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THERMAL MODELING ANALYSIS OF SRS 70 TON CASK

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

J. M. Jordan
Savannah River National Laboratory
Savannah River Site
Aiken, SC 29808
(803) 725-9665
jeffrey.jordan@srnl.doe.gov

S. J. Hensel
Savannah River National Laboratory
Savannah River Site
Aiken, SC 29808
(803) 725-8440
steve.hensel@srnl.doe.gov

ABSTRACT

The primary objective of this work was to perform the thermal calculations to evaluate the Material Test Reactor (MTR) fuel assembly temperatures inside the SRS 70-Ton Cask loaded with various bundle powers. MTR fuel consists of HFBR, MURR, MIT, and NIST. The MURR fuel was used to develop a bounding case since it is the fuel with the highest heat load. The results will be provided for technical input for the SRS 70 Ton Cask Onsite Safety Assessment.

The calculation results show that for the SRS 70 ton dry cask with 2750 watts total heat source with a maximum bundle heat of 670 watts and 9 bundles of MURR bounding fuel, the highest fuel assembly temperatures are below about 263°C. Maximum top surface temperature of the plastic cover is about 112°C, much lower than its melting temperature 260°C. For 12 bundles of MURR bounding fuel with 2750 watts total heat and a maximum fuel bundle of 482 watts, the highest fuel assembly temperatures are bounded by the 9 bundle case. The component temperatures of the cask were calculated by a three-dimensional computational fluid dynamics approach. The modeling calculations were performed by considering daily-averaged solar heat flux.

Keywords: Shipping Cask, Computational Heat Transfer, Computational Fluid Dynamics, Thermal Performance

INTRODUCTION

This calculation is to verify the thermal performance of the SRS 70-ton cask for transporting spent nuclear fuel (SNF) assemblies within the site boundaries. The cask is a rectangular and finned container comprised of stainless steel (304L) and lead of about 9-inch thickness with a removable lid. The objective of the work is to perform the thermal calculations to evaluate the maximum water and fuel assembly temperatures inside the SRS 70-ton cask under the current OSA thermal loading limits of 70-Ton Cask for wet storage and for dry storage. As one of the loading limit criteria, maximum fuel temperature inside the cask cavity is kept less than 260°C to ensure that the aluminum cladding is kept from being excessively corroded. Cross-sectional views of the wet and dry casks are schematically shown in Figs. 1 and 2, respectively. The initial analysis was performed with 9 fuel bundles. An additional analysis was performed with 12 fuel bundles. The model is the same except for an additional layer of fuel bundles as shown in Figure 3. The modeling calculations have been made by a three-dimensional steady-state Computational Fluid Dynamics (CFD) method.

This evaluation is limited to onsite transport/transfer among SRS facilities of MURR bounding fuel in cylindrical bundles since the MURR assembly has the highest decay power.

MODELING APPROACH AND SOLUTION METHOD

The original work considered two initial baseline calculations and two performance analyses. Table 1 summarizes the analysis cases considered in the analysis. The baseline calculations assume that the 70-ton cask containing the 9 fuel bundles is cooled by constant ambient temperature of 27 °C. All the performance calculations used 38°C for the conservative evaluation. As shown in Fig. 5, the calculation model assumes that thermal loadings remain symmetrical along the cross-sectional central plane of the cask for a computational efficiency. An additional performance case was created to examine the case of 12 fuel bundles. The total wattage for this case is kept at 2750 watts and, as a result, the maximum bundle wattage is lower.

Material and thermal properties for the key components used for the calculations are shown in Table 2.

Table 1. Analysis cases considered by the present work

Analysis Models	Storage	Total Heat Load (watts)	Loading Method	No. of bundles (No. of fuel assbly)*	Bundle power (watts)	Purpose
Baseline**	Wet	1896	Uniform	9 (5)	169	Initial scoping calculations
Baseline**	Dry	1950	Uniform	9 (5)	173	Initial scoping calculations
Performance	Dry	1950 to 4500	Uniform	9 (5)	148 to 400	To estimate max. fuel temperature
Performance	Dry	1659 to 2766	Uniform and Non-uniform	9 (4)	81 to 670	To estimate max. fuel temperature
Performance	Dry	2749 to 2750	Non-uniform	12 (4)	105 to 482	To estimate max. fuel temperature

