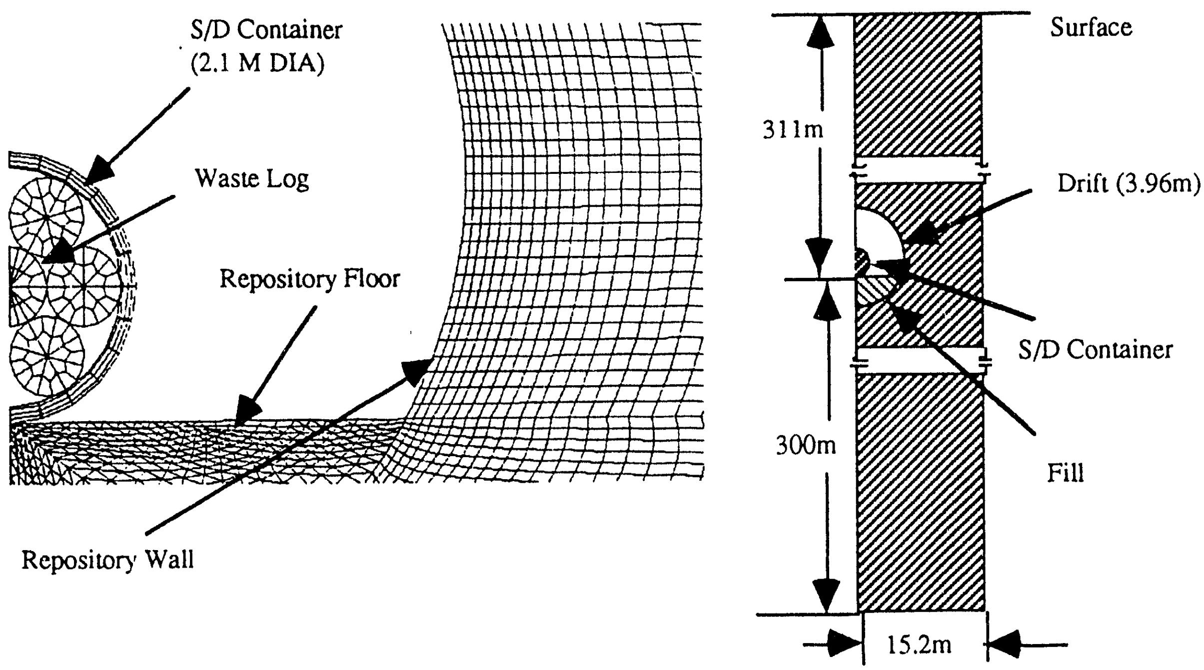

Figure 1. S/D Container and Repository Thermal Model

thermal model, the disposal thermal model was modified and used to analyze the storage condition of the S/D container. The modified disposal thermal model was used in order to reduce analysis time. The repository was thermally disconnected from the S/D container by fixing the temperature of the repository wall and floor to the ambient temperature of the on-site storage condition.

The storage thermal model used both radiation and convection heat transfer. Radiation and convection was used to transfer heat from the S/D container to the ambient boundary condition. The heat transfer between the DHLW canisters and between the outer DHLW canisters and inner surface of the S/D container was assumed to be radiation only. An emissivity of 0.5 was used for the DHLW canister and inner and outer package surfaces.[4] Solar loading was also included.

2. Disposal thermal model. The disposal thermal model was based on an in-drift emplacement geometry.[5] The S/D container was thermally coupled to the repository wall and floor by radiation heat transfer only. The radiation-only coupling is a conservative assumption, and produces an upper bound on the maximum temperatures in the S/D container. Steady-state analyses indicate that the temperatures calculated with radiation-only coupling are on the order of 4 to 5 percent higher than temperatures calculated including convection effects. Heat transfer between the DHLW canisters and between the outer DHLW canisters and inner surface of the S/D container were also assumed to be radiation only. An emissivity of 0.5 was used for the DHLW canister and inner and outer package surfaces.[4] An emissivity of 0.83 was used for the rock tuff and rock fill.[4] P/Thermal was used to calculate radiation shape factors.

