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Thermal Predictions of the Cooling of Waste Glass Canisters

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Thermal Predictions of the Cooling of Waste Glass Canisters

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INTRODUCTION

Radioactive liquid waste from five decades of weapons production is slated for vitrification at the Hanford site. The waste will be mixed with glass forming additives and heated to a high temperature, then poured into containers and canisters within pour caves where the glass will cool and solidify into a stable waste form for disposal. Computer simulations were performed to predict the temperatures within the glass and the heat rejected from the containers and canisters during cooling. Four different waste glass compositions with different thermophysical properties were evaluated. Container and canister centerline temperatures and the total amount of heat transfer from the canisters to the surrounding air are reported.

PROBLEM DESCRIPTION AND METHODOLOGY

Vitrification of the 56-million gallons (212-thousand m^3) of radioactive sludge and liquids stored in 177 underground tanks into a stable glass form for permanent disposal is scheduled to begin in 2019. The Hanford Waste Treatment Plant (WTP) will process both low-activity waste (LAW) and high-level waste (HLW) streams from the tanks. The radioactive waste glass that will be produced is a durable borosilicate glass specifically designed for the immobilization of radioisotopes from nuclear waste streams. Glass-forming frit will be mixed with the radioactive waste, melted in large Joule-heated melters and poured into stainless steel containers or canisters inside of a pour cave. To support the heating, ventilation and air conditioning (HVAC) design for the pour cave, a transient finite-element heat transfer analysis was performed to determine the heat rejected from waste glass containers and canisters to the surrounding air.

Heat generated by the radioactive decay of the various isotopes present in the waste glass can vary depending upon the amount and characteristics of the waste [1]. The radioactive waste glass inside the container/canister is modeled as a solid circular cylinder with a bounding uniform heat generation rate of 1500 W_{th}. In the simulation, the entire contents of the container/canister are poured instantaneously in a single pour and cooled for 40 hours. Dimensions of the HLW canisters and the LAW containers are given in Table 1. The containers and canisters are fabricated from 3/8" (0.009525 m) thick 304L stainless steel. The HLW canisters and LAW containers will weigh more than 4 short tons (3600 kg) and 7 short tons (6300 kg), respectively. Figure 1 shows the relative sizes of the HLW canister and the LAW container.

Table 1. Waste glass container/canister model dimensions.

Waste Type	Height (m)	Diameter (m)	Volume (m^3)
HLW	4.5	0.61	1.23
LAW	2.29	1.22	2.59

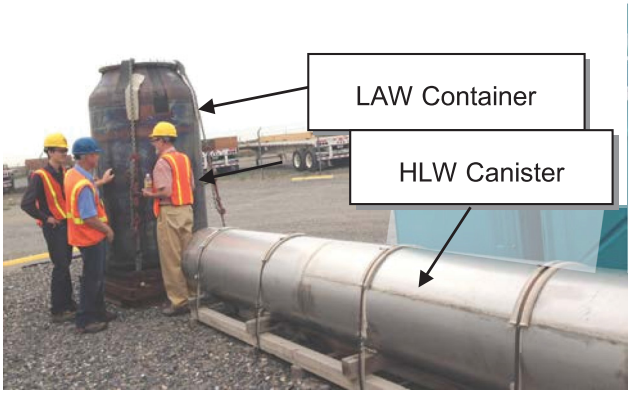

Fig. 1. LAW container and HLW canister at the Hanford WTP site.

The following assumptions apply to the analysis:

1. The heat load from the lighting in the pour cave is negligible in comparison with the heat load supplied by the radioactive waste glass.
2. Uniform energy generation within the waste glass.
3. Negligible thermal contact resistance at material interfaces.
4. Heat transfer through the bottom and top of container/canister is neglected.