Note:*Number of fuel assemblies inside each bundle, assuming that each fuel tube in Fig. 2 contains one fuel bundle.
**Total heat loads from the previous work [5]

Table 2. Material/thermal properties used for the calculations

Components	Density (kg/m^3)	Thermal conductivity (W/m-K)
Fuel (MURR-uranium-aluminum)	2493 (for wet assembly); 2093 (for dry assembly)	39.7 (for wet assembly; 39.5 (for dry assembly)
Lead	11258	35.0
Stainless steel	8030	16.3
Plastic	1060	0.173
Air	Ideal gas law	0.03
Water	998.2 (Boussinesq approx.)	0.68

The present calculations used the following assumptions:

1. For the calculations, solar heating effect was considered as the daily averaged steady-state heat source as shown in Fig. 6 (400 watts/m^2 for top surface; 200 watts/m^2 for side surface).

2. All of the assemblies inside the cask are assumed to be MURR fuel for the conservative estimate.

3. All the assemblies are stacked together with no gaps between two adjacent assemblies along the fuel tube for the conservative estimate.

4. All the fuel bundles are located at the right-hand-side corner of the fuel tubes for the conservative estimate.

5. For the wet storage case, water is filled up to 8 inches below the lead lid as shown in Fig. 1.

6. For the dry storage case, some residual water remains inside the cask cavity to a depth of 4 inches from the bottom of the cavity as shown in Fig. 2.

7. The thin steel liners attached to the lead material are assumed to have negligible thermal resistance.

8. The current calculations are based on the conduction-convection-radiation coupled model.

9. The gap size between the two plastic regions is assumed to be uniform (~0.5 inches) and it is treated as the air-plastic combine region by using the effective thermal conductivity.

10. The fin cooling/heating effects are assumed to be negligible for the present conservative calculations.

11. The bottom wall surface is cooled only by natural convection for the conservative evaluations.

12. Evaporative cooling effects are not considered at the interface of water and air inside the cask cavity.

13. Ambient temperature is assumed to be constant (27 ^{o}C for the baseline calculations, 38 ^{o}C for the final performance analysis).

RESULTS AND DISCUSSIONS

A steady-state Computational Fluid Dynamics (CFD) approach was taken to conduct the thermal performance calculations of the SRS 70-ton cask. Each fuel bundle is placed in one of the nine fuel tubes. Each fuel tube was assumed to contain five assemblies for the initial baseline calculations under uniform fuel bundle loading and four assemblies for the final performance analysis under uniform and non-uniform loadings as shown in Table 1. The calculation model considered the conduction-convection cooling mechanism coupled with radiative cooling. The convection effect driven by the density gradient of air was considered by ideal gas law. About 3 million mesh nodes were established for the base calculations. The 12 bundle case was a larger model, with around 7 million nodes. A commercial CFD code FLUENT^{TM} [2] was used to perform the computations. This computer code meets software level B QA requirements [3]. Work was performed in accordance with the WSRC E-7 manual [4]. The analysis results were processed using the post processor of the computer code FLUENT^{TM}

Baseline Analysis for the Wet 70-Ton Cask

The modeling geometry of the wet storage case containing MURR assemblies is shown in Fig. 1. The scoping calculations for the wet 70-ton cask were performed by steady-state CFD method to assess the maximum water and fuel assembly temperatures inside the case. The initial scoping calculations for the wet cask were performed for total thermal load of 1896 watts from the previous conditions [5]. Each bundle power inside the cask was assumed to be the same. In this case, one of the performance criteria for the wet cask was to keep the water temperature below 90^{o}C to ensure that the cavity water remains unboiled. The results show that maximum fuel and water temperature at the central cavity region can reach about 95 and 92^{o}C, respectively, as shown in Fig. 7. It is noted that maximum water temperature is 2^{o}C higher than the performance criterion.

Baseline Analysis for the Dry 70-Ton Cask

The modeling geometry of the dry storage case containing MURR assemblies is shown in Fig. 2. The calculations for the dry 70-ton cask were performed by applying the daily-averaged solar heat flux to the exterior wall boundary of the cask for the assessment of the maximum water and fuel assembly temperatures inside the case. The initial scoping analysis for the dry cask was performed for total thermal load of 1950 watts from the previous work [5]. Each bundle power inside the cask was assumed to be the same. Each bundle was also assumed to have five fuel assemblies. In this case, one of the performance criteria for the dry cask keeps maximum fuel temperature not to exceed 200^{o}C to ensure that the fuel assemblies avoid being excessively corroded. As shown in Fig. 8, the results show that maximum fuel temperature can reach about 137^{o}C at the central fuel tube of the cavity region. It is noted that about 90% of total heat load is cooled by side and bottom surfaces since solar heat flux imposed at top surface is two times higher than that of the side surface. The scoping results for the wet and dry storage cases clearly show that the dry storage potentially has the higher thermal loading limit allowable under the same configurations of the SRS 70-ton cask.