The thermal analysis started with a steady-state analysis to define the temperature gradients in the S/D container. The next step in the analysis was to perform a transient thermal calculation. The transient analysis used the steady-state results to define the initial temperature distribution within the S/D container. Since the objective of the analysis was to calculate maximum temperatures in the S/D container, a 50-year simulation time period was used.

B. Material Properties

The materials used in the thermal analysis were stainless steel, depleted uranium, vitrified waste, air, rock tuff, and rock backfill. Variable temperature material properties were used for the thermal conductivity and specific heat of stainless steel, waste, and air. The heat capacity of the rock tuff was also a variable temperature material property. The remaining material properties did not vary with temperature. Tabulated data was used for the stainless steel and air material properties. Table 1 presents the thermal properties used in the analysis for stainless steel, vitrified waste, air, rock tuff, and rock backfill at room temperature.

The waste thermal conductivity and heat capacity were modeled with linear polynomials. The waste thermal

Table 1. Storage/Disposal Container and Repository Material Properties

Material	Thermal Conductivity (W/m-C)	Thermal Capacitance (J/cm^3-C)
Stainless Steel	13.4	3.98
Waste	0.876	2.0943
Air	0.0242	0.00129
Depleted Uranium	25.6	2.548
Rock Tuff	2.1	2.14
Rock Fill	0.65	1.53

conductivity was 0.845+.00123*T(°C) W/m-C. The waste specific heat was 2.071+0.000935*T(°C) J/cm^3-C. The heat capacity of the rock tuff was 2.14 J/cm^3-C below 94°C, 10.48 J/cm^3-C between 94° and 114°C, and 2.18 J/cm^3-C above 114°C.

C. Boundary Conditions

1. Storage boundary condition. The storage thermal model ambient temperature was fixed at 38°C. Solar loading was included by applying a heat flux of 387.5 W/m^2 to the surface of the container. A convection coefficient of 5 W/m^2-°C was used to simulate natural convection from the container in still air.

2. Disposal boundary condition. Constant temperature boundary conditions were used for the upper and lower horizontal surfaces of the repository portion of the disposal model. The upper horizontal surface, representing an average surface temperature, was fixed at 18°C. The bottom horizontal surface was fixed at 31.7°C. The vertical surfaces were lines of symmetry and assumed to be adiabatic.

3. Waste heat. Heating from the waste was included in the S/D container. The waste heat loading decayed with time[6] and tabulated values were used to describe the waste heat loading. Three initial waste heat values were used in the analysis. The values were chosen to bound the range of expected waste heat generation. The first waste heat loading[7] was 450 W/m^3, the second waste heat loading was 200 W/m^3, and the third waste heat loading was 100 W/m^3.

III. RESULTS

A. Storage

Figure 2 presents the waste heat-maximum temperature during storage plot for the S/D container surface, center waste DHLW canister, and outer waste log. A quadradic polynomial curve fit of the form

$$T=C_0+C_1Q+C_2Q^2$$

where

T = temperature (C), and
Q = waste heat (W/m^3)

was used to produce the curves presented in Figure 2. The curves in Table 2 are intended as a design tool for futher development of the S/D container. Table 2 presents the coefficient for each curve in Figure 2.

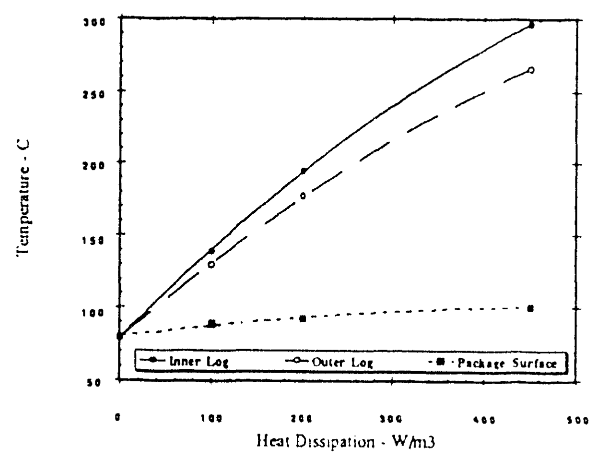

Figure 2. S/D Temperatures as a Function of Heat Dissipation for the Storage Condition

B. Disposal

Figure 3 presents a time-temperature plot for each waste heat loading of the S/D container in the repository. The S/D container surface and waste DHLW canister centerline temperatures are plotted. Figure 4 presents a waste heat-maximum temperature plot for the S/D container surface, center waste DHLW canister, and outer waste log.

