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THERMAL ASPECTS OF SAFETY ANALYSIS FOR SHIPMENT OF WEST VALLEY MELTER

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ABSTRACT

The thermal aspects of a safety analysis for shipment of the West Valley melter are presented. The West Valley melter was used from 1996 to 2002 to vitrify regionally sourced high level radioactive waste. The U.S. Department of Energy (DOE) set up the West Valley Demonstration Project to encase this melter and grout it in low density cellular concrete, for disposal. DOE-West Valley requested the Savannah River National Laboratory to prepare a Safety Analysis Report.

The thermal portion of the safety analysis covers Normal Conditions of Transport (NCT) and Hypothetical Accidents Conditions (HAC), as defined in the Code of Federal Regulations. For NCT, it is assumed that the encased melter is stored in either shade or direct sunlight at an ambient temperature of 311 K (100 °F). The defining HAC is exposure to a 1075 K (1475 °F) fire for 30 minutes. Finite element computer models were used to compute temperature profiles for NCT and HAC, given the thermal properties of the melter and its contents and tabulated radiolytic heating source concentrations. The resulting temperature conditions were used to estimate the pressurization due to evaporation of water from the concrete. The maximum calculated pressures were

determined to be 81 kPa (12 psig) for NCT and 503 kPa (73 psig) for HAC.

INTRODUCTION

The West Valley Development Project (WVDP) vitrification melter contained residual radioactivity associated with spent nuclear fuel reprocessing at the West Valley site. At the heart of the vitrification plant was the slurry-fed vitrification melter. The melter consisted of an electrically heated box structure approximately 3.05 m (10 ft) on each side containing refractory material, with an outer shell of stainless steel. The vitrification melter was used from 1996 through 2002 to heat high-level waste slurry and glass-forming chemicals to produce a molten homogeneous mixture that was poured into stainless steel canisters, where it hardened to produce a highly stable glass waste form.

In 2004, West Valley procured a specially designed container for the melter. This approximately 94,300-kg carbon steel container consists of 0.152-m (6-in.) thick sidewalls and 0.102-m (4-in.) thick top and bottom walls. The package was designed so that once the melter was loaded, and prior to shipment, the interstitial spacing within the melter and the spacing between the melter and the container could be filled with Low Density Cellular Concrete (LDCC) to form a Grouted

Melter Package (GMP). The GMP secures the melter and provides impact limiting resistance in the event of an accident. In 2004 the melter was transferred into the container and placed into storage until 2013, when the LDCC was added.

In 2014, it was determined that the melter was required to be shipped in either a Type B certified package or under a Special Package Authorization (SPA) granted by the U.S. NRC. Since the melter was already in the GMP and encased in LDCC, it was necessary to submit an application to the U.S. NRC for a SPA. The thermal and pressurization analyses presented in this paper comprise a portion of the safety analysis that was prepared for this application.

West Valley shipped the WVMP to the Waste Control Specialists (WCS) low-level waste facility in Texas for disposal in 2016. Figure 1 shows the WVMP and two associated feed tanks off-loaded at the WCS facility.



FIG 1. MELTER PACKAGE (RIGHT) AND TWO FEED TANKS AT WCS FACILITY

NOMENCLATURE

A_i	surface area for the i^{th} surface, m^2
a_j	activity of the j^{th} isotope, C_i
A_r	pre-exponential Arrhenius constant for cement dehydration, dimensionless
c_p	heat capacity of the material, J/kg/K
$c_{p,s}$	ordinary heat capacity for cement solids exclusive of reaction or phase change, J/kg/K
E_a	activation energy for cement dehydration, J/mole
e_j	decay energy of the j^{th} isotope, W/Ci
h_i	surface heat transfer coefficient for the i^{th} surface (applies only to surface nodes), $\text{W/m}^2/\text{K}$
ΔH_r	heat of reaction for breaking hydrate bond, $\text{J/mol H}_2\text{O}$
k	thermal conductivity of material, W/m/K