It is noted that maximum water temperature for the wet cask reaches 2^{o}C higher than the 90^{o}C limit to prevent boiling, while fuel assembly temperature for the dry cask reach up to 145^{o}C, about 55^{o}C lower than the limit criterion to prevent excessive corrosion. When total thermal loading of the dry cask increases from 1950 to 4500 watts under the uniform loading condition, maximum fuel temperature increases by about 85^{o}C. The calculation results indicate that maximum fuel temperature reaches 200^{o}C at total loading of 3900 watts for 27^{o}C ambient temperature, which is equivalent to about 350 watts MURR bundle power. For this thermal loading, maximum temperature for the top surface of the plastic material is about 108^{o}C, which is much lower than its melting temperature of 260^{o}C. Two different ambient temperatures of 27^{o}C and 38^{o}C were evaluated. For the dry cask with uniform thermal loading, maximum fuel temperatures are compared for the two different ambient temperatures as function of the cask loading in Fig. 9. The results show that maximum fuel temperature increases by about 8^{o}C when ambient air temperature increases from 27^{o}C to 38^{o}C.

Based on the initial calculation results of the baseline analysis, the cask loaded with dry fuel assemblies was chosen for the thermal performance analysis to determine the maximum loading limit allowable for the prevention of excessive corrosion of the aluminum cladding material. The higher possible ambient temperature – 38^{o}C – was chosen for the performance case since it results in higher fuel temperatures.

Performance Analysis for the Dry 70-Ton Cask (9 bundles)

Based on the results of the baseline calculations, the SRS 70-ton cask loaded with dry fuel assemblies was chosen for the thermal performance analysis to support the technical input for the maximum allowable loading limit as defined by the Onsite Safety Assessment (OSA) document. As discussed earlier, the steady-state performance analysis for the computational domain as defined in Fig. 5 was done by applying the daily-averaged solar heat flux to the exterior wall surface of the cask.

The baseline results indicate that maximum fuel temperature is always located at the central fuel bundle inside the fuel cavity region because of the higher solar heat flux at the top surface of the SRS 70-ton cask. Based on this information, when the central fuel tube is occupied by a MURR fuel bundle with the highest power, and the peripheral tubes are filled with the lower assemblies, it provides the highest fuel temperature among the same thermal loading of the cask. Each fuel bundle contains four fuel assemblies. When three central bundles are loaded with 628, 642, and 654 watts for a total thermal loading of 2750 watts, the maximum fuel temperature reaches 259^{o}C in the middle of the central fuel bundle. Figure 10 shows that when fuel bundle power for the central fuel tube increase from 306 to 670 watts under non-uniform loading pattern for the dry cask of 2750 watts, maximum temperature increases from 188 to 263^{o}C. In this case, the temperature for the top plastic surface is increased by less than 1^{o}C from 111^{o}C. It is noted that when the cask is loaded uniformly by keeping each of nine fuel bundle powers equal for a given total loading of 2750 watts, maximum temperature is less than 200^{o}C as shown in Fig. 9.

For the non-uniform and dry cask containing 656 watt bundle at the central fuel tube, maximum temperatures are evaluated for various total thermal loads under the same operating conditions. When the SRS 70 ton dry cask is loaded with different bundle powers under the total load of 1950 watts, maximum fuel temperature is about 228°C instead of 137°C under the worst loading pattern for uniform loading because of uneven solar heat at the exterior boundary of the container. When the highest bundle power is changed from 656 to 670 watts (by about 2%) for a given total load, maximum fuel temperature is changed by less than 1.5 °C as shown in Fig. 11.

From the initial scoping calculations and the final performance results, it is concluded that the dry cask option has the advantage of higher allowable thermal loading limit, and non-uniform thermal loading has the disadvantage of less allowable thermal loading limit to prevent excessive aluminum corrosion due to uneven cooling capability of the cask. In addition, when a fuel bundle with the highest decay power is located at the central fuel tube, the highest fuel temperature is reached for the same total loading conditions.

