THERMAL ANALYSIS OF A NAC-LWT CASK UNDER NORMAL AND FIRE ACCIDENT CONDITIONS

Ketan Mittal
Undergraduate Research Assistant
Mechanical Engineering Department
University of Nevada, Reno, Reno, Nevada 89557, USA
kmittal@unr.edu

Miles Greiner, Ph.D., ASME Fellow
Professor of Mechanical Engineering
University of Nevada, Reno
Reno, Nevada 89557, USA
greiner@unr.edu

ABSTRACT
Two and three dimensional thermal models of a Nuclear Assurance Corporation Legal Weight Truck (NAC-LWT) cask were constructed using the PATRAN commercial finite element package. The two-dimensional model included the effect of radial stiffeners in the package’s external neutron shield but three-dimensional model did not. A normal conditions of transport (NCT) simulation using both models predicted the peak cladding temperature was roughly 210°C. The NCT package temperatures were used as initial conditions for transient fire/post-fire simulations. Different assumptions were used to determine when the neutron shield liquid drained from the tank and was replaced by air. When the liquid was assumed to remain within the tank during and after the fire, the peak cladding temperature was predicted to exhibit a temporal maximum of roughly 300°C, approximately 6 hours after the end of the fire. If the liquid drained from the tank during the fire, the cladding temperature did not exhibit a temporal peak. Rather, it eventually reached a maximum temperature of roughly 280°C, which is the steady state NCT peak temperature when air is in the neutron shield tank. This undergraduate project will be used to lay down a foundation for further research on NAC-LWT casks. Two and three dimension package of the cask will be constructed using ANSYS, and simulations will be run for NCT and fire/post-fire conditions. The models will also be linked to Container Analysis Fire Environment (CAFE) to predict response of the package in fire.

NOMENCLATURE
s Axial coordinate system in figure 2a
r Radial coordinate system in figure 5a
ρc Volumetric Specific Heat
T Temperature
t Time
k Thermal Conductivity
$\Delta T_{2D}$ Temperature difference for the 2D model
$\Delta T_{3D}$ Temperature difference for the 3D model

INTRODUCTION
Used Nuclear Fuel (UNF) assemblies from light water reactors consist primarily of fuel rods held in square arrays by headers and footers and periodic spacer plates [1]. Each rod is a tube with Zircaloy cladding containing highly radioactive fuel pellets and fission gases. Used assemblies are transported away from reactor sites in thick-walled packages. Before a package can receive a Certificate of Compliance from the US Nuclear Regulatory Commission (NRC), Federal Regulations (10CFR71) require its manufacturer to prepare a safety analysis report (SAR) that demonstrates that the package will maintain its containment, shielding and criticality control functions under normal conditions of transport (NCT) and after a series of severe events [2]. These events include a 9-m drop onto an unyielding flat surface, a 1-m drop onto a steel puncture bar, full engulfment in an 800°C-fire for 30 minutes, and water submersion.

The fuel cladding confines the highly radioactive fuel pellets and fission gases, and its integrity must be protected to maintain the assemblies in the same configuration that is assumed during regulatory analysis. During NCT, radial hydrides may form within the fuel cladding and make it brittle if its temperature exceeds 400°C [3]. The cladding may experience creep deformation or burst rupture if its temperature exceeds 570°C or 750°C [4], respectively, during a fire.