k_{eq}	equivalent thermal conductivity for mixture of melter refractory and steel, W/m/K
k_{ref}	thermal conductivity of the refractory material in the melter, W/m/K
k_{ss}	thermal conductivity of melter steel, W/m/K
m_{glass}	mass of glass in melter, kg
$M_{\text{H}_2\text{O}}$	molecular mass of water, 0.018 kg/mole
$m_{\text{H}_2\text{O}}$	mass of water in LDCC hydrate, kg
m_{LDCC}	mass of LDCC, kg
m_m	total melter mass, kg
n_{air}	number of moles of air initially in the air gap
$n_{\text{H}_2\text{O}}$	number of moles of water vapor generated by dehydration of the LDCC
P	maximum pressure for NCT or HAC, Pa
P_0	initial pressure, assumed to be equal to atmospheric pressure, Pa
Q	internal heat generation rate for radiolytic heating of the glass, W
q''_i	surface heat flux due to insolation over the i^{th} surface (applies only to surface nodes), W/m^2
R_g	gas constant, 8.314 J/mol/K
t	time, s
T	temperature, K
T_0	initial temperature in the air gap, assumed to be equal to 20°C or 293.15 K
T_a	ambient temperature (or fire temperature for the HAC), K
T_{avg}	average temperature in the air gap between the LDCC and the frame, K
T_{fire}	fire temperature, K
T_r	relative temperature
$T_{r,b}$	relative temperature at the normal boiling point (373.15 K), J/mol
$T_{s,i}$	temperature of the i^{th} surface, K
V_{air}	volume of the air gap, m^3
$V_{\text{air},1}$	volume air pocket above LDCC inside WVMP, m^3
$V_{\text{air},2}$	volume of air pocket inside melter, m^3
V_{glass}	glass volume, m^3
V_i	total interior volume of WVMP, m^3
V_{LDCC}	total LDCC volume, m^3
V_{Mono}	volume of Monofrax TM refractory inside melter, m^3
V_{ref}	WVMP interior volume minus volume of glass, m^3
V_{ss}	volume of metal inside melter, m^3
V_{Zirm}	volume of Zirmul TM refractory inside melter, m^3

α	cumulative fraction of calcium silicate oxides that have undergone dehydration
ε_i	emissivity for i^{th} surface, dimensionless
λ	heat of vaporization, J/mol
λ_b	heat of vaporization at the normal boiling point
ρ	density of the material, kg/m ³
$\Delta\rho$	difference between gas density at top and bottom of gap, kg/m ³
ρ_{glass}	glass density, kg/m ³
$\overline{\rho}_{\text{H}_2\text{O,LDCC}}$	minimum average bulk concentration of hydrated water in the LDCC, kg/m ³
$\rho_{\text{H}_2\text{O,LDCC},0}$	initial concentration of hydrated water in the LDCC, kg/m ³
ρ_{LDCC}	LDCC density, kg/m ³
ρ_{Mono}	density of Monofrax TM , kg/m ³
ρ_{ss}	density of Type 304L stainless steel, kg/m ³
ρ_{Zirm}	density of Zirmul TM , kg/m ³
σ	Stefan-Boltzmann constant, W/m ² /K ⁴
∇	dispersion operator, 1/m

MELTER PACKAGE DESCRIPTION

The West Valley Melter Package (WVMP) is a rectangular shaped packaging 4.80 m (15 ft, 9 in.) long by 3.84 m (12 ft, 7 in. wide by 3.82 m (12 ft, 6.5 in.) high containing the GMP, surrounded by eight shock absorbers and an Impact Limiter (IL). The maximum fully loaded weight is approximately 177,300 kg and the minimum empty weight is approximately 94,300 kg.

The WVMP container is fabricated with SA516, Grade 70 carbon steel. It has a bolted side door recessed into the container secured with 32 ASTM A193-B7 0.0381-m (1.5-in.) diameter bolts. This bolted side door has a neoprene gasket. The container was designed, constructed, and procured under the WVDP's quality assurance program. Figure 2 shows a cutaway view of the WVMP.

As illustrated by Figure 3, the melter content is comprised of a stainless steel outer housing and an exterior structural steel frame with the interior lined with refractory materials. The maximum envelope dimensions of the melter are 3.61 m (11 ft, 10 in.) long by 3.30 m (10 ft, 9.75 in.) wide by 3.19 m (10 ft, 5.5 in.) high. All external surfaces of the melter are coated with three layers of Bartlett's Polymeric Barrier System (PBS) contamination fixative. The interior of the melter contains refractory material, vitrified glass, and LDCC.

The melter structure is comprised of Inconel[®], Type 304 stainless steel, and Type 304L stainless steel.¹ The refractory material is a combination of MonofraxTM K-3 and ZirmulTM.¹

