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HEAT TRANSFER ANALYSIS FOR NUCLEAR WASTE SOLIDIFICATION CONTAINER

Si Y. Lee
Savannah River National Laboratory
Savannah River Site
Aiken, SC 29808
Phone: (803) 725-8462; (803) 725-8203
si.lee@srnl.doe.gov

ABSTRACT

The Nuclear Nonproliferation Programs Design Authority is in the design stage of the Waste Solidification Building (WSB) for the treatment and solidification of the radioactive liquid waste streams generated by the Pit Disassembly and Conversion Facility (PDCF) and Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF). The waste streams will be mixed with a cementitious dry mix in a 55-gallon waste container. Savannah River National Laboratory (SRNL) has been performing the testing and evaluations to support technical decisions for the WSB. Engineering Modeling & Simulation Group was requested to evaluate the thermal performance of the 55-gallon drum containing hydration heat source associated with the current baseline cement waste form.

A transient axi-symmetric heat transfer model for the drum partially filled with waste form cement has been developed and heat transfer calculations performed for the baseline design configurations. For this case, 65 percent of the drum volume was assumed to be filled with the waste form, which has transient hydration heat source, as one of the baseline conditions. A series of modeling calculations has been performed using a computational heat transfer approach.

The baseline modeling results show that the time to reach the maximum temperature of the 65 percent filled drum is about 32 hours when a 43°C initial cement temperature is assumed to be cooled by natural convection with 27°C external air. In addition, the results computed by the present model were compared with analytical solutions. The modeling results will be benchmarked against the prototypic test results. The verified model will be used for the evaluation of the thermal performance for the WSB drum. Detailed results and the cases considered in the calculations will be discussed here.

Keywords: Waste Solidification, Computational Heat Transfer, Natural Convection, Thermal Performance

INTRODUCTION

The Nuclear Nonproliferation Programs Design Authority is in the design stage of the Waste Solidification Building (WSB) for the treatment and solidification of radioactive liquid waste streams generated by the Pit Disassembly and Conversion Facility (PDCF) and Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF). The waste streams will be mixed with a cementitious dry mix in a 55-gallon waste container. The drum container will be a cylindrical stainless steel drum with 22.5 in diameter and 33 in tall [See Attachment]. Under the current formulation, the drum will be filled with cement waste form up to maximum 75 percent.

The Savannah River National Laboratory (SRNL) has performed the modeling evaluations to support technical decision for the WSB [2]. Recently, SRNL prepared a sample of the baseline High-Activity Waste (HAW) form and measured the heat of hydration associated with the cement waste form [2]. In the case of handling the WSB drum, there are concerns about the transient thermal response rates and the maximum transient temperatures reached for partially-loaded drums containing the hydration heat source. Fast thermal response and high peak temperature can lead to unacceptable consequences such as cement degradation and solution boiling.

The primary objective of this work is to develop a heat transfer model for the 55-gallon WSB drum partially filled with the cement and to evaluate the thermal performance of the drum package containing hydration heat source associated with the current baseline cement waste form.

A series of sensitivity calculations for different air space heights was also performed to examine the impact of the peak cement temperature due to the change of the air space height above the top cement surface. This paper will discuss the modeling and analysis results.
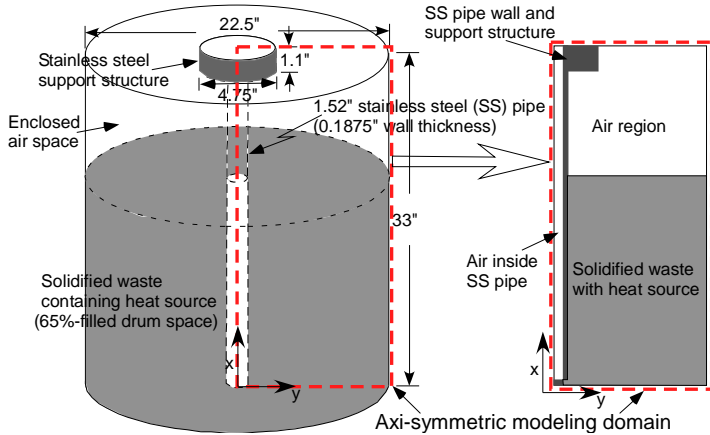

Figure 1. Modeling domain and geometry used for the present work (1" = 0.0254m).

NOMENCLATURE

A	Area (m^2)
°C	Degree Centigrade (or Celsius)
d	Diameter (m)
ft	Foot (=0.3048m)
h_w	Wall heat transfer coefficient (W/m^2-K)
hr	Hour
in	Inch (=0.0254m)
J	Energy unit (Joule)
K	Absolute temperature (=273.15+ °C)
kg	Kilogram
L	Length (m)
m	Meter
min	Minute
q'''	Volumetric heat source (W/m^3)
(q''')$_{avg}$	Time-averaged volumetric heat source (W/m^3)
R	Energy residual (W)
Re	Reynolds number (dρu/μ)
s or sec	Second
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
t	Time (second) or degree Centigrade
T_∞	Ambient temperature (K)
V_F	Cement volume containing the hydration heat (m^3)
W	Watts (J/sec)
x, y	The coordinate system for the two-dimensional domain as shown Fig. 1
ρ	Density (kg/m^3)
β	Thermal expansion coefficient (K^{-1})
μ	Dynamic viscosity (kg/m-s)
ν_f	Kinematic viscosity (m^2/s)

