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Donna Post Guillen

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Donna Post Guillen
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, ID 83406
Donna.Guillen@inl.gov

ABSTRACT

The Global Threat Reduction Initiative (GTRI) has many experiments yet to be irradiated in support of the High Performance Research Reactor fuels development program. Most of the experiments will be irradiated in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL), then later shipped to the Hot Fuel Examination Facility (HFEF) located at the Materials and Fuels Complex for post irradiation examination. To date, the General Electric (GE)-2000 cask has been used to transport GTRI experiments between these facilities. However, the availability of the GE-2000 cask to support future GTRI experiments is at risk. In addition, the internal cavity of the GE-2000 cask is too short to accommodate shipping the larger GTRI experiments. Therefore, an alternate shipping capability is being pursued. The Battelle Energy Alliance, LLC, Research Reactor (BRR) cask has been determined to be the best alternative to the GE-2000 cask. An evaluation of the thermal performance of the BRR cask is necessary before proceeding with fabrication of the newly designed cask hardware and the development of handling, shipping, and transport procedures. This paper presents the results of the thermal evaluation of the BRR cask loaded with a representative set of fueled and non-fueled experiments. When analyzed with identical payloads, experiment temperatures were found to be lower with the BRR cask than with the GE-2000 cask. From a thermal standpoint, the BRR cask was found to be a suitable alternate to the GE-2000 cask.

KEYWORDS
Thermal analysis, shipping cask, irradiated experiments

1. INTRODUCTION

The Global Threat Reduction Initiative (GTRI) has many experiments yet to be irradiated in support of the High Performance Research Reactor fuels development program. The GTRI experiments are in the form of mini-plate capsules, full plates and elements [1]. Most of the experiments will be irradiated in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL), then later shipped to the Hot Fuel Examination Facility (HFEF) located at the Materials and Fuels Complex for post irradiation examination. The General Electric (GE)-2000 cask is currently qualified for use at the ATR and HFEF facilities and has been used to transport GTRI experiments between them. However, the availability of the GE-2000 cask to support future GTRI experiments is at risk. It is not certain that GE will re-certify the liner and lid. The current

GE-2000 liner lid does not fit properly and hasn't been previously used for shipping experiments at INL. If the GE-2000 cask liner is no longer available, the required cool-down times prior to shipment may be excessively long. Also, the internal cavity of the GE-2000 cask is too short to accommodate shipping the larger GTRI experiments. These factors may make GE-2000 shipments impractical.

The Battelle Energy Alliance, LLC, Research Reactor (BRR) cask has been determined to be the best alternative to the GE-2000 cask. Both the GE-2000 and BRR casks have a cylindrical internal volume, but have different dimensions for the height, volume, weight, and shielding. They both are made of stainless steel and use lead for radiation shielding. A comparison of the geometrical features of the BRR cask is compared to those for the GE-2000 cask in Table 1. As can be seen in the table, the inside diameter of the BRR cask is smaller than the GE-2000 and the internal volume of the BRR cask is less than the volume of the GE-2000 (with or without the liner). The GE-2000 with the liner adds additional shielding, but also significantly reduces the overall payload capacity of the cask. The BRR cask has a taller internal cavity, which can accommodate the longer experiments and the built-in shielding is comparable to that of a GE-2000 with a supplemental lead liner.

Table 1. Comparison of BRR and GE-2000 shipping cask dimensions [1].

	GE-2000 Cask	GE-2000 Cask w/ Liner	BRR Cask
Interior Height (m)	1.372	1.080	1.372
Interior Diameter (m)	0.673	0.514	0.406
Wall: Lead Thickness (m)	0.102	0.159	0.203
Wall: Steel Thickness (m)	0.051	0.070	0.081
Base: Lead Thickness (m)	0.000	0.057	0.196
Base: Steel Thickness (m)	0.152	0.171	0.053
Top: Lead Thickness (m)	0.140	0.267	0.246
Top: Steel Thickness (m)	0.076	0.095	0.089
Internal Volume (m^3)	0.488	0.224	0.178

Thermal limitations for shipping spent fuel are given in the Code of Federal Regulations (CFR) Title 49, Section 173.442 [2]. The external temperature of the BRR cask must not exceed 50°C due to the decay heat from the loaded experiments. In addition, to meet programmatic objectives and keep the experiments from being damaged by excessive heat, the maximum experiment temperature must not exceed the threshold temperature determined by experimenters.