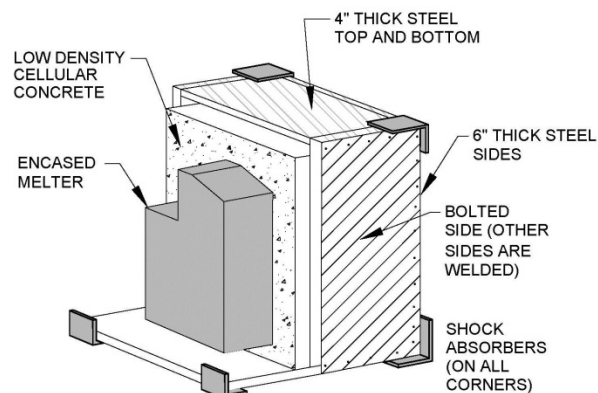


FIG 2. MELTER PACKAGE (RIGHT) AND TWO FEED TANKS AT WCS FACILITY

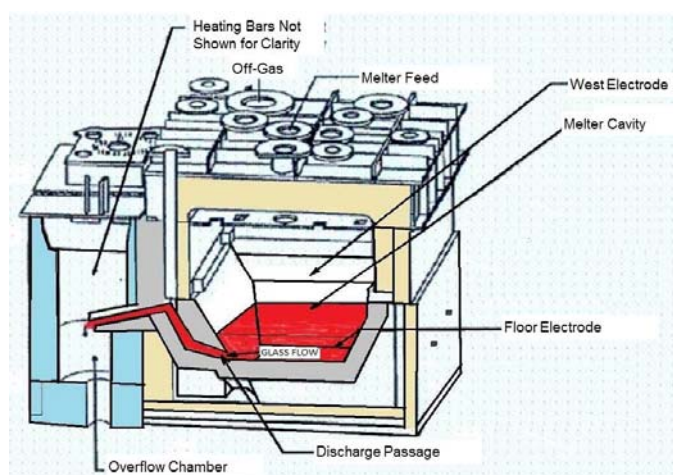


FIG 3. WVDP MELTER

HEAT TRANSFER ANALYSIS

Thermal analyses are provided for NCT and HAC. The conditions for NCT and HAC are stipulated in 10 CFR 71 of the U.S. Code of Federal Regulations. NCT covers conditions for outdoor storage of the waste package, including heat transfer to ambient air and sun exposure (insolation). The HAC assume exposure to a 1075 K (1475 °F) fire. The thermal analysis does not account for the presence of the Impact Limiter (IL) added to the exterior of the WVMP. For the thermal analysis, the omission of the IL is conservatively bounding since it does not include the insulation it provides. The WVMP without the IL component is referred to as the Grouted Melter Package (GMP) component.

The analysis of temperatures for NCT follows the requirements of 10 CFR 71.71.² The required temperatures are:

- (1) The maximum temperatures for exposure to 311 K (100 °F) air at steady state.
- (2) The maximum temperatures for exposure to 311 K (100 °F) still air with insolation of 3.35E07 J/m² (800 cal/cm²)

[®] Inconel is a registered trademark of Special Metals Corporation of New Hartford, New York.

TM Monofrax is a trademark of RHI Monofrax Ltd. of Falconer, New York.

TM Zirmul is a contraction of the mineral names zirconia and mullite. Zirmul is a registered trademark of North American Refractories Company of Pittsburgh, Pennsylvania.

on the top surface and $8.37\text{E}06 \text{ J/m}^2$ (200 cal/cm^2) on the side surfaces for a period of 12 hours. The package bottom is assumed to be an adiabatic surface.

(3) The minimum (surface) temperature for exposure to a cold environment of 244 K (-20°F), with no insolation.

(4) The minimum (surface) temperature for exposure to a maximum cold environment of 233 K (-40°F), with no insolation.

The WVMP accessible surface temperature in still air at 311 K (100°F), with no insolation, must not exceed the exclusive use shipment limit of 358 K (185°F), as specified in 10 CFR 71.43(g).³ In addition, there must be no loss of the radioactive contents, no significant increase in external surface radiation level, and no significant decrease in package effectiveness, as stated in 10 CFR 71.43(f) and 71.51(a)(1).^{3,4} To address this requirement, the maximum pressure that can develop inside the WVMP during NCT is calculated for use in the structural analysis.

The analysis of temperatures for HAC follows the requirements of 10 CFR 71.73.⁵ These requirements specify the package is exposed to an engulfing 1075 K (1475°F) fire for 30 minutes, followed by a cool down to ambient conditions. The fire emissivity is specified as 0.9 and the surface emissivity for the surface of the package is set at 0.8. The requirements also specify the use of a convective heat transfer coefficient appropriate for the fire.

The HAC analysis must demonstrate the activity release during the HAC will not exceed the limits established by 10 CFR 71.51(a)(2).⁴ To demonstrate no release of activity will occur, the maximum pressure that can develop inside the WVMP during the HAC is calculated for use in a structural analysis.

Overview of Heat Transfer Calculations

The heat transfer calculations model the WVMP, minus the steel rails, gaskets, shock absorbers and impact limiters. Exclusion of these components yields conservatively bounding values for the calculated temperatures, since they provide added insulation for the interior of the WVMP when it is heated by either insolation or by the fire.

The thermal analysis was performed using Version 4.3a of the finite element modeling code COMSOL® Multiphysics. The COMSOL® model uses the actual outer dimensions for the container and approximates the contents of the WVMP as a nested series of cubes, with the innermost cube comprised of the radioactive glass in the melter heel, the spout, and any glass dispersed into the refractory of the melter. In the model, this inner core is surrounded by a layer comprised of the melter refractory and structural steel, a layer of the LDCC used to stabilize the melter in the package, and the steel container walls. There also is a 0.25-m (10-in.) thick air space between the top surface of the LDCC and the top container wall. This air pocket is present because the WVMP was not completely filled with LDCC.