Transportation risk studies assess the response of certified packages to all possible types of accidents (which may be more severe than the regulatory sequence), as well as the likelihood that packages will be involved in those events [4, 5]. The NRC worked with the National Institute of Standards and Technology (NIST) and the Pacific Northwest National Laboratory (PNNL) to assess the response of certain UNF transport packages to specific historical, severe, long-duration fires. They considered fires that took place in the Caldecott roadway tunnel near Oakland, California in 1982 [6, 7], and the Howard Street rail tunnel in Baltimore, Maryland in 2001 [8], among others. These studies were conducted to determine if the fire resistance requirements of the federal regulations are adequate for those accident conditions [9-12].
The studies predicted the response of a NAC-LWT cask [13], assuming it was in proximity to these fires. The NAC-LWT cask is designed to transport one pressurized water reactor (PWR) fuel assembly. Its body is cylindrical and has a removable lid at one end. It is constructed from steel and lead layers, which provide containment and gamma shielding, and its sides are surrounded by an annular tank containing a 56%-water/ethylene glycol mixture, which provides neutron shielding. Honeycomb-filled impact limiters on each end are used to protect it during collisions. The impact limiter on the lid end of the package also provides insulation that protects the lid seal during a fire. Under some circumstances the NAC-LWT cask is transported inside an International Organization for Standardization (ISO) container.

In the current work, two thermal models of the NAC-LWT cask are constructed using the PATRAN commercial finite-element package. One is a two-dimensional model of the package cross-sectional, and the other is a three-dimensional model of the full package. These models are used to predict the peak temperature the fuel cladding reaches during steady-state NCT (the peak cladding temperature is the highest value experience over all locations once steady state is reached). The NCT package temperatures are then used as the initial conditions in a transient fire/post-fire simulation to predict the maximum temperature the cladding reaches after being subjected to a 30-minute regulatory fire (the maximum cladding temperature is the highest value over all locations and times after the fire starts).

In this work it is assumed that once the water/ethylene glycol mixture within the neutron shield temperature exceeds its boiling point, pressure relief plugs in the tank walls may release, and the liquid will be rapidly expelled and eventually replaced by air. Simulations are performed using four different assumptions for the conditions that lead to this replacement event. These conditions are:

1. The liquid remains in the tank (and remains a liquid) throughout the fire and post fire periods.
2. The liquid drains at end of the thirty-minute fire.
3. The liquid drains when the average of its minimum and maximum temperatures (at the inner and outer edges of the tank) reaches it boiling temperature of \( T_B = 176^\circ\text{C} \), and
4. The liquid drains when its highest temperature reaches \( T_B \).

In this paper we compare the NCT peak cladding temperature from the two and three-dimensional simulations, and the maximum post-fire temperature from the two- and three-dimensional fire/post-fire simulations for different assumptions regarding the conditions that cause the liquid mixture to drain from the neutron shield tank.

**COMPUTATIONAL MODELS**

This section describes the finite element thermal models of an NAC-LWT cask that were constructed using PATRAN commercial software. In this work the NAC-LWT cask was not placed in an ISO container for simplicity, and because the Certificate of Compliance for the package [15] does not appear to require it for either truck or rail transport.

In this work the majority of dimensions for the NAC-LWT cask were taken from an axis-symmetric HEATING5 thermal model and drawings (Fig. 3.4-1) presented in its SAR [13]. This model used cylindrical regions with equivalent diameters to model the square cross-section of the fuel assembly and the opening within the package into which the fuel is placed. In the current work, the square dimensions of the fuel assembly and opening are taken from another thermal analysis section of the package’s SAR.

**Two-Dimensional Computational Mesh** Figure 1 shows a two-dimensional cross sectional model of an NAC-LWT cask. At the center is a square 21.4-cm by 21.4-cm fuel region. In this work the fuel pellets, cladding, assembly spacers, cover gas, header and footer are all replaced by a heat-generating solid with “equivalent” properties, which are discussed in a later section. The fuel is within a 32.72-cm-diameter aluminum basket insert. There is a square 22.54-cm by 22.54-cm opening at the center of the insert, and the fuel is assumed to float within it, equidistant from the surface of the insert. The 0.57-cm thick gap between the fuel and opening surfaces is filled with helium gas, and is referred to as Gap 1. There is a 0.635 cm thick helium gap (Gap 2) between the basket insert and the 1.9 cm thick stainless steel package inner body. Outside the inner body are a 14.5-cm-thick lead gamma shield, a helium-filled 0.127-cm-thick gap (Gap 3), and a 2.85-cm-thick stainless steel package outer body.

