USE OF FUEL ASSEMBLY/BACKFILL GAS EFFECTIVE THERMAL CONDUCTIVITY MODELS TO PREDICT BASKET AND FUEL CLADDING TEMPERATURES WITHIN A RAIL PACKAGE DURING NORMAL TRANSPORT

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ABSTRACT
Two-dimensional finite element thermal simulations of a generic rail package designed to transport twenty-one spent PWR assemblies were performed for normal transport conditions. Effective thermal conductivity models were employed within the fuel assembly/backfill gas region. Those conductivity models were developed by other investigators assuming the basket wall temperature is uniform. They are typically used to predict the maximum fuel cladding temperature near the package center. The cladding temperature must not exceed specified limits during normal transport. This condition limits the number and heat generation rate of fuel assemblies that can transported. The current work shows the support basket wall temperatures in the periphery of the package are highly non-uniform. Moreover thermal resistance of those regions significantly affects the maximum fuel clad temperature near the package center. This brings the validity of the fuel/backfill gas thermal conductivity models into question. The non-uniform basket wall temperature profiles quantified in this work will be used in future numerical and experimental studies to develop new thermal models of the fuel assembly/backfill gas regions. This will be an iterative process, since the assembly/backfill model affects the predicted basket wall temperature profiles.

INTRODUCTION
A variety of boiling water reactor (BWR) and pressurized water reactor (PWR) fuel assembly configurations are used in power reactors [1]. They consist primarily of long zircaloy rods held in a square array by periodic metal spacers. Most of the rods contain fuel pellets. In some configurations there are also hollow instrument sheath and guide thimble tubes, and/or a zircaloy channel that encircle the rod array.

Spent nuclear fuel is transported away from power reactors in thick walled rail and truck casks [2, 3]. They are placed in the containment region at the center of the cask where they are supported horizontally within square cross section tubes of a basket structure. Before transport, the containment region is evacuated and backfilled with a non-oxidizing gas. Packages are designed to provide confinement, shielding and criticality protection during both normal and severe transport conditions.

Heat generated within the fuel (and solar heating) make the package hotter than its surroundings. Package manufacturers must demonstrate that the zircaloy cladding temperature does not exceed a long term temperature limit of 400°C during normal transport [4]. This generally limits the number and heat generation rate of the fuel assemblies that can be transported in a package.
Analysts typically employ finite element models of loaded packages to predict their temperatures [3]. It is computationally intensive to calculate heat transfer within the multiple fuel assembly/backfill gas regions. Under certain circumstances thermal radiation and natural convection contribute significantly to transport within these regions. In finite element models, the fuel assembly volume is generally replaced by a solid [3]. The heat generated by the assembly is distributed throughout the solid as a volumetric heat generation rate, and an effective thermal conductivity models is used to calculate transport.

Effective thermal conductivity models of the fuel assembly/backfill gas region have been developed by a number of investigators [1, 3, 5, 6, and 7]. These models were developed assuming the basket walls surrounding the region are at a uniform temperature. This is a reasonable approximation for assemblies near the package center (where the hottest cladding reside). However, we will see from the current work, this assumption is not valid near the package periphery.

Thermal conductivity models approximate heat flux at a location based on the temperature and its spatial gradient at that location. However, natural convection heat transfer is affected by the local fluid velocity, which depends on temperatures at other locations. Moreover, the radiant heat flux at a given location is affected by temperatures at a distance from that location. As a result, a thermal conductivity model that is valid for a basket cell near the package center (with nearly uniform wall temperature) may not be valid near the periphery (with significant wall temperature variation). We demonstrate in this paper that the thermal resistance of the periphery cells affects the maximum cladding temperature. This is because heat generated at the center of the package must diffuse through the outer cells.

These shortcomings lead to uncertainty in both the predicted maximum clad temperature for a given heat load, and the heat load that brings it to the limit value. Package designers address this uncertainty by reducing the number and/or heat generation rate of assemblies that may be loaded in casks compared to the prediction to assure that the cladding temperature limit is not exceeded. However, under-loading casks increases the number of shipments and the associated risk to the public. Accurate models for predicting fuel cladding temperatures therefore has potential public safety consequences.