Performance Analysis for the Dry 70-Ton Cask (12 bundles)

Based on the results of the baseline calculations and the 9 bundle analysis, the SRS 70-ton cask loaded with dry fuel assemblies was chosen for the thermal performance analysis for the 12 bundle case to support the technical input for the maximum allowable loading limit as defined by the Onsite Safety Assessment (OSA) document. As discussed earlier, the steady-state performance analysis for the computational domain was done by applying the daily-averaged solar heat flux to the exterior wall surface of the cask. Seven cases were run for the 12 bundle scenario with peak bundle wattage ranging from 454 to 482, but a total wattage of 2750 for all cases.

The baseline results indicate that maximum fuel temperature is always located at the central fuel bundle inside the fuel cavity region because of the higher solar heat flux at the top surface of the SRS 70-ton cask. Based on this information, when the central fuel tube is occupied by a MURR fuel bundle with the highest power, and the peripheral tubes are filled with the lower assemblies, it provides the highest fuel temperature among the same thermal loading of the cask. The narrow peak bundle range of 454-484 yielded a narrow peak temperature range. The peak temperature for the seven 12 bundle cases ranged from 223°C to 230°C. As seen for the prior cases, the peak occurs in the center of the assembly. The peak of 230°C is well below the peak temperature from the 9 bundle case.

CONCLUSION

The initial scoping and final performance calculations and analyses have been performed to support the SRS 70 Ton Cask Onsite Safety Assessment. The work used the steady-state heat transfer model with the daily-averaged solar heat flux at the exterior surfaces of the top and side surfaces of the cask. The original calculations are based on the 9-fuel tube model filled with the MURR bounding fuel assemblies for conservative estimate. Additional analysis was performed on a 12-fuel tube model filled with the MURR bounding fuel assemblies, which maintained the same 2750 watt maximum for the cask. The peak temperatures for the 12 bundle case with lower peak wattage are bounded by those of the 9 bundle case.

Main conclusions are as follows:

- The dry cask option has higher thermal loading limit in terms of maximum allowable fuel temperature criterion.
- Non-uniform thermal loading has less allowable thermal loading limit to prevent excessive aluminum corrosion due to uneven cooling capability of the cask. For the 9 bundle case with a total loading of 2750 watts containing a 670-watt bundle, the maximum fuel temperature is no more than 263°C. For the 12 bundle case with a total loading of 2750 watts containing a 482-watt bundle, the maximum fuel temperature is no more than 230°C.
- When a fuel bundle with the highest decay power is located at the central fuel tube, the highest fuel temperature is reached for the same total loading conditions.
- For non-uniform dry loading conditions, maximum fuel temperature is sensitive to the change of bundle powers.

ACKNOWLEDGMENT

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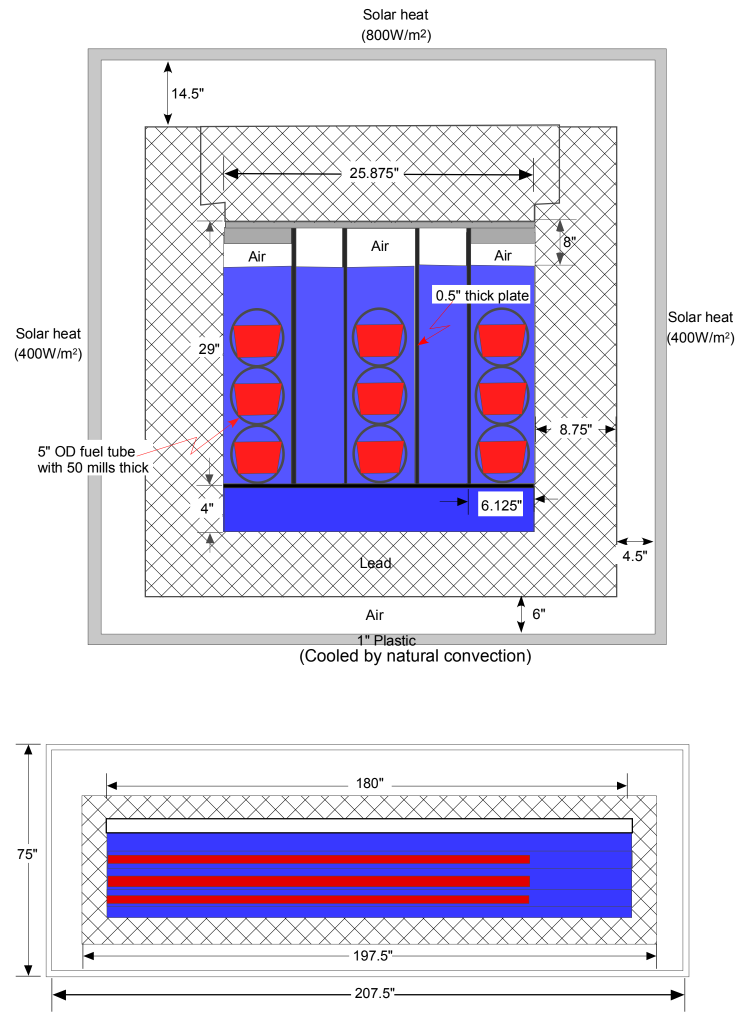