The purpose of this analysis is to determine whether the BRR cask is a suitable alternate to the GE-2000 cask. This paper presents the results of a thermal analysis for the BRR shipping cask loaded with selected fueled experiment capsules and a representative ATR National Scientific User Facility (NSUF) non-fueled experiment. The experiments inserted into the cask for this analysis are part of an evaluation of the cask for a "typical" ATR experiment and not for a planned shipment, since these capsules have already been shipped. Rather, this analysis serves as a baseline to compare the thermal performance of the BRR shipping cask to the GE-2000 shipping cask with identical payloads. The model built for this analysis can be easily modified and adapted to incorporate other payloads. The model, analysis details and results are discussed in the following sections.

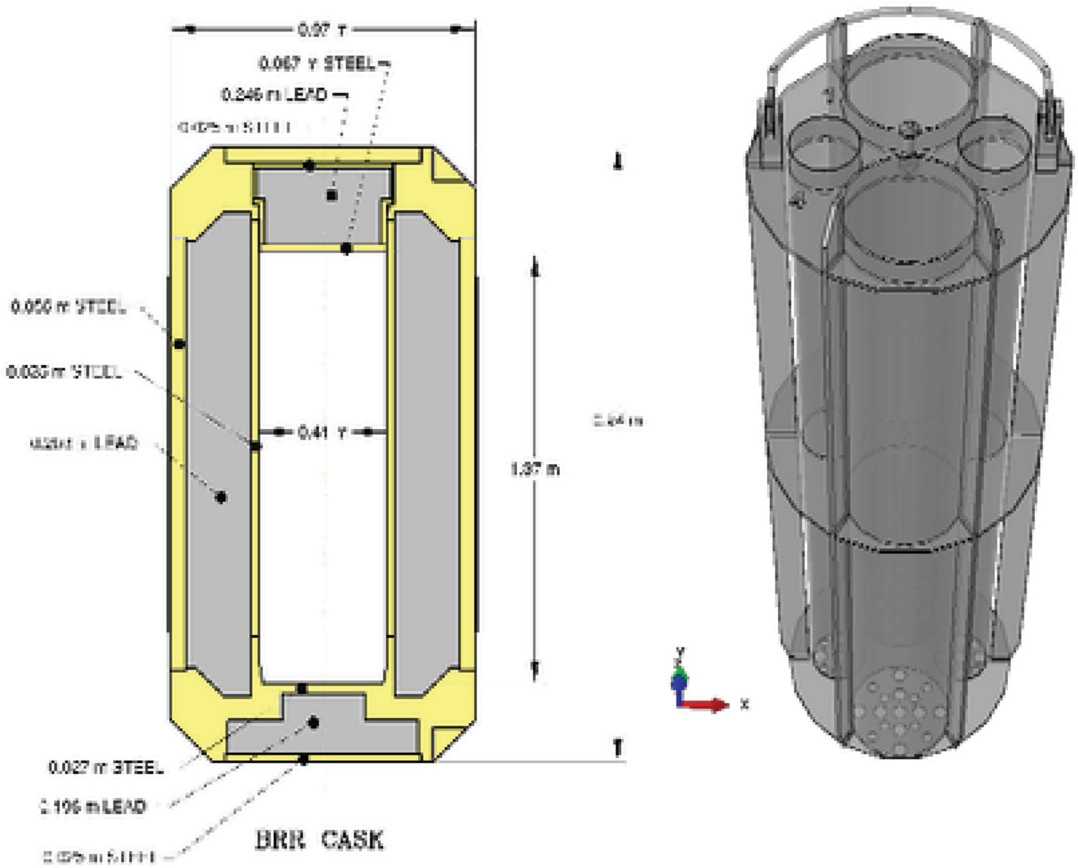
2. MODELING INFORMATION

The cask and associated components are designed to safely transport irradiated experiments from the ATR reactor to the HFEF hot cell for post irradiation examination. In order to use the BRR cask at the INL, ancillary pieces of equipment were designed or modified to adapt to the BRR cask geometry. Figure 1 shows the overall dimensions of the cask, with the respective thicknesses of the stainless steel and lead shielding, along with an illustration of the cask insert that was custom designed for this application. The BRR cask has built-in lead shielding and therefore does not require a supplemental lead liner.