To simplify the heat transfer analysis, it is assumed that the glass, steel, refractory, and LDCC layers form concentric, symmetrical cubes within the container walls and upper air pocket. The symmetry provides a conservative, lower bound to the actual overall rate of heat transfer in that it averages out any variations in the thicknesses of the insulation provided by the LDCC and the refractory. Any asymmetrical variations would increase the local, and the average, rate of heat transfer. A lower bound to the heat transfer rate is desired because it maximizes the surface temperature for insolation and fire exposure and maximizes increases in the glass temperature due to radiolytic heating for the case of no insolation. (The maximum glass temperature is used to estimate the bounding surface temperature without insolation, to account for asymmetries in the thickness of the LDCC around the melter.)

The COMSOL® model utilizes bilateral symmetry along the length and width of the WVMP to reduce the volume analyzed to a one-quarter corner of the WVMP that extends from the top surface to the bottom surface. Figure 4 depicts the simplified COMSOL® model, with the various materials shown, and shows the discretization mesh for the finite element calculations. The total number of calculation nodes is 125,148. Trial calculations were performed to ensure that the discretization was sufficiently refined.

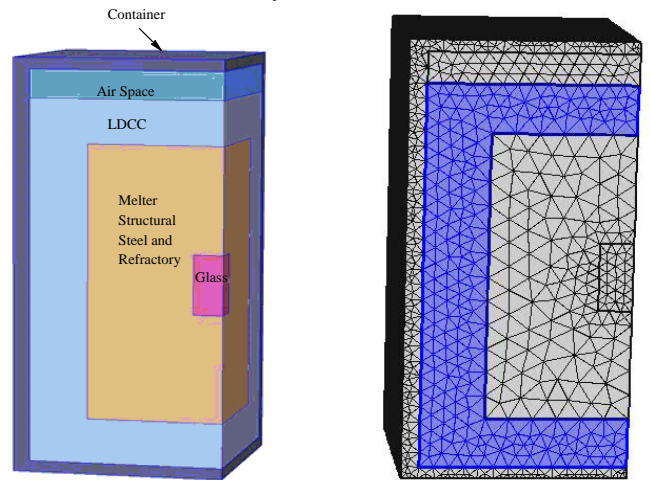


FIG 4. FINITE ELEMENT MODEL OF WVMP

The volumes occupied by each type of material were calculated by dividing the estimated mass of the material by its density. The WVMP interior volume, i.e., the interior volume minus the volume of the glass remaining in the melter, is estimated indirectly from the equation.

$$V_{\text{ref}} = V_i - V_{\text{air},1} - \frac{m_{\text{LDCC}}}{\rho_{\text{LDCC}}} - \frac{m_{\text{glass}}}{\rho_{\text{glass}}} \quad (1)$$

The volume of the structural metal inside the melter is given by

$$V_{\text{ss}} = \frac{m_m - \rho_{\text{Mono}} V_{\text{Mono}} - \rho_{\text{Zirm}} V_{\text{Zirm}}}{\rho_{\text{ss}}} \quad (2)$$

® COMSOL Multiphysics is a registered tradename of COMSOL, Inc., of Burlington, Massachusetts.

Any portion of the melter volume that is not metal or refractory is assumed to be an air pocket. The melter air pocket volume is calculated by subtracting the metal and refractory volumes from the total refractory volume given by Equation 1:

$$V_{\text{air},2} = V_{\text{ref}} - V_{\text{ss}} - V_{\text{Mono}} - V_{\text{Zimm}} \quad (3)$$

Radiolytic Heat Generation Calculation

The heat generation rate in the glass is calculated from a RADCALC[®] analysis of the activity in the glass¹ and tabulations of the energy emissions for each radionuclide from the International Committee on Radiological Protection (ICRP) tables.⁶ The maximum decay heat is 9.21 W.

Material Properties for Heat Transfer Analyses

For all WVMP components except the LDCC, the only material properties required for the heat transfer analyses were the density, the heat capacity, and the thermal conductivity. Properties for the refractory materials (Monofrax[™] K-3 and Zirmul[™]) are from Reference 7, properties for the oxides present in the melter are from References 8 and 9, properties for the steel are from Reference 10, and properties for the glass are from Reference 11.