MODELING APPROACH AND SOLUTION METHOD

For the evaluation of thermal performance of the WSB drum package, the baseline design involves a 55-gallon drum with dimensions of 33 in. tall and 22.5 in. diameter, which is filled with cement waste form by 65 percentages of the drum volume. The drum container will be filled with the cement up to 75% drum volume. Geometrical configurations and dimensions for the present analysis are shown in Fig. 1. The cement region has transient heat source associated with the hydration of the cemented waste mixture. Figure 2 presents the measured heat loading per unit mass of the cement waste. In the figure it is also compared with the polynomially-fit curve obtained by using a least-square method. Average heat source density over 70-hour transient period of the cement waste form is about 0.373 W/kg. When the drum is filled with the cement waste by 65 vol%, total heat loading of the WSB drum corresponding to the average heat source density is about 115 watts during the 70-hour transient period. It corresponds to about 3.1 W/gallon of volumetric heat source.

For the thermal performance analysis of the drum package, this heat loading will be assumed to be cooled through a coupled conduction and natural convection heat transfer mechanism under the baseline operating conditions. Detailed modeling conditions used for the baseline analysis are provided in Table 1. For computational modeling purposes, a conservative approach was taken by assuming that the primary cooling mechanism of the drum was a coupled heat transfer process of conduction and natural convection, and that radiative heat removal from the top surface of the cement waste form inside the drum was negligible since maximum temperatures under the nominal operating conditions are expected to be lower than 100°C.

An axi-symmetric two-dimensional transient heat transfer model coupled with convective momentum driven by temperature gradient across the boundary layer was developed to assess the thermal performance of the WSB drum partially filled with the cement waste form containing heat source under the prototypic geometry as shown in Fig. 1.

The drum configuration shown in Fig. 1 involving the enclosed air region above the 65%-filled cement waste region will serve as the initial and baseline configuration. Alternative configurations involving two different percentages of fill volume such as 50% and 75% will be also evaluated for sensitivity analysis. The measure data for the hydration heat source was polynomially fitted by a least square method. The fitted equation is compared with the data in Fig. 2.
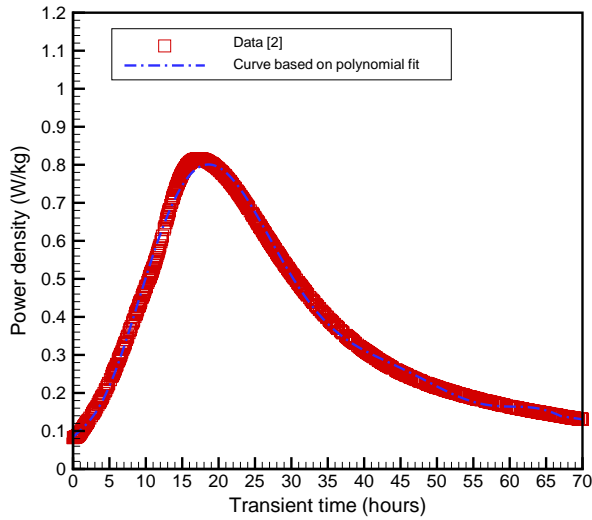
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Figure 2. Heat source per unit mass as function of time

Table 1. Modeling conditions for the heat transfer analysis of the 55-gallon WSB drum package.

Parameters		Modeling conditions
Drum dimensions	Diameter	22.5 in
	Height	33 in
Level of cement waste form inside 55-gallon drum		16.6 in (50%-filled)[+], 21.45 in (65%-filled)*, and 24.75 in (75%-filled) [+]
Initial temperature of cement waste form		26.85°C[+], 43°C*
Ambient temperature		26.85°C
Heat source averaged over the 70-hour transient period		0.373** W/kg (Transient heat source due to cement hydration as shown in Fig. 2)

Note: * Baseline operating conditions
+ For the sensitivity analysis

** Computed by $(q''')_{avg} = \int_{t=0}^{t=70\,hrs} q'''(t)\,dt$

The model considers three basic cases as shown in Table 2. The first case, Case 1, is assumed to have 65%-filled drum package and involve internal heat transfer by conduction for the cement waste form and by a coupled mechanism of conduction

and convection for the enclosed air region above the cement region. Heat transfer at the walls involves natural convection from the external wall boundary to the ambient air, with the assumption that the air serves as an infinite heat sink at constant temperature as shown in Table 1. Cases 2 and 3 shown in Table 2 are the WSB drum packages filled with 75% and 50%, respectively. All three cases are assumed to have the same volumetric heat load under the same initial and boundary conditions as provided in Table 1. In this case, it is assumed there is no heat loss at the bottom wall boundary of the drum (adiabatic boundary) and all heat transfer through the other wall surfaces to the ambient is via natural convection. Heat transfer analysis of the drum package for the basic cases is performed for a given boundary condition by using a computational heat transfer approach on a Cartesian x-y grid.