![Figure 1 Material Regions of two-dimensional mesh of an NAC-LWT package](image-url)
temperature conditions during the fire, the liquid may rapidly drain from the tank and be replaced by air.

Three-dimensional Computational Mesh Figure 2 shows the three-dimensional computational mesh of the NAC-LWT cask used in this work. Figures 2a and 2b show axial-section and cross-section views. Figure 2a shows that the NAC-LWT consists of a long cylindrical package body with honeycomb-filled impact limiters on each end. There is a lid on the left end (as shown in Fig. 2a) which is removed when the package is loaded or unloaded. The impact limiter on the lid-end is not the same size as the one on the opposite, base-end of the package. The axial, s-coordinate is defined in Fig. 2a and its origin is at the outer edge of the base-end impact limiter.

The diameter of the base-end impact limiter is 153.16 cm (60.3 in.), and it extends from s = 0 to 71.89 cm. The diameter of the lid-end impact limiter is 165.86 cm, and it is located between s = 512.29 and 588.89 cm. The package body is between s = 41.4 and 548.77 cm, and the neutron shield tank is between s = 73.15 and 488.44 cm. A 5.72 cm-thick overflow tank surrounds the portion of the neutron shield tank between s = 398.27 and 488.44 cm, and it has outer and side skins of thicknesses 0.635 cm and 1.27 cm, respectively. The overflow tank contains 8 radial stainless steel stiffeners.

The two-dimensional mesh in Fig. 1 represents a cross section of the package body that does not include the overflow tank, such as the location of AA in Fig. 2a. In the two-dimensional model in Fig. 1, separate regions are used for the radial stiffeners and the liquid or air between the stiffeners. However, in the three dimensional model of the neutron shield and overflow tanks, the stiffeners and liquid/air are not modeled separately. A single region is used within each tank. The region in each tank is assigned equivalent mixture properties, which are described in the next section.

The package base is a stainless steel cylinder of diameter 72.69 cm and length 26.67 cm that is a permanent part of the package body. A lead base-end gamma shield, of length 7.62 cm and diameter 52.73 cm is centered within the base. A toroidal collar is a permanent part of the lid-end of the package body, and the lid is bolded into it. Together the collar and lid make up a stainless steel cylinder of length 36.2 cm and diameter 72.7 cm. There is a square 21.4 cm by 21.4 cm indentation of depth 7.62 cm centered on the inside surface of this cylinder (it is a continuation of the square opening in the basket insert). Metallic or Tri-Fluoroethylene (TFE) O-rings seal the gap between the collar and lid. They form a 40-cm-diameter ring in a plane 20.3 cm inside of the lid outer surface. Vent and drain ports are located near the lid end of the package outer body, between the impact limiters and the neutron shield tank. They are placed 22.5 degrees below the top center of the package, and are sealed using TFE or Viton O-rings.

The cylindrical basket insert is located between s = 68.07 and 512.57 cm. The fuel block is within the basket, and it extends from s = 94.74 to 488.44 cm. At each end of the fuel there are stainless steel spacers, with the same square 22.5-cm by 22.5-cm cross section as the fuel. The spacers near the lid-end and base-end of the package are located between s = 489.46 and 499.87 cm, and s = 85.85 and 93.47 cm, respectively.

Figure 2 Three-dimensional computational grid and material regions of the NACLWT package. (a) Axial cross section. (b) Cross section view A-A as seen in part (a)

The cylindrical basket insert is located between s = 68.07 and 512.57 cm. The fuel block is within the basket, and it extends from s = 94.74 to 488.44 cm. At each end of the fuel there are stainless steel spacers, with the same square 22.5-cm by 22.5-cm cross section as the fuel. The spacers near the lid-end and base-end of the package are located between s = 489.46 and 499.87 cm, and s = 85.85 and 93.47 cm, respectively.