The heat capacity of the LDCC is set equal to a typical value for a cement mix with a water content close to that estimated for LDCC. LDCC contains on average 303 kg/m³ (510 lbm/yd³) cement, with added water amounting to 20% of the cement by weight, and enough sand to increase the density to the specified value. The result for the given density of 1141 kg/m³ (71.2 lbm/ft³) is 303 kg/m³ cement, 777 kg/m³ sand (SiO₂), and 61 kg/m³ water.^{12,13} The water content is 5.3 wt %. The closest value for which a cement heat capacity is reported is a mix with 3 wt % water, for which the heat capacity was measured to be 765 J/kg/K.¹⁴ The LDCC thermal conductivity is set at its minimum value for its density, which is approximately 0.26 W/m/K.¹⁵

The only significant change to component properties during the fire exposure would be dehydration of the LDCC, i.e., loss of the cement waters of hydration. The Arrhenius correlation of the fractional dehydration is based on data for crystalline calcium silicates, which are by far the major constituents of typical cement. It is assumed that the LDCC is fully cured so that there is no free water in the cement pores and so that, consequently, all dehydration involves the breaking of crystalline bonds, followed by evaporation of liquid water. For tricalcium silicate hydrate (3CaO:SiO₂:2H₂O), the fractional dehydration is correlated as an Arrhenius function of the form.¹⁶

$$\alpha = A_r \exp\left(-\frac{E_a}{R_g T}\right) \quad (4)$$

The Arrhenius equation was fit to the dehydration data below 773 K (500 °C) to obtain values of 15.426 for A_r and 3397 K for $\frac{E_a}{R_g}$.

(3.1.1-3)

The heat of hydration for tricalcium silicate is 65.59 kJ/mol H₂O,¹⁷ and the heat of hydration for calcium oxide is 63.92 kJ/mole H₂O.¹⁸ The tricalcium silicate heat of hydration is used in the thermal analysis, since it is more representative of the LDCC composition.

The heat of vaporization for water is added to the heat of reaction for dehydration. The heat of vaporization is correlated as a function of temperature by.¹⁹

$$\lambda = \lambda_b \left(\frac{1 - T_r}{1 - T_{r,b}} \right)^{0.38} \quad (5)$$

The relative temperature is normalized with respect to the critical temperature for water, which is 373.99°C or 647.14°K.²⁰ The heat of vaporization of water at the normal boiling point is 40,657 J/mol.²⁰

Heat Transfer Analysis

The COMSOL[®] heat transfer equation for the glass takes the form

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = \frac{Q}{V_{\text{glass}}} \quad (6)$$

The radiolytic heat generation rate is expressed as the sum of the products of the specific activity of the isotopes that are present in the glass and the decay energy for each isotope:

$$Q = \sum_j a_j e_j \quad (7)$$

The total radiolytic heat generation rate is the sum of the individual heat generation rates for the glass in the melter heel, the glass in the melter spout, and the glass embedded in the melter refractory. In the model it is assumed that radiolytic heating occurs at a uniform rate throughout the glass. In itself, this is not necessarily a conservative assumption. However, because the melter glass has a relative high thermal conductivity compared to the LDCC, when it is modeled as a monolith, the melter glass should be at a relatively uniform temperature regardless of the distribution of the radiolytic heating. The assumption that the glass is concentrated in one central volume should yield a conservatively high estimate for the maximum temperature in the glass.

The heat transfer equation for the melter steel and refractory and the LDCC is

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = 0 \quad (8)$$

The equivalent thermal conductivity of the melter steel and refractory is computed by taking the volume average of the individual thermal conductivities of the steel and refractory:

$$k_{\text{eq}} = \frac{V_{\text{ref}} k_{\text{ref}} + V_{\text{ss}} k_{\text{ss}}}{V_{\text{ref}} + V_{\text{ss}} + V_{\text{air},2}} \quad (9)$$

[®] RADCALC is a registered tradename of LifeLine Software, Inc., of Austin, Texas.

This linear averaging method is consistent with an arrangement where structural steel beams radiate outward from the melter glass to the inner edge of the LDCC and provide a continuous path for heat transfer through the steel. The averaging accounts for the fraction of the total cross-sectional heat transfer area occupied by the refractory. Linear averaging provides a more realistic model for heat transfer in the melter than reciprocal averaging, which would follow from an assumption that the refractory and structural steel were randomly mixed. Melter glass temperatures calculated using a reciprocal averaging method for the combined thermal conductivity of the refractory and steel would yield calculated glass temperatures that would be unrealistically high. The same linear volume averaging is used to compute the equivalent density and heat capacity for the melter steel and refractory.

Heat losses and heat transfer associated with dehydration of cement hydrates in the LDCC are included in the COMSOL[®] model by incorporating the heat of dehydration into the effective heat capacity for the LDCC. The contribution of the combined heats of dehydration and evaporation equals the product of the heats of dehydration and evaporation, the mass fraction of hydrate in the LDCC, and the derivative of the fractional dehydration with respect to temperature.

Differentiation of the Arrhenius expression for the fraction dehydration and substitution in the expression for the effective LDCC heat capacity yields the following equation.

$$c_p = c_{p,s} + \frac{(\Delta H_r + \lambda) m_{H_2O} A_i E_a}{m_{LDCC} M_{H_2O} R_g T^2} \exp\left(-\frac{E_a}{R_g T}\right) \quad (10)$$

Natural convection is incorporated into the heat transfer equation for the air gap adjacent to the LDCC using the Globe and Dropkin correlation for natural convection in a horizontal, enclosed gap.²¹ Natural convection heat transfer is included only for HAC, where it is assumed that the gap is heated from below. Heat transfer in the air gap for NCT is modeled using molecular conduction only.