For heat transfer analysis, the actual baseline drum design involves a cement waste region with 21.45 in high, resulting in a 11.55 in height for the enclosed air region. This height is believed to have an impact of natural convective cooling on the coolability of the WSB drum package. The drum design is annular due to the presence of a center pipe with an outside diameter of 1.52 in. The center pipe will be filled with air. At the top of the pipe there is a sintered metal filter to release hydrogen generated in the cementation process of the waste streams.

Table 2. All the cases for the thermal analysis of the 55-gallon WSB drum package.

Cases	Primary purpose	Cement vol. % of drum	Height* of the enclosed air region above the cement region (in)
Case 1	Baseline	65	11.55
Case 2	Sensitivity	75	8.25
Case 3	Sensitivity	50	16.5

Note: *Total drum height is 33 in.

Table 3. Material and thermal properties for the analysis.

Region	Density (kg/m^3)	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)	Thermal diffusivity (m^2/sec)
Air	Ideal gas	1006.4	0.0242	2.4x10^{-5}
Stainless steel	8030	502.5	16.27	4.0x10^{-6}
Cement mixture	2200	736	0.53	3.3x10^{-7}

The WSB drum forms a thin layer of stainless steel wall material surrounding the cement waste form filled inside the 55-gallon cylindrical container with the 1.52-in stainless steel center pipe filled with air. Potential cooling mechanisms of the drum system are conduction and natural convection driven by temperature gradient. The drum design considered for the present work is shown in Fig. 1. Thermal and material

properties for the modeling calculations were obtained from the literature [6,7].

The heat generated by the cement hydration will be transferred by conduction through a cementation medium and eventually will be transported to the ambient room through the physical processes of conduction and convection heat transport. The heat transfer rate at the solid-fluid interface boundary is computed using the fluid temperature gradient and heat transfer coefficient at the solid wall boundary with given ambient temperature. For the present work, the heat transfer coefficient will be estimated by the literature correlation [5,7].

When cooled by natural convection, the fluid temperature gradient in the drum depends on the external gas flow field that is driven by the density gradient at the wall boundary layer and is dependent on the rate at which the gas fluid convects the heat away. Typical air flow and temperature profiles are formed along the solid-fluid interface under actual energy transport processes such as buoyancy-driven natural convection due to the fluid temperature gradient. Temperature decreases rapidly due to the convective cooling effect within a boundary layer region. The boundary layer flow is a buoyancy-induced motion, resulting from body forces acting on masses, which arise from temperature gradients in the fluid. It is virtually impossible to observe pure heat conduction in a gas medium because as soon as a temperature difference is imposed on a fluid, natural convection currents will occur as a result of force imbalances caused by density differences. Thus energy transport is coupled to the momentum transport through the wall interface of the solid and fluid regions, but in this case, the ambient temperature and the heat transfer coefficient at the solid wall are assumed to be constant. This will lead to the reduction of computational time. However, the enclosed gas region above the cement waste region is considered a coupled momentum-energy cooling mechanism.

For the present analysis, the heat source term q''' in the energy balance equation is included since a significant amount of hydration heat is transiently generated from the drum filled with the cement waste form through the cementation process. In eq. (4), energy terms within a control volume of a solid medium in the drum include conduction ($k\nabla T$) and energy storage due to transients ($\rho C_p\,\partial T/\partial t$). In this situation, the radiation term in the energy balance equation was neglected. k in eq. (4) is thermal conductivity of the medium in the computational domain. This property value will be provided by input as provided in Table 3. The drum containing the cement waste with transient volumetric heat source q''' will be cooled down by a natural convection process through its wall surface as shown in Fig. 1. In this case, when wall boundary and initial conditions are provided, the governing equations are complete. They are

$$-\left(k\nabla T\right)_{wall} = h_w\left(T - T_\infty\right)_{wall}\tag{1}$$

In Eq. (1), h_w and T_∞ are wall heat transfer coefficient and ambient temperature, respectively.

The heat transfer coefficient at the outside wall of the column (h_w) is obtained by using the empirical correlation available in the literature [5]. In this situation, the natural convection flow regime for the air-cooled design should be estimated based on the non-dimensional Grashof number (Gr$_L$), which is the parameter describing the ratio of buoyancy to viscous forces for a vertically-oriented cylinder with height L. The Grashof number performs much the same function for natural convection flow as the Reynolds (Re) number does for forced convection. Under normal conditions one may expect that the laminar-to-turbulent transition will take place at about $Gr_L \approx 10^9$.

For a typical air-cooled system without forced air circulation,

$$Gr_L = \frac{g\beta L^3\left(T_w - T_\infty\right)}{\nu_f^{\,2}}\tag{2}$$

where L = characteristic length parameter (~ 0.85 m),
  $\beta = 3.34 \times 10^{-3}\ \mathrm{K^{-1}}$,
  $\nu_f = \left(\mu_f\big/\rho_f\right) = 1.60 \times 10^{-5}\ \mathrm{m^2/sec}$.

In eq. (2), the Grashof number was estimated less than 10^9 for the present conditions in order to examine the boundary layer flow regime of natural convection. This corresponds to the laminar flow according to the literature [8].