In this work, the fuel generates a total of 2342 W between s = 109.04 and 474.4 cm, which represents the fuel rod region of the assembly. The 14.3 and 13.97 cm long regions at the lid and base end of the fuel block represent the package header and footer, where no heat is generated. The fuel heat generation rate varies with axial location, as shown in Fig. 3 [13]. For this profile the peak volumetric heat generation rate is \( q_p = 16,544 \) W/m\(^3\) and is located at s = 223.8 cm, the average is \( q_A = 13997 \) W/m\(^3\), corresponding to a peaking factor of \( P = q_p/q_A = 1.182 \). Heat is generated uniformly within each cross section.
Material Properties  To the extent possible, this work uses the material properties presented in PNNL’s Caldecott and Howard Street Tunnel Fire Reports [9, 11]. Table 1 lists the different materials that have been used for different components of the cask, and Figure 4 shows the temperature-dependent properties used for each component of the two-dimensional and three-dimensional NAC-LWT models. Properties are given for the temperature ranges experienced by each component during NCT and fire accident conditions.

Figure 4a shows the material thermal conductivity of the 304 stainless steel, used in the package inner and outer bodies, and its base, collar, lid, skin and radial stiffeners; the aluminum basket insert; the lead gamma shield; the helium (He) gas in Gaps 1, 2 and 3 (in future work air will be used in Gap 3); and the air that replaces the liquid mixture in the neutron shield under high temperature conditions. Figure 4a shows that the lead conductivity exhibits a step reduction at its melt temperature of 327°C.

Table 1 List of materials that have been used for different components of the NAC-LWT cask.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Block</td>
<td>Zircaloy</td>
</tr>
<tr>
<td>Basket Insert</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>Inner &amp; Outer Body</td>
<td>304 Stainless Steel</td>
</tr>
<tr>
<td>Radial and Base Gamma Shield</td>
<td>Lead</td>
</tr>
<tr>
<td>Neutron Shield &amp; Overflow Tank Skin</td>
<td>304 Stainless Steel</td>
</tr>
<tr>
<td>Neutron Shield</td>
<td>56% Ethylene Glycol Solution/Air</td>
</tr>
<tr>
<td>Impact Limiters</td>
<td>6061-T6 Aluminum Honeycomb</td>
</tr>
<tr>
<td>End Fittings</td>
<td>304 Stainless Steel</td>
</tr>
</tbody>
</table>

Figure 4a also shows regional effective thermal conductivities of the lid-end and base-end impact limiter honeycomb, and the fuel block [16]. These effective conductivities are used to account for both conduction and radiation heat transfer within these components. Due to the structure of the fuel assemblies, the effective conductivities in the axial (parallel to the fuel rods) and radial (from rod to rod) directions are not the same. However, in this work the effective radial conductivity [16] is used in both the radial and axial directions (future models will use a different conductivity in the axial direction). Moreover, the same conductivities are used in both the fuel rod (heat generating) and header/footer (non-power-generating) regions of the fuel block (in future models the conductivity of solid Zircaloy will be used in the header/footer regions).

The effective conductivities of the liquids in the neutron shield and overflow tanks of the three-dimensional model, and the neutron shield tank of the two-dimensional model are also shown in Fig. 4a. These liquids fill the tanks under normal conditions of transport and at the beginning of the fire. The effective conductivities of the liquids are higher than the material properties to include the effect of buoyancy and natural convection, which increase heat transfer compared to a stagnant fluid. Radial stiffeners are included in the two-dimensional model, and the effective liquid/air conductivities are applied between the stiffeners. Stiffeners are not included in the three dimensional model of the neutron shield or overflow tanks. Future work will include the effect of conduction through these stiffeners, either by modeling them explicitly in the computational mesh, or by including the effect of their conductivity in the effective neutron shield liquid conductivity.