Convection was included in the steady-state initial analysis for the 450-kW waste heat loading case. The temperature

Table 2. Curve Fit Coefficients for Figure 2

Location	C_0	C_1	C_2
Inner Log	79.333175168	0.64666878182	-0.00036568034469
Outer Log	79.332388954	0.54122813057	-0.00028099273654
Container Surface	80.224551834	0.082433620098	-8.1676926479e-05

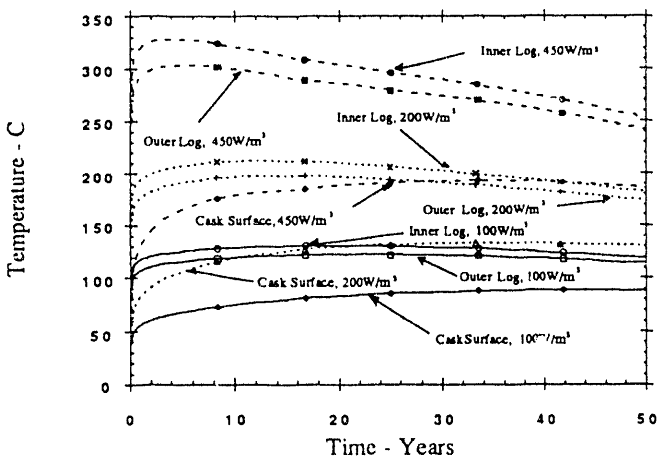

Figure 3. S/D Container Temperatures as a Function of Time and Waste Heat

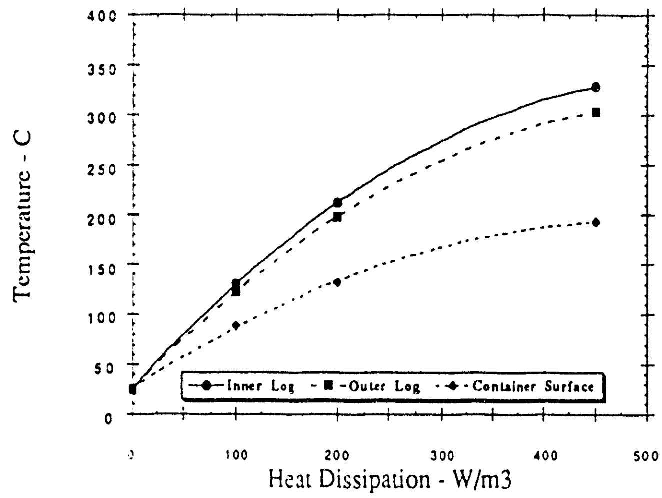

Figure 4. Maximum S/D Container Temperatures as a Function of Heat Dissipation

difference between the radiation-only and radiation-convection case is between 4 and 5 percent, so, for this thermal analysis, the primary mode of heat transfer is radiation. Conduction was not included from the S/D container to the repository, so the actual maximum temperatures are expected to be lower that the temperatures presented in this paper.

A quadradic polynomial curve fit was used to produce the curves presented in Figure 4.

Table 3 presents the coefficient for each curve in Figure 4.

The calculated maximum centerline temperature for the center waste DHLW canister at 450 W/m^3 was 328°C and occurred at 2 years after insertion into the repository. The calculated maximum centerline temperature for the outer waste DHLW canister also occurred at 2 years and was 303°C. The calculated maximum S/D container surface temperature was 193°C and occurred at 35 years after the S/D container was placed in the repository.