Heat is transferred from the waste glass to the stainless steel container/canister by conduction, and from the canister to the surrounding air by free convection and radiation. It is assumed that the glass is in direct contact with the container/canister. The initial temperature of the molten glass is 1423K. The external surface of the

container/canister is cooled by ambient air at a sink temperature of 283.15K. A conservatively low ambient temperature was used to maximize the heat rejected to the ambient air. The properties of air were allowed to vary with temperature by applying regression to the tabulated data given in [2]. Ambient air properties are evaluated at the film temperature and used in the free convection correlation for a heated vertical wall to determine the heat transfer coefficient. The Raleigh number, Ra_H, is calculated by [3]

$$Ra_H = \frac{g\beta(T_s - T_\infty)H^3}{\nu\alpha} \quad (1)$$

where

- g = gravitational acceleration (m/s^2)
- β = volumetric thermal expansion coefficient (K^{-1})
- T_s = wall surface temperature (K)
- T_∞ = ambient air temperature (K)
- H = container or canister height (m)
- ν = kinematic viscosity (m^2/s)
- α = thermal diffusivity (m^2/s).

Calculated Raleigh numbers are in the turbulent flow range (10^9 Ra$\leq 10^{13}$) [3]. Equation 2 is used to determine the Nusselt number, Nu_H [3]

$$Nu_H = \left\{0.825 + \frac{0.387Ra_H^{\frac{1}{6}}}{\left[1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2 \quad (2)$$

The variable, Pr, is the Prandtl number. The convection heat transfer coefficient, h_{conv}, is calculated from the following relation

$$h_{conv} = \frac{Nu_H k}{H} \quad (3)$$

where k is the thermal conductivity. A linearized heat transfer coefficient for thermal radiation, h_{rad}, is given by

$$h_{rad} = \varepsilon o\left(T_s^2 + T_\infty^2\right)\left(T_s + T_\infty\right) \quad (4)$$

An emissivity, ε, of 0.82 was used for the stainless steel [2]. The thermal conductivity of stainless steel was input as a function of temperature [2,4], whereas constant values of density and specific heat were used.

Two HLW glass formulations (designated HLW04-09 and HLW-E-A127) and two LAW glass formulations (LAWA44 and ORPLA20) were evaluated. The volumetric heat capacity and thermal conductivity for the four different glass compositions [5] are shown in Figures 2 and 3. The HLW glasses have a larger volumetric heat capacity than the LAW glasses. The overall trend is a decrease in volumetric heat capacity with temperature (except for the HLW04-09 glass, which displays a peak at 1273K attributed to crystallization and dissolution during the heating ramp). The specific heat data used in this analysis is for heating, rather than cooling, since the heating curve is bounding. The data ranges from the nominal temperature of the molten glass in the melter (1423K) to 1073K, a temperature well above the glass transition temperature (typically ~773K). Thermal conductivity increases with temperature for all of the glass compositions. The thermal conductivity of the ORPLA20 glass is three to four times higher than that of the other glass formulations. The ORPLA20 glass is a light-colored glass, whereas the other glasses are dark in color. Thermal properties were extrapolated to lower temperatures to provide a comparison to initial design calculations made by the WTP contractor.

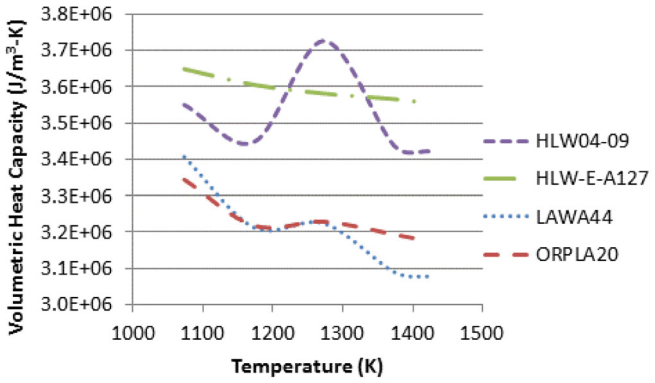

Fig. 2. Variation of volumetric heat capacity with temperature for four waste glass compositions [5].