Figure 1. Vertical cross-sectional and central plane views for modeling geometry of the wet storage case containing MURR assemblies

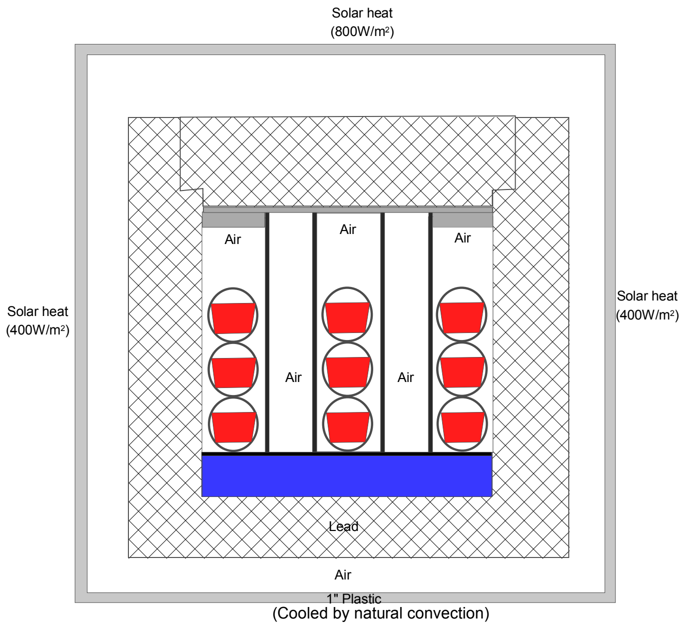

Figure 2. Cross-sectional view for modeling geometry of the dry storage case

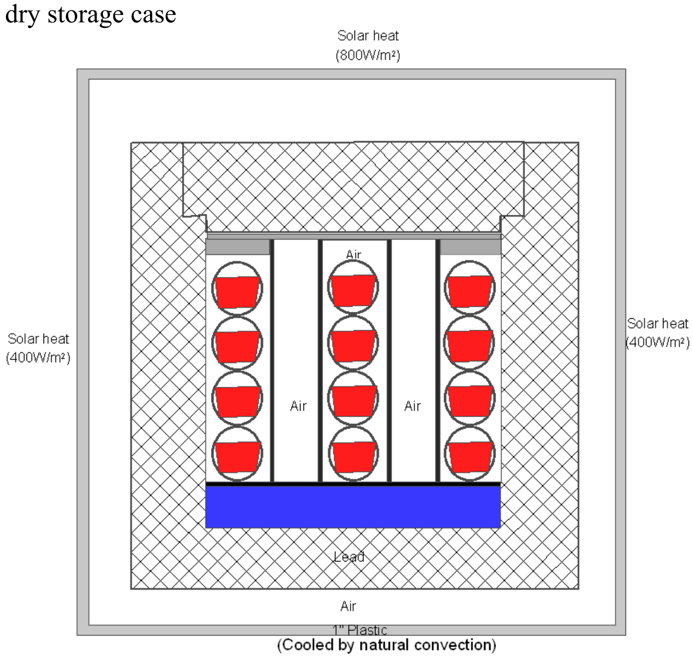

Figure 3. Cross-sectional view for modeling geometry of the 12 fuel bundle case