For the analysis, the natural convection regime around the WSB drum package is assumed to be laminar. As shown in Fig. 1, geometrical configurations for the present analysis involving a vertically-oriented cylindrical column. However, literature results [7] show that when the geometrical ratio of the diameter (D) to the height (L) is greater than or equal to $35(Gr_L)^{-0.25}$, the natural convection correlation for vertical flat-plates can be applied to the vertical cylinder equally. For the present configurations of the 22.5-in drum,

$$\left(\frac{D}{L}\right)_{min.} = 0.68 > \left(35\,Gr_L^{-0.25}\right)\approx 0.36\tag{3}$$

Warner and Arpaci [5] performed an experimental investigation of natural convection in air from a vertical heated plate. The results of this study showed good agreement with the following correlation for Grashof number up to 10^{12}:

$$Nu_L = \left(\frac{h_w L}{k_f}\right) = 0.10\left(Pr_f\,Gr_L\right)^{1/3}\tag{4}$$

In Eq. (4), Pr_f is Prandtl number.

In eq. (4) h_w is natural convection heat transfer coefficient at the heated solid wall. k_f is thermal conductivity of fluid at the fluid temperature T_f. Potential range of heat transfer coefficients at the wall surface of the 55-gallon drum was

estimated as shown in Fig. 4. Averaged heat transfer coefficient of 2.5 W/m²-K was used for the present calculations.

The material and thermal properties for the components of the 55-gallon drum package in a WSB facility are provided in Table 3. Using these thermal properties, a two-dimensional transient heat transfer model was performed to predict transient thermal responses of the WSB drum partially filled with the cement waste form. For computational efficiency, effective thermal conductivity for the composite cement region was used as shown in Table 3. Thus, computational time can be reduced by modeling a single-material region with the effective thermal conductivity instead of modeling a multi-material region composed of several different materials.
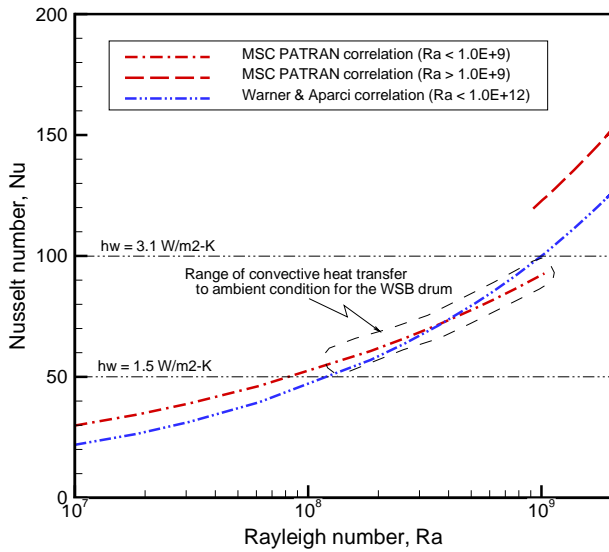

Figure 3. Heat transfer coefficients at the wall surface of the 55-gallon drum for the present modeling calculations

Modeling boundaries and conditions for the cases considered here are shown in Fig. 1 and Table 1. Implicit and iterative solution techniques were used to solve the transient governing equations [3,4].

The overall energy balance should be checked to demonstrate the adequacy of the grid fineness used. This was done by using Eq. (5).

$$R = -\int_{A_W} q''_w \, dA + q''' V_F \qquad (5)$$

The volumetric heat source term, q''', in eq. (11) is given by the code input. A_w is the entire wall surface area for the heat

transfer of the drum package cooled by the ambient conditions. V_F is the cement volume containing heat source. For all the cases considered here, energy residual (R) is less than about 0.1 watt. For the present analysis, an optimum grid of about 12,000 cells has been established from the grid sensitivity analysis under the Linux HP DL585 platform.

In order to achieve the modeling objectives, a computational approach was taken by applying the previous solution method [1,3,4]. This work started with the baseline model, assuming that the cement waste form fills the WSB drum by 65% in volume for the treatment and solidification of the radioactive liquid waste streams generated by the PDCF and MFFF.

Transient heat transfer calculations for the 55-gallon WSB drum will be performed for the evaluation of the thermal performance for the drum package containing hydration heat source associated with the current baseline cement waste form. Transient calculations will use the following main assumptions:

- Pouring process of the cement waste form into the drum is assumed to be instantaneous.

- For the evaluation of thermal performance for the WSB drum, there is no flow communication through the sintered metal filter located at the top center of the drum.

- Radiative heat transfer is negligible compared to the conduction and convection cooling mechanisms since maximum component temperatures are expected to be lower than 100°C.

- For conservative estimate, there is no heat transfer through the bottom surface of the drum package.

- Top surface of the waste form cementation is formed in a horizontally smooth way.

- No air pocket within the cement region is generated through the mixing and cementation process of the WSB waste form.

- For conservative heat transfer calculations, the heat source was estimated for a uniformly-distributed cement region.

- Constant thermal conductivity for each material was assumed instead of considering temperature-dependency for the energy equation.