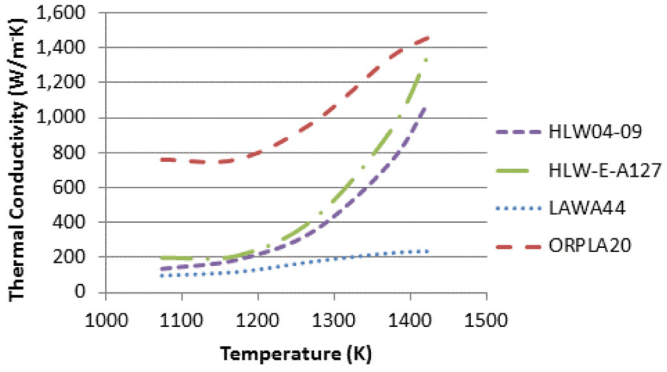

Fig. 3. Variation of thermal conductivity with temperature for four waste glass compositions [5].

RESULTS

The heat rejected from the container/canister to the surrounding air as a function of time up to 40 hrs. of cooling time is shown in Figure 4. The heat rejection from the containers/canisters drops sharply over the first several hours after pouring, then decreases more gradually until it reaches steady-state conditions where the heat rejected eventually equals the heat generated by radioactivity (i.e., 1500 W_{th}). The two HLW canisters have a very similar cooling curve; similar results are seen for the two LAW containers. At 40 hours, the heat rejected from the LAW containers is greater than that from the HLW canisters. This is due to the larger volume of glass contained by the LAW containers, which takes a longer time to cool. Container/canister centerline temperatures as a function of time are shown in Figure 5. Again, the HLW canisters exhibit similar behavior, as do the LAW containers. The centerline temperature of the LAW containers is consistently higher than that of the HLW canisters.

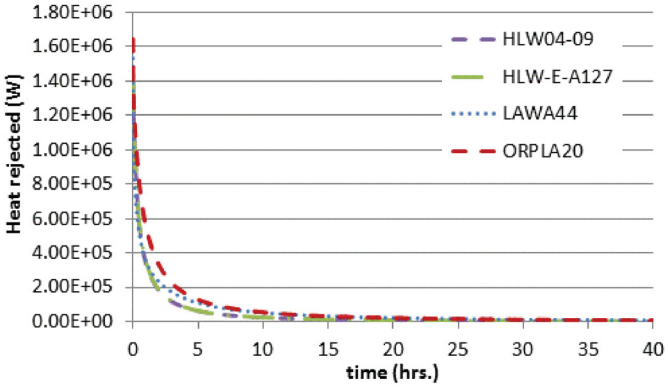

Fig. 4. Heat rejected (W) from container/canister as a function of cooling time.

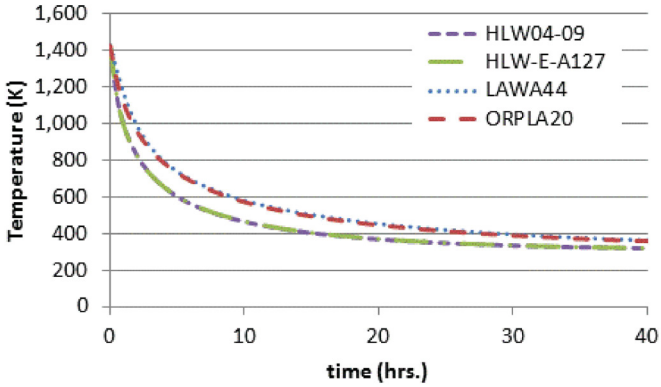

Fig. 5. Container/canister centerline temperature (K) as a function of cooling time.

Temperature gradients within the glass are small as can be seen in Figure 6. This can be explained by calculating the Biot number [3]

$$Bi = \frac{h_{tot} R}{k} \tag{5}$$

where R is the container/canister radius and h_{tot} is the sum of the convection and radiation heat transfer coefficients

$$h_{tot} = h_{conv} + h_{rad}. \tag{6}$$

Since the resulting Biot number is very small (<<1), the resistance to conduction within the glass is much less than the resistance to heat transfer from the external surface to the surroundings. After 40 hours of cooling, the temperature difference between the center of the containers/canisters and the external surface is only several degrees for all four glass compositions analyzed. The peak temperatures in the HLW canisters are lower than in the LAW containers, which can be attributed to the taller and narrower shape of the HLW canisters.