Under high temperature conditions, the effective liquid conductivity is replaced by the material conductivity of air. While conduction through the air is calculated, the effect of natural convection and surface-to-surface radiation in neglected. These effects will be included in future work.

In the current simulations the Impact Limiters are assumed to remain intact during and after the fire, even though portions of the outer region reach the aluminum melt temperature. This simplification is not expected to strongly affect the peak or maximum clad temperatures since the impact limiters are located near the package ends, while the hottest fuel location is generally near the package mid-plane. Future simulations will include a more realistic impact limiter damage model, which may include removal of melted aluminum, and surface-to-surface radiation and conduction across the resulting air-filled gap.

Figure 4 Temperature-dependent material and effective properties used in NACLWT model (a) Thermal Conductivity (b) Volumetric specific heat
Figure 4b shows the temperature-dependent volumetric specific heat (density multiplied by the mass specific heat at constant volume, $\rho c_v$). In this work latent heat of phase change of the materials is not included. It will be included in future simulations.

**TWO-DIMENSIONAL SIMULATION RESULTS**

**Normal Conditions of Transport (NCT) Simulations** In the current work steady state package component temperatures are calculated for a NCT environment, as defined in federal regulations [2]. This environment consists of still air at 38°C (100°F), and solar heat flux of 194 W/m$^2$ on surfaces (Future work will use 194 W/m$^2$ on all curved surfaces, and 97 on all flat surfaces). The solar heat flux and the heat generated within the fuel are dissipated to the environment by natural convection and radiation heat transfer. The NCT natural-convection heat transfer coefficient and external surface emissivity used in this work are 5.06 W/m$^2$K and 0.85, respectively [9].

In the two-dimensional simulations, the maximum volumetric fuel heat generation rate in Fig. 3, 16,544 W/m$^3$ is applied uniformly within the fuel region. Figure 5a shows the NCT temperature contours within the two-dimensional domain when the neutron shield is filled with liquid. The highest temperatures are located in the center of the fuel, and they decrease as the surface is approached. The diagonal coordinate system, $r$, is defined in this figure and its origin $r = 0$ is at the package center.

In Fig. 5b the line marked “Liquid in NS” shows the simulated temperature along the diagonal coordinate versus distance from the package center. The radial extent of different package components relative to the $r$-coordinate is shown. The temperature exhibits relatively small gradients in the neutron shield, outer body, gamma shield, inner body and basket insert, due to their relative high thermal conductivities. The gradient is much larger in the helium gaps and within the fuel block. The peak clad temperature predicted by the two-dimensional mode is $T_{PC} = 218°C$ and this value is included in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Maximum Fuel Cladding temperatures [°C] for NCT for steady state and post fire conditions.</th>
<th>2D Model</th>
<th>3D Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Conditions of Transport - Liquid in NS</td>
<td>218</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td>Normal Conditions of Transport - Air in NS</td>
<td>272</td>
<td>286</td>
<td></td>
</tr>
<tr>
<td>Liquid remains in NS during and after fire</td>
<td>294</td>
<td>301</td>
<td></td>
</tr>
</tbody>
</table>

| Table 3 | Peak Normal Conditions of Transport temperatures [°C] predicted by different computational models. | Component | PNRL [9] | Current 2D | $\Delta T_{2D}$ | Current 3D | $\Delta T_{3D}$ |
|---------|---------------------------------------------|----------|----------|-------------|----------|-------------|
| Fuel | 210 | 218 | -8 | 204 | 6 |
| Basket Insert | 109 | 108 | 1 | 99 | 10 |
| Inner Body | 88 | 83 | 5 | 77 | 11 |
| Radial Gamma Shield | 87 | 82 | 5 | 76 | 11 |
| Neutron Shield Skin | 70 | 74 | -4 | 70 | 0 |
| Neutron Shield | 73 | 77 | -4 | 72 | 1 |
| Impact Limiters | 56 | - | - | 60 | -4 |