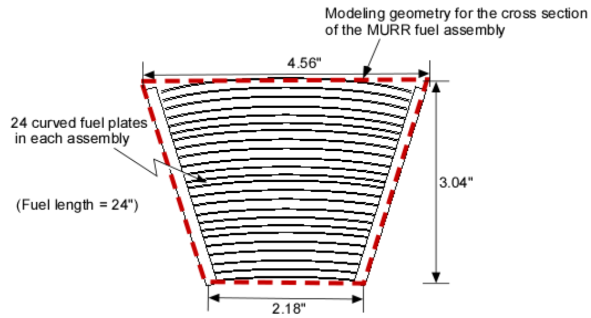

Figure 4. Cross-sectional view of a MURR fuel assembly

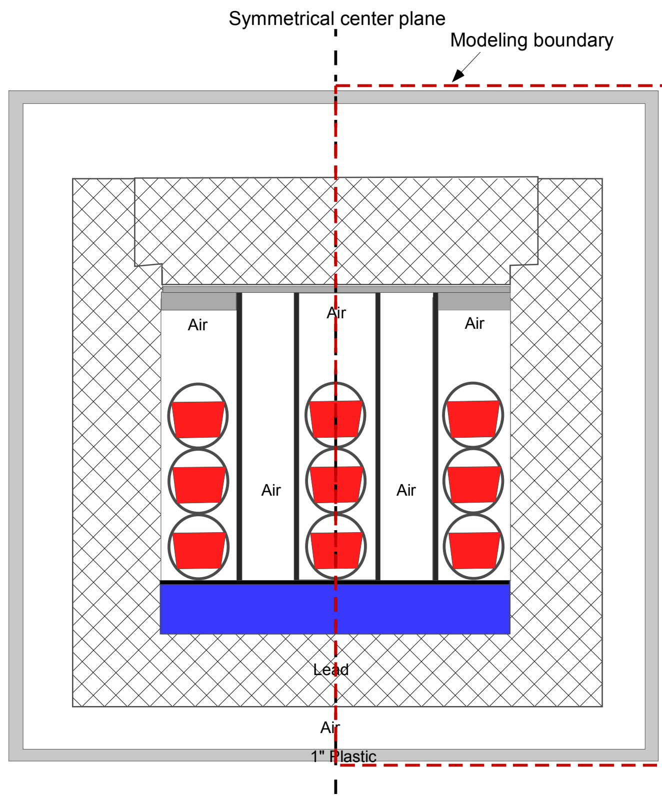

Figure 5. Computational modeling domain for the analysis

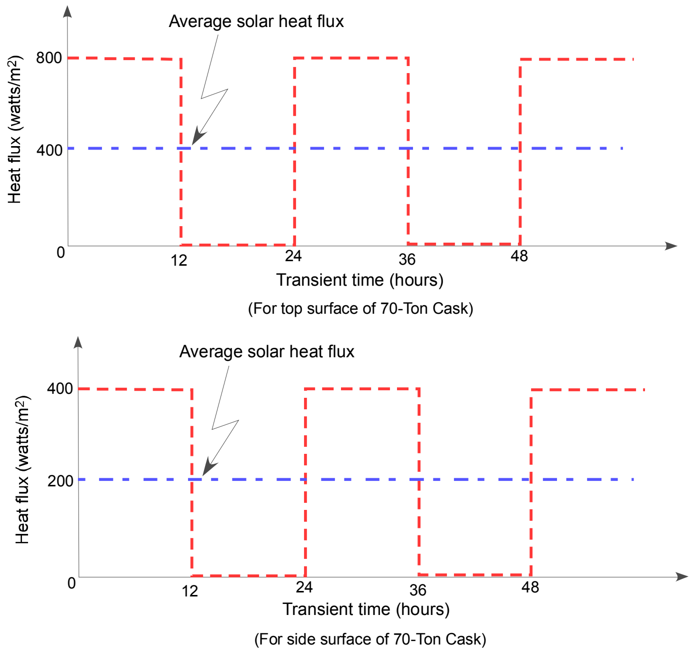

Figure 6. Averaged steady-state solar heat fluxes for the top and side surfaces of 70-ton cask