The calculated maximum centerline temperature for the center waste DHLW canister at 200 W/m^3 was 212°C and occurred at 2 years after insertion into the repository. The calculated maximum centerline temperature for the outer waste DHLW canister also occurred at 2 years and was 198 °C. The calculated maximum S/D container surface temperature was 133°C and occurred at 35 years after the S/D container was placed in the repository.

The calculated maximum centerline temperature for the center waste DHLW canister at 100 W/m^3 was 130°C and occurred at 20 years after insertion into the repository. However, the calculated centerline temperature reached 125°C at 5 years. The calculated maximum centerline temperature for the outer waste DHLW canister occurred at 22 years and was 123°C. The calculated maximum S/D container surface temperature was 89°C and occurred at 42 years after the S/D container was placed in the repository.

IV. CONCLUSIONS

The maximum calculated temperature for the S/D container in storage is under 300°C and occurs at the centerline for the inner DHLW canister. The maximum calculated temperature is lower than the softening temperature, 470°C, of the vitrified waste. Therefore, the S/D container will have adequate thermal performance in storage for waste heat loads as high as 450 W/m^3. The maximum surface temperature is 20°C higher than the surface temperature calculated with zero waste heat loading. This represents the maximum possible surface temperature since the analysis was steady-state and did not take into account any transient thermal response to the diurnal ambient temperature and solar loading cycles.

Table 3. Curve Fit Coefficients for Figure 3

Location	C_0	C_1	C_2
Inner Log	25.408743104	1.1481690305	-0.0010576702906
Outer Log	25.285596286	1.0654578496	-0.0009965773222
Container Surface	25.927534422	0.67303743413	-0.0006716364822

The primary mode of heat transfer from the S/D container to the repository, for this analysis, is radiation heat transfer. Two methods can be used to increase the thermal coupling between the S/D container and repository. The first method is to increase the surface area of the S/D container. The approach for increasing surface area needs to be carefully planned, since the amount of surface area seen by the repository walls needs to increase, not just the surface area of the S/D container.

The second method is to increase the emissivity of the S/D container outer surface. Increasing the emissivity can be accomplished by a selective coating. Potential coating candidates are paints and plating. Increasing the emissivity of the outer surface of the DHLW canisters and inner surface of the S/D container would also increase the heat transfer between the DHLW canisters and the S/D container. The increased internal heat transfer would lower the DHLW canister centerline temperatures.

Reducing the initial heat loading of the DHLW canisters shows two trends. The first trend is the lower the initial heat loading, the lower the calculated maximum container surface and DHLW canister centerline temperatures. This is an obvious trend, but needs to be mentioned. This trend also implies that the longer the container is in storage before disposal, the lower the calculated maximum temperatures of the container.

The second trend is the relationship between heat load and the time when the calculated maximum temperatures occur. The calculated maximum surface temperature occurred at 2 years for the 450-W/m^3 and 200-W/m^3 heat loads. For the 100-W/m^3 heat load, the calculated maximum surface temperature occurred at 20 years. However, the surface temperature was within 5°C of the calculated maximum surface temperature for 15 years prior to the occurrence of the calculated maximum surface temperature. The overall trend is the lower the heat load, the longer the time until the calculated maximum temperature of the DHLW canister centerline and container surface. This trend is due to the decay rate of the waste radioactivity and the associated heat load.

This analysis is a first-order analysis. No attempt has been made to model the complex heat transfer mechanisms, such as moisture migration, in the repository. By assuming a two-dimensional model, a line heat source was used instead of discrete heat sources separated by a prescribed distance. In order to improve the thermal calculations, a three-dimensional model with discrete heat sources will be necessary. Conduction through the S/D container support structure was not included in this analysis. Including conduction through the S/D container support structure will also improve the thermal calculations. However, including the S/D container support structure also implies a three-dimensional modeling effort and a finely detailed model.

The results from this analysis can be used as an aid to designers in the development and operation of the S/T+D package. When final design specifications are established, this work can be used as a first-order basis for determining if the repository acceptance criteria has been met. However, it must be stressed that the analysis presented in this paper is conservative and actual temperatures are probably going to be lower than presented in this work.

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