Table 3 shows maximum NCT component temperatures predicted by different models. The first column of data shows temperatures predicted by a three-dimensional model constructed by PNRL [8]. That model used slightly different dimensions than the current work, and included Fiberfrax layers between the gamma shield and the inner and outer package body. That model also used a total fuel heat generation rate of 2500 W, which is 7% higher than the value used in the current work. The column marked Current 2D shows results from the two-dimensional results shown in Fig. 5. The column marked

Maximum. The peak cladding temperature eventually reaches 272°C, which is the value for NCT when air is in the neutron shield (Table 2).

In Cases 3 and 4, the liquid drains when, respectively, the average of its maximum and minimum temperature, or its maximum temperature, reaches the liquid's boiling point. In Cases 3 and 4, drainage take place at times $t = 16$ and $3$ minutes, respectively. Since drainage occurs during the fire, there is less heat transfer to the package through the neutron shield than in Case 2, and so the peak clad temperatures of these cases rise more slowly. Even though drainage takes place earlier in Case 4 than in Case 3, the peak clad temperatures for these simulations are nearly identical. In both cases the maximum cladding temperature again reaches 272°C (Table 2).

From these simulations of a thirty-minute fire, it appears that if liquid drains from the neutron shield during the fire, the maximum cladding temperature is reached only after the package reaches the steady state condition associated with air in the neutron shield. If the liquid remains in the tank during and after the fire, then the fuel cladding reaches its maximum temperature a few hours after the fire goes out and then decreases. While the maximum temperature for this case is higher than when liquid drains form the tank, it does not appear to be realistic to assume liquid will remain in the tank. These conclusions may be different for longer duration fires. Moreover, including radiation heat transfer across the tank when it is filled with air will also affect these results.

**Fire/Post Fire Simulations**

The steady-state NCT temperatures are used as initial conditions for a transient simulation of a regulatory 30-minute, fully engulfing fire [2]. During the fire the environment temperature is assumed to be 800°C, and be characterized by a thermal radiation emissivity of 0.9. The package surface emissivity is assumed to be 0.85 [9]. In the current work, convection heat transfer between the fire and package surface is neglected (the effect of convection will be included in future simulations). After the fire ends at time $t = 30$ minutes, the surrounding are assumed to return to normal conditions of transport. In this work, the maximum cladding temperatures during and after the fire were determined.

Figure 6 shows the maximum cladding temperature versus time during and after regulatory 30-minute fires. Results from four simulations are shown. Each simulation uses a different assumption for the conditions that cause the neutron shield liquid to drain and be replaced by air, as listed in the Introduction. The liquid has a higher thermal conductivity than air, and radiation across the air-filled neutron shield tank is neglected in this work. As a result the rates of heat transfer to the package during the fire, and from the package after the fire, are higher when the tank has liquid in it than when it does not. In these simulations, when the tanks drain, the air that replaces it is assumed to have the same temperature as the liquid. Since the liquid has a higher specific heat, a large amount of sensible energy leaves the package with the liquid.

In Case 1, the neutron shield is filled with liquid during and after the fire. In that simulation the peak cladding temperature does not exhibit a significant rise until after the fire is extinguished. Heat continues to diffuse from the hot package periphery to its relatively cool center after the fire is out, causing the fuel temperature to rise. The peak cladding temperature reaches is maximum value of 294°C (See Table 2) at $t = 5.25$ hr, and then decreases. Long after the fire is out, the peak cladding temperature returns to its NCT value, because liquid remained in the neutron shield tank.