An aluminum alloy insert with four positions for experiments has been designed for use with the BRR cask. There are two large tubes (0.1615 m ID) and two small tubes (0.0856 m ID) that are 1.28 m long to hold irradiated experiments. The configuration analyzed includes five fueled capsules, along with various non-fueled NSUF experiment capsules. The five fueled experiment capsules occupy two of the four cask insert positions. Two capsules are stacked axially in one position and the other three capsules are stacked in another position. The capsules are placed inside baskets that fit into the insert. The capsules are stacked one on top of the other to distribute the heat load along the basket length. Three capsules are located in one insert position, and two capsules are located in another position. This analysis conservatively assumes that the fueled capsules are located in the large tube positions in the insert, which provides a larger gas gap than the smaller insert positions. Each capsule is 0.2 m long and has a maximum width of 0.0328 m. The NSUF experiments are 0.0254 m in diameter and occupy the full length of one of the small insert positions. It is unimportant to the analysis which of the two remaining positions is occupied by the NSUF experiments. The NSUF experiments are placed within a basket inside of an insert tube.

A finite element model was developed to determine the maximum temperatures during shipping. The shipping cask was modeled using ABAQUS CAE [3] for construction of the finite element model and ABAQUS Standard to calculate steady-state temperatures and heat fluxes. This software has been validated using a standard set of textbook problems [4]. The finite element model geometry was constructed using three-dimensional solid elements using 8-node linear brick elements. The modeled assembly includes the cask, cask insert, baskets, position tubes and experiments.

Figure 2 shows a cutaway view of the entire model. Figure 3 shows a view from the top of the cask loaded with the insert and experiments. In the figure, the capsules are loaded in the large insert positions. The rod in the small insert position of Figure 3 represents the NSUF experiments. The fourth insert position, located at the left, is empty. The spacer plates used for positioning of the capsules are not modeled. Instead, they are represented by a simple position tube centered in the basket. This is conservative, since it increases the distance across the gas gap through which the heat must be transferred. The cask lid is not modeled since its effect on the heat transfer analysis is minimal. The drain holes in the cask insert lower support plate are not modeled; rather, the lower support plate is modeled as a solid plate.



(a) (b)

Figure 1. (a) BRR shipping cask (cross-section view), (b) new cask insert.

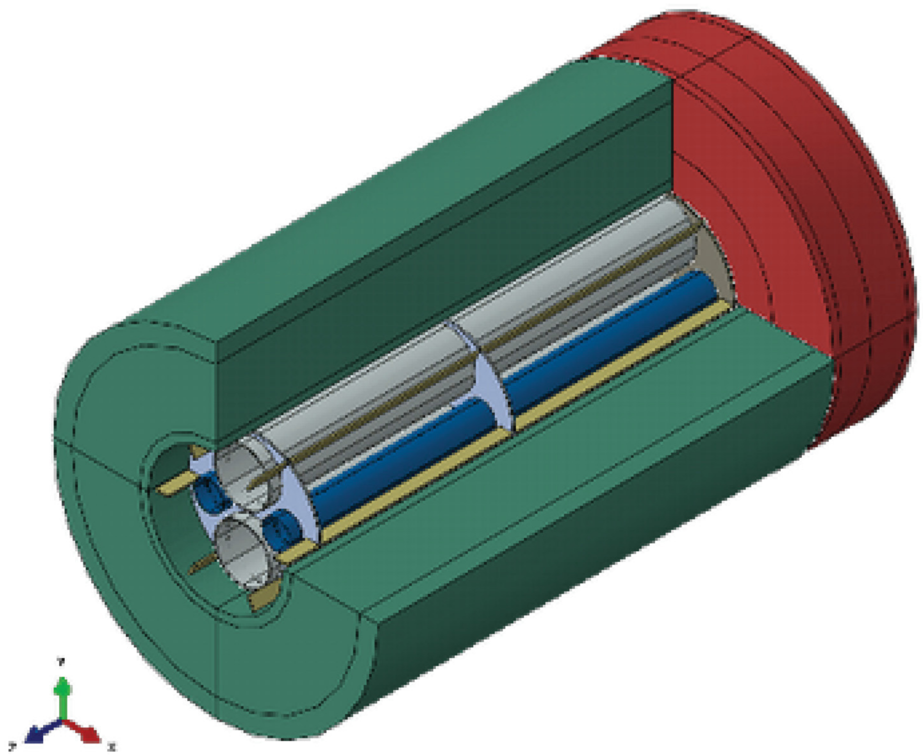
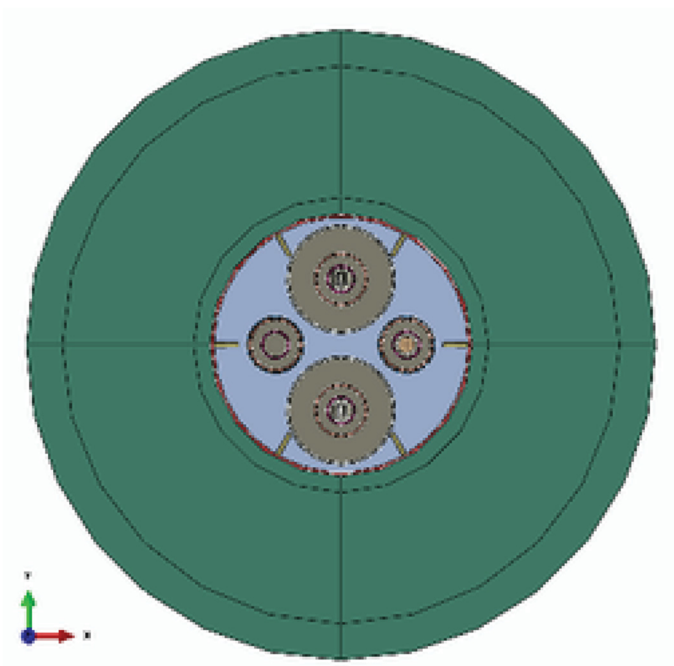
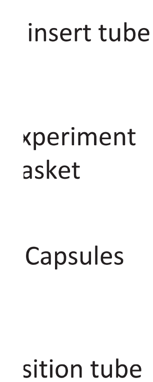