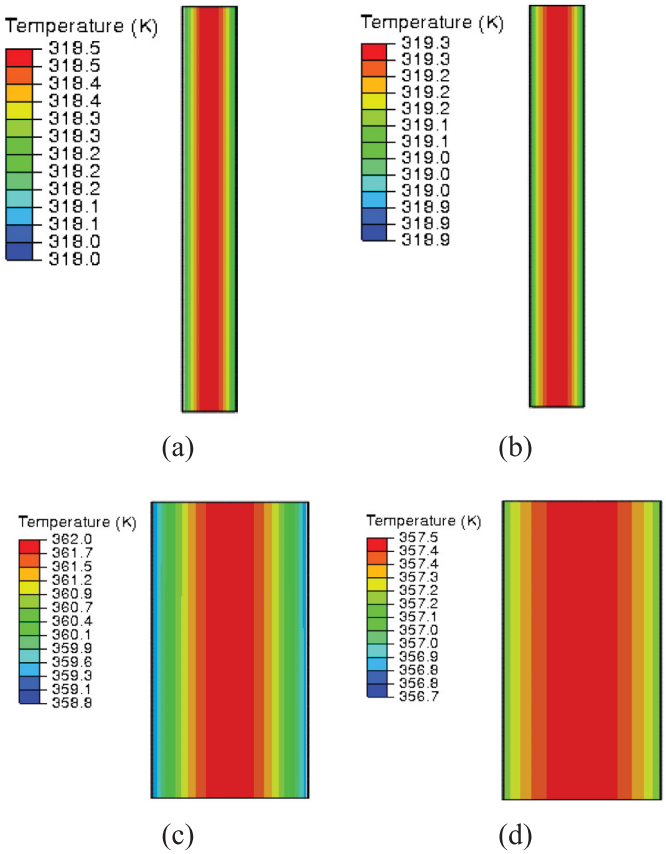

Fig. 6. Temperature distribution at 40 hrs. cooling time (cutaway view) for the different glass formulations (a) HLW04-09, (b) HLW-E-A127, (c) LAWA44, and (d) ORPLA20.

The relative contribution to the heat transfer to the surrounding air from thermal radiation versus free convection ranges from approximately 1.5 at lower temperatures (longer time) to around 17 at higher temperatures (initial times). The ratio of the radiation to the free convection heat transfer coefficient is shown in Figure 7. Initially, the dominant mode of heat transfer is radiation. As the container/canister cools, the contribution from radiation becomes nearly comparable to that from convection.

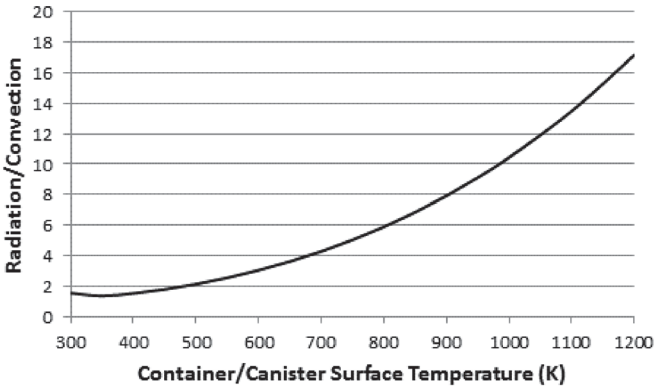

Fig. 7. Relative contribution of thermal radiation to free convection for cooling of the container/canister.

SUMMARY

The results presented in this paper provide a bounding estimate for the amount of heat rejected from the waste glass containers/canisters during cooling. Four different waste glass formulations were evaluated – two HLW compositions and two LAW compositions with different thermophysical properties. The thermal properties and heat generation rate used in the analysis are conservative and were chosen to match those used in the HVAC design by the WTP contractor. The two HLW formulations exhibit similar temperature distributions within the glass after 40 hrs. of cooling, as do the two LAW formulations. At initial times after pouring, thermal radiation is the dominant mode of heat transfer. At longer times, the contribution from thermal radiation to heat loss from the container/canister becomes nearly comparable to that from free convection. Thermal gradients within the glass canister are less than several degrees. Future work includes simulating the heat transfer to the surroundings resulting from discrete pours of molten glass into the containers/canisters. This will provide a more realistic estimate of the heat rejected from the containers/canisters as a function of time during cooling.

ACKNOWLEDGMENTS

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