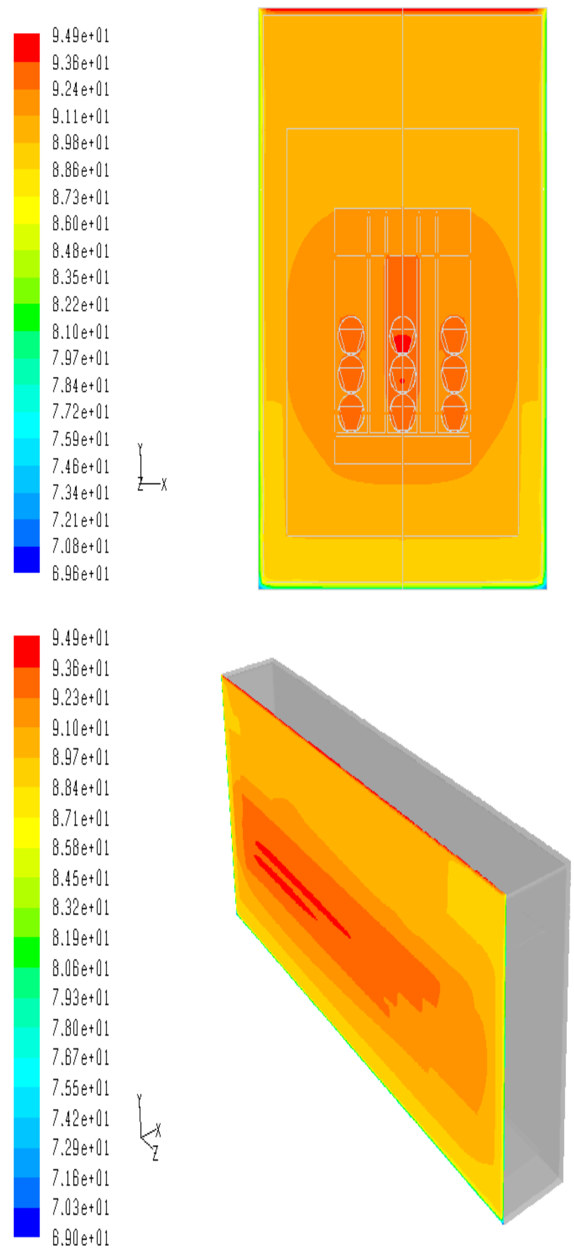

Figure 7. Temperature distributions for the vertical cross-sectional and center planes for the wet cask with uniform loading

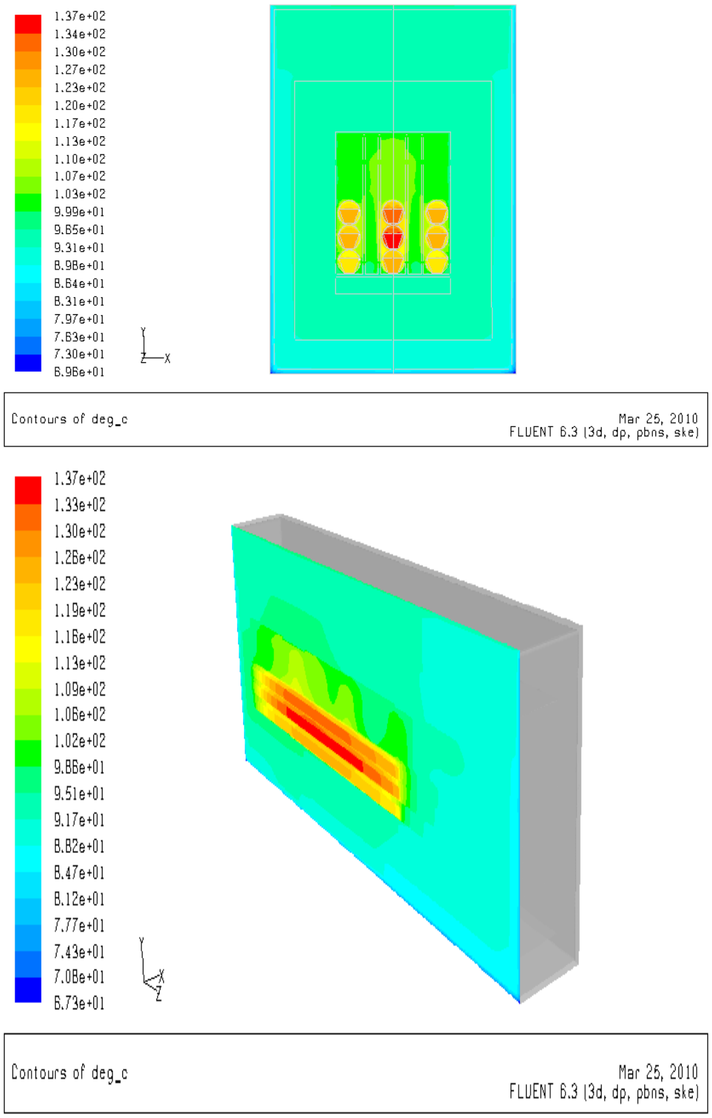

Figure 8. Temperature distributions for the vertical cross-sectional and center planes for the dry cask with uniform loading