Based on the modeling assumptions, a two-dimensional axi-symmetric model was used to calculate transient temperature distributions for the WSB drum package partially filled with the cement waste form containing transient heat source. Baseline design and operating conditions of the heat transfer analysis are presented in Table 1.

As needed, based on the results of the transient evaluations, steady-state calculations was conducted under the same conditions listed above to compare the temperature

distributions and buoyancy-driven flow characteristics associated with natural convection cooling mechanism. The modeling results provide quantitative information associated with the optimal operating configuration such as cooling time and waste form loading.

RESULTS AND DISCUSSIONS

An axi-symmetric two-dimensional approach has been taken to compute temperature distributions within the modeling domain shown in Fig. 1 and to investigate transient temperature responses to hydration heat loads for the enclosed 55-gallon drum partially filled with cement waste form. For three modeling Cases 1, 2, and 3 as shown in Table 2, these drums are assumed to be cooled primarily by natural convection at the external drum walls and through the enclosed gas region above the cement region. For Case 1, 65%-filled drum was considered as the baseline operating condition to evaluate maximum cement waste and drum surface temperatures under convective cooling mechanism. Modeling conditions used for the calculations are summarized in Tables 1 and 2.

For the benchmarking test of the model, an infinite plate of thickness L shown in Fig. 4 was considered. Initially the plate is at uniform temperature T_i, and at time zero the surfaces are suddenly lowered to $T = T_w$. Under transient conditions, the energy equation for the slab with effective thermal conductivity $k_{b,eff}$ becomes

$$\frac{\partial T(x,t)}{\partial t} = \left(\frac{k_{b,eff}}{\rho C_p}\right)\left(\frac{\partial^2 T(x,t)}{\partial x^2}\right)$$

$$= \alpha\left(\frac{\partial^2 T(x,t)}{\partial x^2}\right) \qquad (6)$$

By using the separation of variable technique, final series solution at position x and time t can be obtained from the initial and boundary conditions. That is,

$$T(x,t) = T_w + (T_i - T_w)\left(\frac{4}{\pi}\right)\left[\sum_{n=1}^{\infty}\frac{1}{n}\exp\left\{-\alpha\left(\frac{n\pi}{L}\right)^2 t\right\}\sin\left(\frac{n\pi x}{L}\right)\right]_{n=1,3,5,7,\cdots} \qquad (7)$$

When an infinite stainless steel slab plate as shown Fig. 4 is 100°C initially, and its wall surfaces are suddenly cooled down to 20°C, the transient temperature responses are benchmarked against the theoretical results shown in Eq. (7). The modeling predictions are in agreement with theory within about 0.5%. Detailed spatial and transient distributions are also compared with the theoretical results as shown in Figs. 5 and 6.
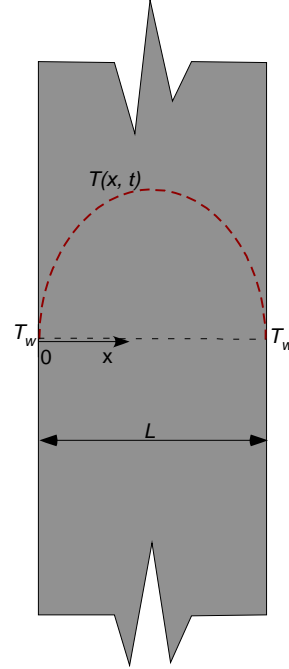

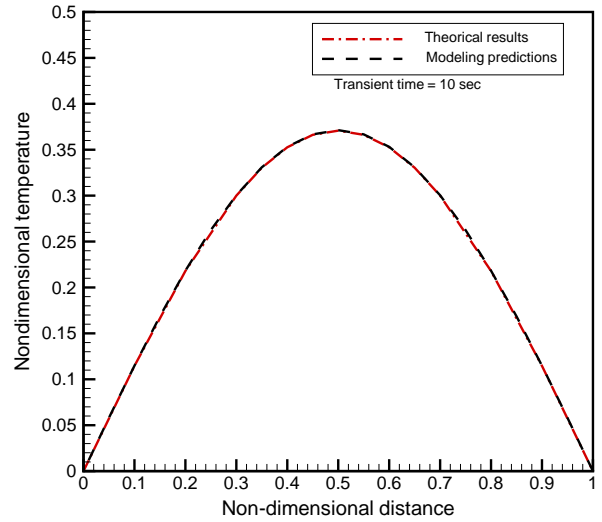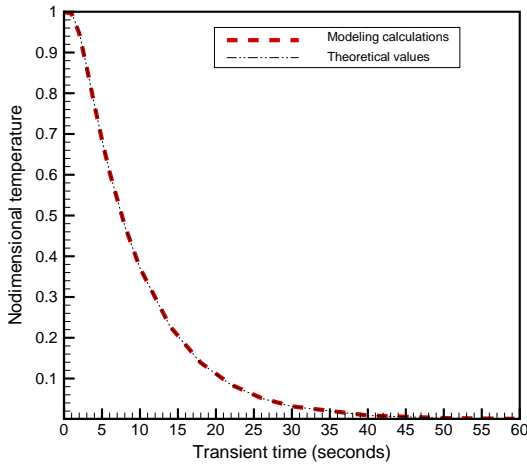Figure 4. Infinite slab plate subjected to sudden cooling of surfaces