In Case 2, the liquid drains from the package at the end of the thirty-minute fire. This reduces the rate at which heat conducts through the neutron shield and out of the package after the fire compared to Case 1. However, when the liquid drains from the package it removes sensible energy. As a result the peak cladding temperature does not rise as fast for Case 2 as it does in Case 1. The cladding temperature does not exhibit a temporal maximum. The peak cladding temperature eventually reaches

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**THREE-DIMENSIONAL SIMULATION RESULTS**

Figure 7 show NCT temperature contours form three dimensional simulations with liquid in the neutron shield and overflow tanks. Figures 7a and 7b show, respectively, contours in axial and cross sectional planes. The maximum temperature is located along the package centerline, roughly halfway...
between the package ends. The NCT peak fuel clad temperature is 204°C, and is included in Table 2. It is 15°C cooler than the peak temperature predicted from the two-dimensional simulations. Axial conduction in the three-dimensional model causes the maximum temperature to be lower than in the two-dimensional simulation, which does not include axial conduction. However, the three-dimension model does not include the effect of the neutron shield or overflow tank stiffeners, which tends to cause the peak temperature to be higher than the two-dimensional model.

In Table 3, the column for Current 3D shows the peak temperatures for different components of the package. The column headed $\Delta T_{3D}$ shows the difference between these peak component temperatures and those from the PNNL model [9]. The maximum difference between these three-dimensional models is 11°C. These differences may be caused by the different dimensions used in the two models, the difference in modeling the neutron shield tank, and the different fuel heat generation rates.

Figure 8 shows the simulated peak cladding temperature versus time during and after a thirty-minute fully-engulfing fire from the three-dimensional model. Results are shown for Case 1, in which liquid remains in the neutron shield during and after the fire, and Case 2, in which the liquid drains at the end of the thirty minute fire. Similar to the results from the two-dimensional simulations, the peak cladding temperature reaches a maximum of 301°C at roughly 6 hours after the end of fire. This maximum temperature is included in Table 2 and is 7°C warmer than the value predicted using the two-dimensional model. For Case 2, in which the liquid drains from the neutron shield at the end of the 30 minute fire, the cladding temperature does not exhibit a temporal maximum. Rather, it increases slowly until it reaches the steady state NCT value associated with air in the neutron shield tank, which is included in Table 2.

SUMMARY

Two- and three-dimensional thermal models of an NAC-LWT cask used nuclear fuel transport package have been constructed using the PATRAN finite element package. The two-dimensional model included radial stiffeners in the external neutron shield tank that is filled with liquid during normal conditions of transport (NCT). These stiffeners were not included in the three-dimensional model. Simulations were performed to predict the peak cladding temperature during NCT, and the maximum cladding temperature caused by 30 minute regulatory fires. Four different assumptions were used with regard to the conditions that lead to the liquid draining from the neutron shield tank and being replaced by air.

The peak cladding temperature when air is in the neutron shield tank is 286°C, which is 82°C warmer than when liquid is in the tank. This difference is larger than for the two-dimensional model, which included the neutron shield radial stiffeners. The peak cladding temperature is less sensitive to whether liquid or air fills the neutron shield tank when the radial stiffeners are included than when they are not included.
current two- and three-dimensional models are within 11°C of the values predicted by and earlier thermal simulations of the NAC-LWT cask. Transient fire/post-fire simulations show that, if liquid is assumed to remain within the neutron shield tank during and after the fire, then the cladding temperature exhibits a temporal maximum roughly 6 hours after the fire goes out. If the liquid is assumed to drain from the tank during the fire the peak fuel cladding temperature increases for several days. It eventually reaches the values associated with NCT with air in the neutron shield tank. This value is lower than the temporal maximum value calculated assuming that liquid remains in the tank.

Future work will include modeling conduction within the neutron shield tank radial stiffeners in the three-dimensional package model, including radiation heat transfer within that tank when it is filled with air, and performing simulations with longer duration fires. A three-dimensional thermal model of the NAC-LWT cask will also be constructed using the ANSYS commercial finite element package. It will be linked to Container Analysis Fire Environment (CAFE) [14] simulations. This linked model will be used to predict the response of the NAC-LWT cask assuming it was in proximity to selected historic, long-duration transportation fires.

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REFERENCES