During NCT, the heat transfer equation for the steel frame is

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = q''_i A_i - h_i A_i (T_{s,i} - T_a) \quad (11)$$

For the fire exposure portion of the HAC transient, the heat transfer equation for the frame is

$$\begin{aligned} \rho c_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T \\ = \varepsilon_i \sigma A_i (T_{fire}^4 - T_{s,i}^4) + h_i A_i (T_{fire} - T_{s,i}) \end{aligned} \quad (12)$$

During the cool down portion of the HAC transient, the heat transfer equation for the frame becomes

$$\begin{aligned} \rho c_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T \\ = q''_i A_i - \varepsilon_i \sigma A_i (T_{s,i}^4 - T_a^4) - h_i A_i (T_{s,i} - T_a) \end{aligned} \quad (13)$$

As stipulated by 10 CFR 71.71, heat transfer coefficients are based on still-air natural convection from exterior surfaces. Due to the large size of the WVMP, the natural convection flow is in the turbulent range on all sides of the exterior for any

significant temperature differences. The COMSOL[®] correlation for the side walls is given by Churchill and Chu.²² For natural convection from the top of the WVMP, COMSOL[®] uses a natural convection correlation recommended by Lloyd and Moran.²³ Finally, for convection from the bottom surface of the WVMP, COMSOL[®] utilizes the generalized correlation for a horizontal plate facing downward.²⁴ This heat transfer coefficient is used only for the HAC analysis.

Surface heat losses during HAC are modeled using forced convection boundary conditions for exposure to the fire and natural convection boundary conditions for the cool-down after the fire. The Churchill and Ozoe correlation is used to model laminar forced convection,²⁵ and a transitional flow correlation is used to model moderately turbulent forced convection.²⁶ No natural convection correlations are used in the modeling of the fire exposure, because the forced convection heat transfer coefficients are much greater than the natural convection heat transfer coefficients. For the post-fire period, it is assumed that the air surrounding the WVMP is still, and the convective heat transfer is restricted to natural convection. The same natural convection correlations are used for both NCT and HAC.

Pressurization Calculations

The maximum pressure is calculated by assuming all of the hydrated water content is released as vapor due to heating of the LDCC and accumulates in the upper air pocket. It is assumed any pressure that might develop internally in the concrete pores is contained within the LDCC layer. The gas volume inside the LDCC pores is conservatively neglected in the pressure calculation. The air pocket pressure computation is based on the ideal gas law and is performed separately from the COMSOL[®] heat transfer calculations. The equation for the maximum pressure is

$$P = P_0 \left(1 + \frac{n_{H_2O}}{n_{air}} \right) \frac{T_{avg}}{T_0} \quad (14)$$

The number of moles of air at the start of the NCT transient is calculated using the ideal gas law relation

$$n_{air} = \frac{P_0 V_{air}}{R_g T_0} \quad (15)$$

The number of moles of water evaporated is computed by taking the difference between the number of moles of hydrated water initially in the LDCC and the minimum number of moles that remain hydrated at any time during the HAC fire or cool-down period:

$$n_{H_2O} = (\rho_{H_2O,LDCC,0} - \bar{\rho}_{H_2O,LDCC}) V_{LDCC} \quad (16)$$

The maximum WVMP pressure is calculated from an assumption that the active pressurization of the container is from the air pocket at the top of the WVMP. The calculated pressure is based on heating of this air from an assumed initial temperature of 293 K to the maximum average temperature during the HAC fire transient. The pressurization also accounts for the vaporization of hydrated water to add to air initially present in the air pocket.

DISCUSSION OF RESULTS

Table 1 summarizes the results of the NCT thermal analysis, with exposure to 311 K (100 °F) air and insolation. Temperatures for exposure to air without insolation did not differ significantly from the assumed ambient air temperatures and hence are not listed. In keeping with the intent of 10 CFR 71.71, the maximum temperature is evaluated only at the end of 30 days, when the postulated diurnal temperature variations approach their cyclic limit. The maximum pressure is computed for the case of insolation and exposure to 311 K (100 °F) air. The maximum NCT pressure of 81.0 kPa is due to heating of the 126 moles of air initially present in the air pocket and evaporation of 62 moles of water from the LDCC.