Figure 5. Benchmarking results of the present model against the theoretical calculations for the spatial temperature distributions across the slab at 10 seconds of transient time

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$$\text{Non-dimensional temperature, } \theta = \left\{ \frac{(T(x,t) - T_w)}{(T_i(x, t=0) - T_w)} \right\}$$

Figure 6. Benchmarking results of the present model against the theoretical calculations for the transient thermal response

Table 4. Transient maximum cement and drum surface temperatures for three different volumes of the cement waste

Cases		Max. cement temp. (Max. surface temp.), ^{o}C		
		Case 1 (Baseline)	Case 2	Case 3
Cement volume % of the drum		65%	75%	50%
Transient time (hours)	0 (initial)	43 (43)	43 (43)	43 (43)
	12	56.3 (42.8)	56.4 (42.8)	56.3 (42.8)
	24	87.5 (57.6)	87.7 (57.6)	86.7 (57.4)
	32	95.5 (59.0)	95.9 (59.1)	93.9 (58.6)
	48	85.1 (52.8)	86.0 (53.0)	82.2 (51.8)
	70	64.0 (43.3)	65.1 (43.7)	61.0 (42.3)

The validated model was subsequently used for thermal performance analysis of the WSB drum geometry partially filled with the cement waste form containing transient hydration heat source. Table 4 shows transient maximum drum content and surface temperatures for the three different volumes of the cement waste form in a WSB drum. The results reveal that the maximum temperature of the WSB drum loaded to 75% cement waste form does not exceed the liquid phase boiling point of ~100°C under natural convective cooling conditions (maximum temperature: 96°C). Figure 7 shows transient maximum drum surface temperature and maximum waste content temperature for the 65%-filled drum package containing transient hydration heat source as provided in Fig. 2 when initial waste and ambient temperatures are 43°C and 27°C, respectively. In the figure, steady state temperatures based on the heat source averaged over the 70-hour period are compared with the transient temperatures under the same boundary conditions. It is noted that transient maximum temperatures reach steady-state maximum temperatures in about 20 hours when initial temperature of the cement waste form is 43°C.

When the baseline drum package is filled with the cement waste form by 65% and initial temperature is 43°C, transient drum surface temperature distributions along the elevation height from the bottom to top of the external drum surface are shown in Fig. 8. Steady state temperature distributions for the heat loading averaged over the 70-hour period are compared in the figure. It is noted that there is a large temperature drop across the solid-fluid interface due to the additional cooling mechanism driven by internal natural circulation inside the enclosed void space above the cement region.
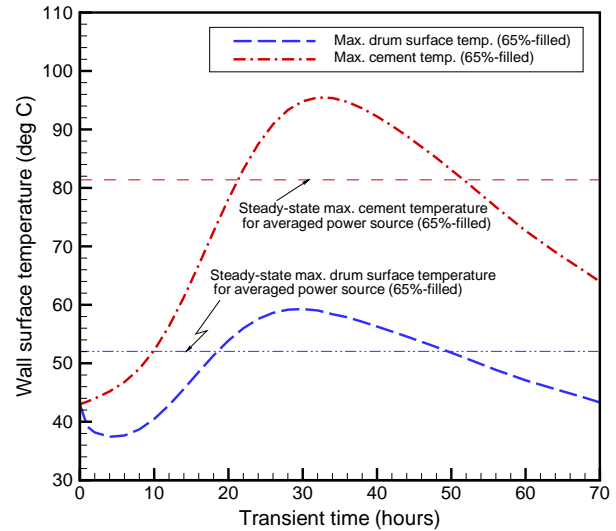

Figure 7. Transient maximum drum surface temperature and maximum waste temperature for 65%-filled heat source provided by Fig. 2 (Initial waste temperature = 43°C and ambient temperature = 27°C, and steady state temperatures based on the heat source averaged over the 70-hour period).
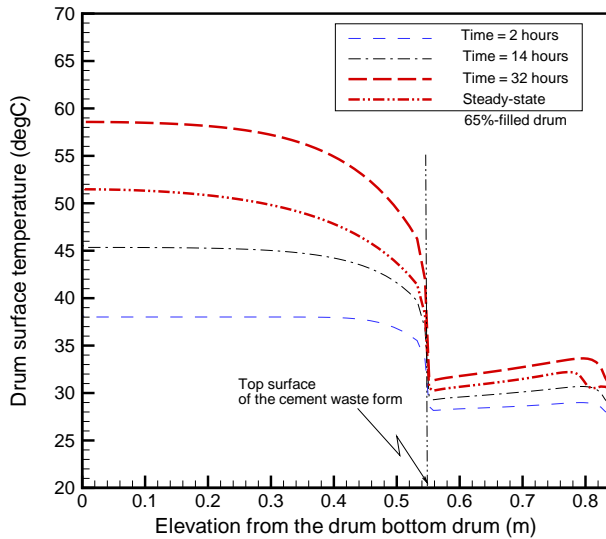
Figure 8. Transient drum surface temperature distributions for 65%-filled heat source provided by Fig. 2 (Initial waste temperature = 43°C and ambient temperature = 27°C, and steady state temperatures based on the heat source averaged over the 70-hour period).