Figure 2. Cutaway view of BRR cask with insert loaded.



(a)



(b)

Figure 3. (a) Top view of cask with experiments loaded, and (b) zoom image of large insert tube with fueled experiment capsules, basket and position tube.

3. CALCULATIONS AND ANALYSIS

The most adverse condition for heat transfer occurs during the vacuum drying process due to the reduction of the thermal conductivity of air at low pressure. During the vacuum drying process, a low pressure (3 Torr) must be maintained for 30 minutes to remove residual water that could deteriorate the materials or lead to a flammable condition caused by the radiolysis of water to free oxygen and hydrogen [5]. This analysis conservatively bounds the requirement by using the thermal conductivity of air at 0.5 Torr in a steady-state calculation. At low pressure, the thermal conductivity of air varies with pressure, as well as temperature [6]. The expression used to calculate the reduced thermal conductivity, k_r, of air during vacuum drying is given as [7]

$$\frac{k_r}{k_0} = \frac{1}{1 + \dfrac{C}{PP}} \tag{1}$$

where k_0 is the thermal conductivity at atmospheric pressure, C is a constant equal to 7.657 x 10^{-5} N/m·K. PP is given by

$$PP = \frac{Pd}{T} \tag{2}$$

where P is the reduced pressure (Pa), d is the gap size (m) and T is the absolute temperature (K).

For the case under consideration here, the environment within the cask consists of air under vacuum drying conditions. Therefore, the reduced thermal conductivity is used to compute heat transfer. Heat transfer coefficients for conduction across gas gaps are calculated as a function of gap size and temperature. Gap conductance is given by the following formula

$$h_{gap} = \frac{k_r}{d} \tag{3}$$

Equation 3 implicitly assumes that the Nusselt number is equal to one and the mode of heat transfer is pure conduction [8]. Contact surfaces for gap conduction are the respective inside surfaces and outside surfaces of components participating in the heat transfer. Radiation heat transfer was also accounted for in the interior of the cask.

The upper and lower impact limiters are not installed during vacuum drying and therefore were not included in the model. The top and bottom surfaces of adjacent capsules are in good thermal contact. The base of the cask in contact with the floor is assumed to be adiabatic. All experiment heating is transferred through the sides of the cask via natural circulation to the surrounding environment.

The ATR canal area where the vacuum drying occurs is a large open space with a high ceiling, so heat transfer to the surrounding air will occur mainly by natural convection. The cask exterior surface is cooled by natural convection (and, to a lesser extent, thermal radiation heat transfer) to ambient air at 38°C. Climatology data for Arco, Idaho shows a historic average high outdoor temperature of less than 30°C for the summer months [9]. Based upon the climate data and the CFR Part 49 requirement, the prescribed sink temperature is a reasonable bounding value.