TABLE 1. LIMITING CONDITIONS FOR NCT WITH INSOLATION

Component	Maximum Temperature	Maximum Pressure
Overall	371.7 K	81.0 kPa
Glass	336.7 K	
Melter	335.7 K	
LDCC	357.3 K	
Air Pocket	371.4 K	
Container	371.7 K	

Figure 5 shows the NCT temperature profile at the end of the 12-hour heating cycle, after 30 days. The transient temperature distribution approaches a limiting profile reasonably closely after one cycle and quite closely after 30 days. Temperatures in the melter and the LDCC are close to the minimum temperature due to the relatively low thermal conductivity of the LDCC. The temperature increases toward the maximum only in the air pocket and the top wall of the WVMP.

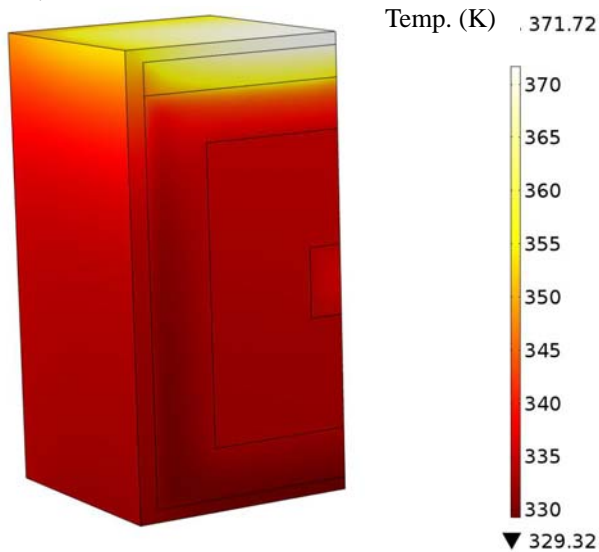


FIG 5. TEMPERATURE PROFILE FOR NCT WITH INSOLATION AFTER 30 DAYS

Table 2 reports the results of the HAC thermal analysis. The maximum temperature is located at the corners of the WVMP. The average temperatures of the LDCC and the air pocket peak 68 minutes after the start of the fire exposure. The temperatures of the melter and the melter glass are virtually unaffected by the 30-min fire. The maximum pressure for HAC of 73.0 psig is calculated based on heating of the 126 moles of air initially in the air pocket to the maximum average air pocket temperature and a maximum amount of evaporation of 249 moles of water. The maximum pressure conditions occur after the end of the fire exposure, during the cool-down period. The exact time at which the pressure peaks is not listed because the maximum pressure is based on a combination of the maximum air pocket temperature and the maximum amount of hydrated water that evaporates; these maximums are reached at different times.

TABLE 2. LIMITING CONDITIONS FOR HAC

Component	Maximum Temperature	Average Temperature	Maximum Pressure
Overall	933.8 K		503.4 kPa
Glass	336.8 K		
Melter	335.9 K		
LDCC	640.7 K	368.7 K	
Air Pocket	656.4 K	588.4 K	
Container	933.8 K		

Figure 6 shows the HAC temperature profile at the end of the 30 minutes fire exposure, when the WVMP wall temperature is at its maximum. The maximum temperature occurs at the eight corners of the WVMP. The average container plate temperatures remain below 700 K. The average temperature of the hottest plate, adjacent to the WVMP air pocket, is 690 K on the outer surface and 604 K on the inside surface. The average plate temperature is approximately equal to the average of these two temperatures, which is 650 K. Except for that portion of the LDCC closest to the container and the air pocket at the end of the WVMP, the temperatures inside the WVMP do not vary significantly from their initial values for NCT with insolation.

Figure 7 shows the variation of the average LDCC and WVMP air pocket temperatures during the HAC fire transient. The average LDCC temperature reaches its maximum value of 368.7 K, 592 minutes after the start of the fire (and 562 minutes after the end of the fire exposure), and the average air pocket temperature peaks at 588.4 K, 68 minutes after the start of the fire. Figure 8 depicts the variation of the average bulk hydrated water content of the LDCC during the fire transient. The minimum hydrated water content, with the evaporation of a maximum 249 moles of water, occurs 256 minutes after the start of the fire.