The results show that natural buoyancy drives air circulation velocity of about 1 ft/sec in 12-in tall enclosure when peak transient temperature is reached under the baseline drum loaded with 65% volume of the cement waste form. It is clearly shown that when temperature gradient across the thermal boundary layer becomes larger, buoyancy-driven velocity becomes larger, leading to the higher ratio of convection to conduction cooling mechanism. In this case, the convection-to-conduction ratio, referred to as Nusselt number, is about 80 when the waste form temperature reaches peak value at transient time of 32 hours under the baseline drum loading (Case 1). This is consistent with the literature information [7].

Two different initial waste temperatures of 43°C and 26.85°C were considered to quantify the sensitivity of transient thermal responses to the same heat loading. Figure 9 compares transient maximum drum surface and waste temperatures between the two different initial waste temperatures under the transient heat source as provided by Fig. 2. The results show that when initial temperature of the cement waste form changes from 43°C to about 27°C, maximum temperature of the WSB drum is reduced by about 6°C at 32 hours of transient time.

When the WSB drum is partially filled with different volumes of the cement waste form, thermal responses to the transient hydration heat loading were evaluated to quantify how quickly the heat loading is dissipated into the ambient environment through the drum package. As shown in Fig. 10, the modeling results of the transient maximum drum surface and cement waste temperatures are compared for different loadings of

cement waste in a drum container when initial waste and ambient temperatures are 43°C and 26.85°C, respectively. Table 7 also shows quantitative comparison of transient maximum cement and drum surface temperatures for three different volumes of the cement waste form.

Figure 20 compares the temperature distributions cooled by natural convection at 32-hour transient time for different sizes of gas enclosures above the top surface of the waste form cement region due to the different loading volumes of the cement waste form under the same color scale. As color scale in the figue, red region represents temperature higher than 96.0°C, and blue one has 26.85°C. Figure 21 shows qualitative comparison of natural circulation patterns driven by the temperature gradients shown in Fig. 20 for different heights of gas enclosures above the top surface of the cement waste form region due to the different loading volume of the cement waste form at the peak temperature time of 32 hours when red region has velocity higher than 0.39 m/sec, and blue one has zero velocity. Table 8 compares quantitative ratios of convection to conduction cooling mechanisms for different heights (H) of the air enclosure above the cement waste form with the same heat loading at 32 hours of transient time during WSB drum storage. These values are referred to as Nusselt number in the literature, and they are representative of the coolability increase of the enclosed waste package due to the buoyancy-driven cooling mechanism such as natural convection during the interim WSB drum storage. It is clearly shown that increasing vertical height of the gas enclosure results in higher coolability due to the increased gas motion.
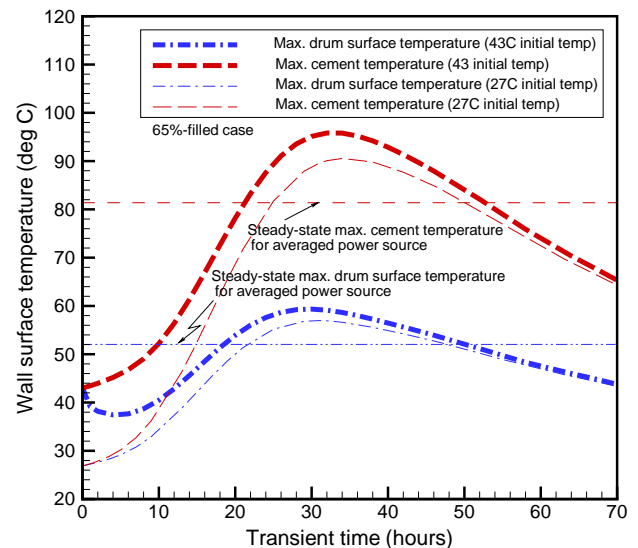

Figure 9. Comparison of transient maximum drum surface and waste temperatures between two different initial waste temperatures.
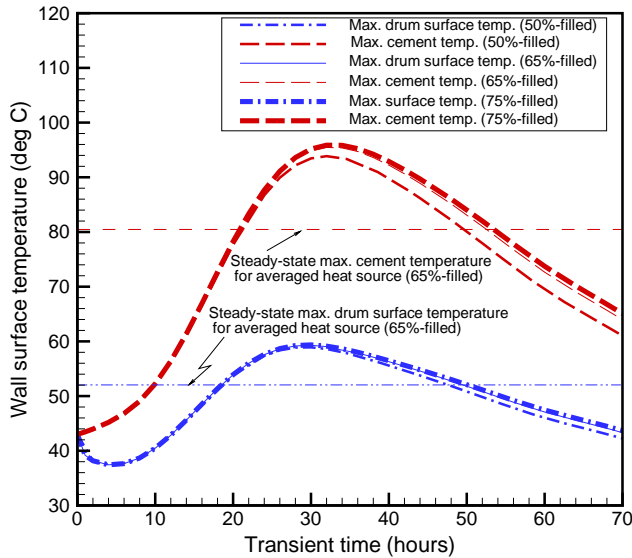
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Figure 10. Comparisons of transient maximum drum surface and cement waste temperatures for different loadings of cement waste in a drum container (Initial waste temperature = 43°C and ambient temperature = 27°C).