The cylindrical-shaped cask has a relatively large curvature. Therefore, it is appropriate to approximate the cask surface as a vertical plate. The following correlation [8] is used for free convection

$$Nu = \left[0.825 + \frac{0.387\left(Ra^{\frac{1}{6}} \right)}{\left[1 + \left(\frac{0.492}{\Pr} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}} \right]^2 \tag{4}$$

where Ra is the Raleigh number and Pr is the Prandtl number evaluated at the air film temperature.

The Raleigh number, Ra, is given by

$$Ra = \frac{g\beta\left(T - T_\infty\right)H^3}{\upsilon\alpha} \tag{5}$$

In Equation 5, g is the gravitational acceleration (9.81 m/s^2), β is the volumetric thermal expansion coefficient, given as the inverse of film temperature (K^{-1}), H is the height of the cask, υ is the kinematic viscosity of air (m^2/s) and α is the thermal diffusivity of air (m^2/s). Fluid properties are evaluated at the film temperature. Temperature-dependent material and fluid properties are used in the analysis.

The fueled experiment decay heat loads are obtained from the nuclear physics analysis, which provides heating rates for the fuel plates that accounts for the gamma distribution throughout the cask. The radiation from the fuel plates in the capsules will be distributed throughout the cask, but most will be absorbed in the lead shielding. The analysis is conservative in that all of the gamma energy remains in the lead and is turned into heat. This is modeled by an energy generation term in the energy equation. For this analysis, the decay heat loads applied to the fuel plates are given in Table 2.

Table 2. Fueled Capsule Heat Loads.

Capsule Identifier	Plate #	Total Gamma Watts	Alpha Beta Watts	Total per plate heating (W)
Capsule 1	1	0.8007	2.6858	3.4866
	2	0.71	1.8999	2.6098
	3	0.5499	1.283	1.8329
	4	0.3787	0.7744	1.153
	5	0.5975	2.6006	3.1981
	6	0.6395	1.8384	2.4779
	7	0.5103	1.2523	1.7626
	8	0.3528	0.7513	1.1041
Capsules 2 & 4	1	0.0196	0.2268	0.2464
	2	0.017	0.1662	0.1833
	3	0.0134	0.1133	0.1266
	4	0.0112	0.0946	0.1058
	5	0.0219	0.2373	0.2592
	6	0.0194	0.1748	0.1942
	7	0.0155	0.119	0.1345
	8	0.0132	0.0999	0.1131
Capsule 3	1	0.5645	1.8198	2.3843
	2	0.4979	1.2451	1.743
	3	0.3849	0.8413	1.2261
	4	0.2665	0.5074	0.7739
	5	0.5925	1.901	2.4935
	6	0.5271	1.3284	1.8554
	7	0.4052	0.8883	1.2935
	8	0.2779	0.5272	0.8052
Capsule 5	1	0.3565	2.1458	2.5023
	2	0.5536	1.6788	2.2324
	3	0.4974	1.4119	1.9093
	4	0.2512	1.2679	1.5191
	5	0.4166	2.5024	2.9189
	6	0.6625	1.9972	2.6597
	7	0.5912	1.6844	2.2756
	8	0.2997	1.5261	1.8258
	Totals	11.816	37.591	49.406

From Table 2, the total heat load in all of the fuel plates is 49.406 W. The total heating generated by the capsules is 91.9 W. All decay heating not deposited in the fuel (~42.5 W) is deposited in the lead portion of the cask. A heat generation rate of 25 W is applied to the rod representing the NSUF experiments.

4. RESULTS AND DISCUSSION

Figures 4 and 5 show the results of the finite-element analysis. The thermal load was evaluated under steady-state vacuum drying conditions. Figure 4 shows a cutaway view of the temperature distribution in the cask components. The gaps surrounding the experiments within the insert positions inhibit heat transfer through the cask during vacuum drying operations. The predicted maximum component temperature is 254.5^{o}C and the maximum cask surface temperature is 47^{o}C. Figure 5 shows the temperature distribution along the mid-plane of the fueled capsules. As expected, the highest temperature occurs in Capsule 1 since it has the highest heat load. The maximum temperature of the NSUF rod (not shown) is 135.2^{o}C. The lead shielding remains below melting temperature 327^{o}C [10]. By comparison, the maximum experiment and external surface temperatures are 269.8^{o}C and 56.3^{o}C, respectively, for an equivalent experiment configuration loaded in the GE-2000 cask.