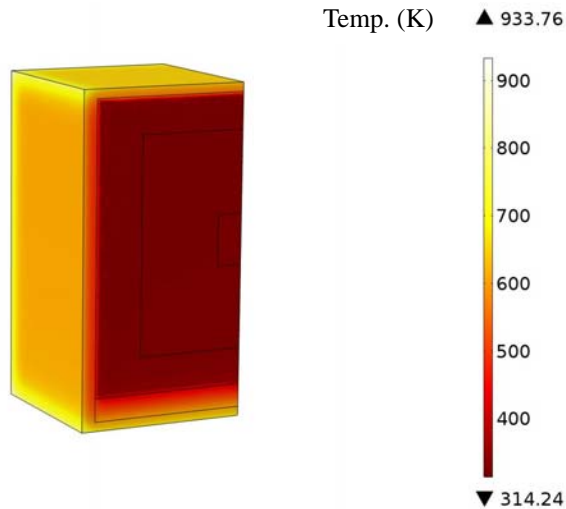


FIG 6. TEMPERATURE PROFILE FOR HAC AFTER 30 MINUTES FIRE EXPOSURE

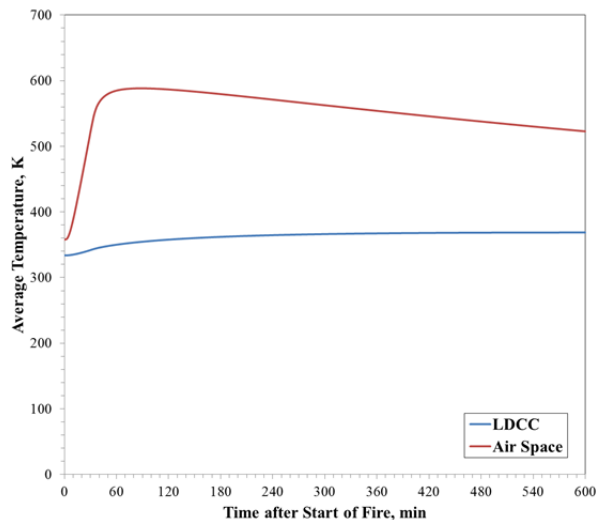


FIG 7. VARIATION OF AVERAGE AIR POCKET TEMPERATURES DURING HAC

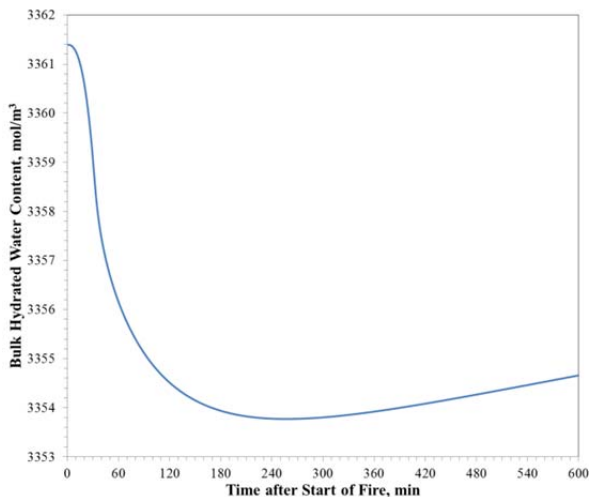


FIG 8. VARIATION OF AVERAGE BULK HYDRATED WATER CONTENT DURING HAC

The calculated maximum gauge pressure inside the melter package for NCT is 81 kPa (11.8 psig), of which 22 kPa (3.2 psig) is due to pressurization by heating and 59 kPa (8.6 psig) is from evaporation of water. For HAC, the maximum gauge pressure is 503 kPa (73.0 psig), of which 102 kPa (14.8 psig) is due to pressurization by heating and 401 kPa (58.2 psig) is from evaporation of water.

The thermal analysis does not address the failure of individual components under pressure, since there is no requirement for individual components to provide pressure confinement. Instead, the analysis estimates a maximum overall pressure under the assumption that the container frame provides pressure confinement. The limiting pressure associated with the maximum pressure generated by heating under HAC is calculated from the applied load due to this pressure and the allowable load when the frame plates are at 700 K (800 °F). The combined primary and secondary allowable stress on the side wall at this temperature is 374 MPa, compared to an applied stress of 325 MPa at the maximum container pressure from the HAC thermal analysis. The maximum container gauge pressure is computed to be 374 MPa / 325 MPa x 503 kPa, or 580 kPa (84.1 psig).

CONCLUSIONS

The thermal analyses show that there are no internal components that will be outside the range of allowable service temperatures or pressures for either NCT or HAC conditions. During the HAC fire exposure, the container plates may exceed their service temperature, which is 644 K (700 °F) for nuclear service and 811 K (1,000 °F) for ordinary service.²⁷ However, the plates will not melt or significantly deform at the fire exposure temperature of 1075 K (1475 °F). The glass, metal, refractory, and LDCC will withstand any temperatures extremes that would occur under NCT or HAC. The maximum LDCC temperature of 640.7 K is well below the limiting LDCC temperature of 922 K (1200 °F), established to approximately equal the temperature at which an LDCC slab will fail under its own weight.²⁸ The melter is thermally insulated from the HAC fire, so its temperature will be significantly lower than the container temperature during the fire.

The calculated maximum internal pressures are within the acceptable limits for nuclear facility components given by the ASME Boiler and Pressure Vessel Code.²⁹ The calculated maximum gauge pressure for NCT, 81 kPa, is well under the ASME limit of 669 kPa (97 psig). The adjusted maximum gauge pressure for HAC, 580 kPa, also is below the ASME limit of 869 kPa (126 psig).

A Safety Analysis Report³⁰ was submitted to the NRC in October 2014 and was subsequently accepted with the addition of supplementary documentation. The WVMP was shipped to the WCS facility in December 2016.

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