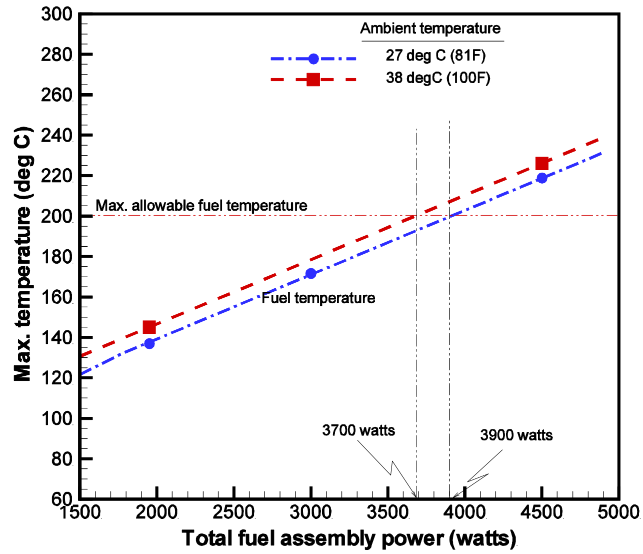

Figure 9. Maximum fuel temperatures for the dry cask under different ambient temperatures as function of total MURR assembly power

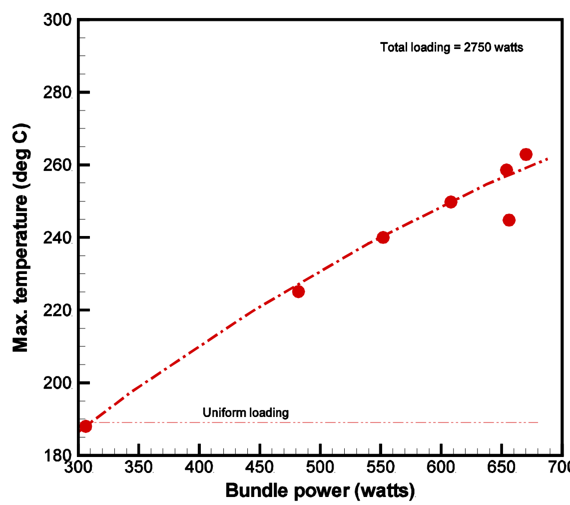

Figure 10. Maximum temperatures for non-uniform fuel loading configurations under the dry cask container under the same total loading of 2750 watts.

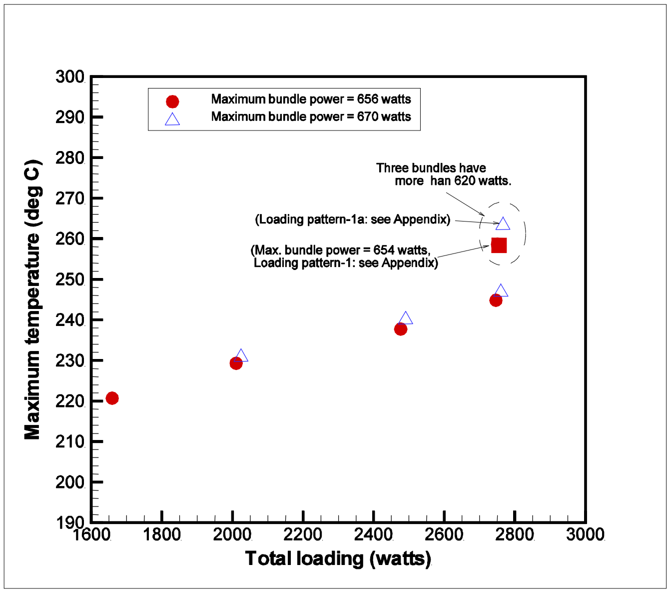

Figure 11. Comparison of maximum temperatures between 656 and 670 bundle powers for non-uniform fuel loading configurations under the dry cask container.