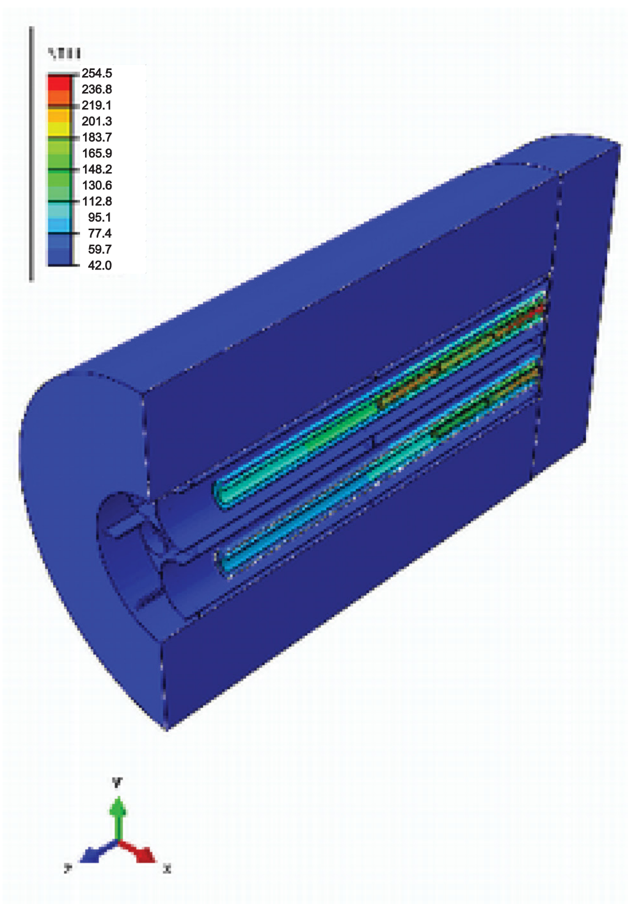


Figure 4. Cutaway view of temperature distribution (^{o}C) in entire BRR cask assembly.

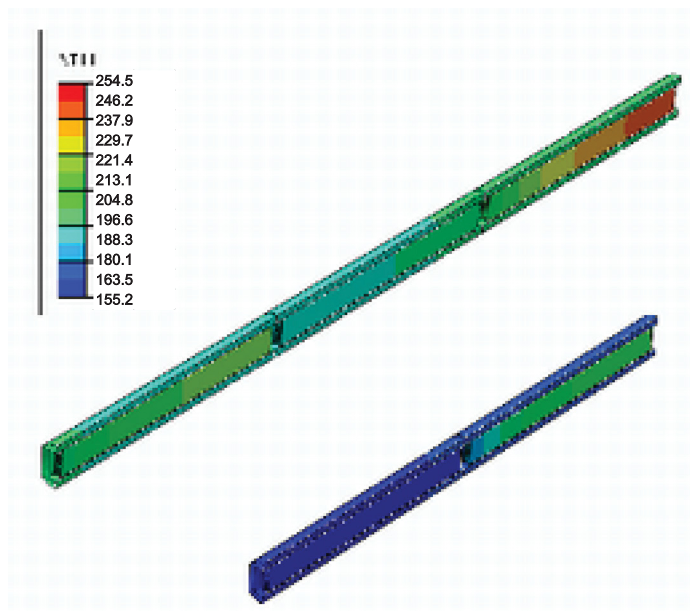


Figure 5. Temperature distribution (^{o}C) of capsules.

There is a 0.005 m thick stainless steel thermal shield permanently affixed to the circumference of the cask body. The results of the analysis show that by incorporating the thermal shield, the maximum temperature of the experiments is lowered by slightly over 1.1°C. This is due to the competing heat transfer effects associated with an increase in cask thickness. The increase in external surface area decreases the convection resistance by more than the increase in thickness increases the conduction resistance.

5. SUMMARY AND CONCLUSIONS

A finite-element analysis was performed to evaluate the thermal performance of the BRR shipping cask loaded with typical irradiated fueled and non-fueled experiments. The thermal load was evaluated for vacuum drying conditions. The results show that the maximum temperature reached in any of the capsules during vacuum drying is 254.5^{o}C. By comparison, the same set of experiments in the GE-2000 is predicted to reach 289.6 ^{o}C. The maximum temperatures of the cask external surface and the lead shielding are within acceptable limits. Therefore, when loaded with an identical payload, the BRR shipping cask has been shown to perform as well or better than the GE-2000 shipping cask. Therefore, from a thermal standpoint, the BRR shipping cask is a suitable alternate to the GE-2000 shipping cask for shipping irradiated GTRI experiments.

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