The results indicate that when the loading volume increases from 50 vol% to 75 vol% for the enclosed drum with initial cement temperature 43°C and ambient temperature 26.85°C, peak temperature increase over the entire drum will be about 2°C for the cement region containing the hydration heat source as defined in Eq. (1) and about 0.5°C for the external surface of the drum package. This means that smaller height of the gas enclosure drives slower gas movement due to the smaller gravity difference between the heated surface and the cooled one under the same heat loading and ambient conditions.

The results demonstrate that the buoyancy-driven gas circulation in the enclosed region above the cement region provides the primary cooling mechanism in reducing the peak drum temperature. Table 9 shows a quantitative comparison of maximum waste and drum surface temperatures under the various loading conditions of the WSB drum.

The transient thermal response of a conduction medium containing a heat source to the cooling environment at a lower temperature is closely related to its thermal diffusivity. The thermal diffusivity, α is defined as the ratio of thermal conductivity to the product of density and specific heat. As shown in Table 3, the drum media during hydration process have small α values of 3.3 x 10^{-3} cm^{2}/sec for cement waste form. This parameter is a measure of temperature-wave penetration depth for a given time. The results showed that peak temperature of the WSB drum containing heat source was

reached at about 32 hours although hydration heat was peak at about 17.5 hours since the initiation of the cementation process. The relatively slow transient thermal response of the drum to the heat load is mainly due to the low thermal diffusivity of the cement waste form material as indicated in the table. The results demonstrate that a naturally-cooled (ambient drum temperature of 27°C with no forced ventilation), 22.5-in drum package under all loading conditions of the cement waste form considered here can stay lower than 100°C in WSB facility.

The results show that increasing the cement volume from 50% to 75% does not greatly impact the maximum temperature or the heat rate. The modeling results indicate that the 1.52-in central stainless steel pipe clearly provides an effective conduction path in dissipating the hydration heat from the cement region containing heat source to the cooler ambient.

Table 8. Comparison of convection to conduction cooling ratios for different height (H) of the air enclosure above the cement waste form with the same heat loading at 32 hours of transient time during WSB drum storage

Cases	Height above the cement region (H)	Ratio of convect. to cond. cooling at top cement surface	Peak temp. of cement region ($^{\circ}$C)
Case 1 (65%-filled)	11.55 in	83	95.5
Case 2 (75%-filled)	8.25 in	78	96.0
Case 3 (50%-filled)	16.5 in	90	94.0

Table 9. Maximum surface and cement temperatures during the transient period of drum storage in a WSB facility

Cases	Max. temperature	
	Drum surface ($^{\circ}$C)	Cement region ($^{\circ}$C)
Case 1 (65%-filled)	59.0	95.5
Case 2 (75%-filled)	59.1	96.0
Case 3 (50%-filled)	58.6	94.0

CONCLUSION

Transient axi-symmetric two-dimensional heat transfer calculations have been performed to assess the thermal performance of the 55-gallon WSB drum container containing hydration heat source associated with the current cement waste form.

A series of the modeling calculations has been performed using a computational heat transfer approach, assuming that the cement waste form with transient heat source is cooled by natural convection of 27°C external air as a primary heat transfer mechanism. For Case 1, 65 percent of the drum volume was assumed to be filled with the waste form to determine the maximum drum surface and cement waste temperatures as the baseline loading condition. For Case 2, transient calculations under the maximum loading conditions of 75 percent filled drum were evaluated to investigate how sensitive the maximum waste and drum temperatures are to the loading volumes of the cement waste form. Case 3 quantified the transient thermal response to the lowest loading conditions of the cement waste form. In addition, the results computed by the present model were verified by the theoretical results. From the present modeling results, the main conclusions are:

- The baseline modeling results show that transit times to reach maximum temperature of the 65%-filled drum are about 32 hours when the 43°C initial cement temperature is cooled by natural convection of 27°C ambient air. In this case, maximum cement and maximum drum surface temperatures are 95.5°C and 59.0°C, respectively.

- When the loading volume increases from 50 vol% to 75 vol% for the enclosed drum with initial cement temperature 43°C and ambient temperature 27°C, the peak temperature over the entire drum increases about 2°C for the cement region and about 0.5°C for the external surface of the drum package.

- It is shown that peak temperature of the WSB drum containing heat source is reached at about 32 hours due to the low thermal diffusivity of the cement waste although hydration heat loading is peak at about 17.5 hours since the beginning of the cementation process.

- The results demonstrate that the buoyancy-driven gas circulation in the enclosed region above the cement region provides the primary cooling mechanism in reducing the peak drum temperature as shown in Table 8.

- The results show that increasing the cement volume from 50% to 75% does not greatly impact the maximum drum temperature or the heat rate.

- It is noted that the central stainless steel pipe (about 1.52 in diameter) clearly provides an effective conduction path in dissipating the hydration heat from the cement region containing heat source to the cooler ambient environment.

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