To our knowledge, the effect of non-uniform wall temperature on heat transfer within fuel assembly/backfill gas regions near the package periphery has not been investigated. Work is underway to develop and experimentally benchmark newer fuel/backfill gas regional heat transfer models [8]. In that work two-dimensional computational fluid dynamics (CFD) simulations of natural convection and radiation heat transfer for a spent fuel assembly are performed assuming the basket wall temperature is uniform. Uniform wall temperature conditions are imposed in this initial study for simplicity and because the level of non-uniformity in a typical transportation package has not been quantified. The maximum fuel cladding temperature is determined for ranges of basket wall temperature, assemble heat generation rate, fuel cladding emissivity and different backfill gases.

In the current work a two-dimensional finite element model of the 125-ton Multi-Purpose Canister (MPC) Rail Package conceptual design [2] is constructed. This package is designed to transport 21 spent PWR fuel assemblies. Fuel assembly/backfill gas thermal conductivity models developed by other investigators are implemented within the fuel basket openings. A uniform volumetric heat generation rate, representative of the peak rate at the assembly’s midplane, is applied to the fuel regions. The maximum fuel cladding temperature (at the center of the package) is calculated as a function of assembly heat generation rate, assuming that rate is the same for all 21 assemblies.

The maximum allowed assembly heat generation rate is determined. This rate brings the hottest fuel cladding to the allowed temperature limit for normal transport [4]. The temperature profile around each basket tube is then determined at the maximum allowed heat generation rate. The maximum allowed assembly heat generation rate and the basket temperature profiles are determined for two different fuel assembly/backfill gas thermal conductivity models. The goal of this work is not to determine which heat transfer model is more accurate. Rather, the goal is to determine a range of appropriate thermal boundary conditions for computational fluid dynamics simulations and benchmark experiments to develop new models. This will be an iterative process, since the assembly/backfill model affects the predicted basket wall temperature profiles.

**NOMENCLATURE**

- \( D \)  
  Distance from the Package center
- \( E_T \)  
  Numerical Error
- \( L_A \)  
  Active fuel rod length
- \( L_B \)  
  Length of fuel basket
- \( L_E \)  
  Length of edge region
- \( L_I \)  
  Length of interior region
- \( N_T \)  
  Number of tubes in a basket
- \( p \)  
  Rod pitch
- \( P \)  
  Peak factor
- \( Q_A \)  
  Maximum allowable heat generation rate at which it reaches the temperature of concern
- \( Q_P \)  
  Total Heat generation rate of the package
- \( R \)  
  The line drawn from the center of the model to the edge
- \( \Delta T \)  
  Maximum Temperature difference in a basket
- \( T_{\text{avg}} \)  
  Weighted Average of the temperature
- \( T_{\text{clad,concern}} \)  
  Temperature of concern
- \( T_e \)  
  Temperature of the environment
- \( T_{F,\text{max}} \)  
  Temperature of the fuel
- \( T_p \)  
  Fuel basket temperature
- \( T_{\text{surf,max}} \)  
  Maximum surface temperature
- \( T_{\text{surf,min}} \)  
  Minimum surface temperature
GENERIC PACKAGE FINITE ELEMENT MODEL

Figure 1 shows a two-dimensional finite element (FE) grid used to simulate the thermal conditions of a plane halfway between the ends of a 125-ton Multi-Purpose Canister (MPC) Rail Package Conceptual Design [2]. In this design, up to 21 spent PWR fuel are loaded into the MPC at a reactor site. The MPC is evacuated, backfilled with helium and welded shut. It serves as the primary package containment vessel. The MPC is loaded into a thick walled transport cask. The cask has a bolted closure, and its ends are protected by large, compliant impact limiters.

The model in Fig. 1 was constructed using the Patran P/thermal commercial finite element package and consists of 12,688 elements. The basket structure at the package center has square cross section openings to support up to 21 PWR fuel assemblies. The basket opening dimension is \( L_B \) by \( L_B \), where \( L_B = 22.35 \) cm. The basket is housed within the MPC, which is surrounded by a multi-layered transport package.

The central basket walls are a sandwich composite of 0.6-cm-thick borated aluminum plates between 0.4-cm-thick stainless steel. The portions near the package periphery have helium gaps in place of the borated aluminum. The 2.54-cm-thick stainless steel MPC shell is separated from the 3.8-cm-thick stainless steel cask liner by a 0.8-cm-thick helium gap. The inner liner is surrounded by a 3.8-cm-thick layer of depleted uranium and a 1.27-cm-thick layer of lead, which are gamma shielding materials. These components are surrounded by the 6.36-cm-thick stainless steel cask body. A 15.24-cm-thick polypropylene neutron shield, which is covered by a 0.63-cm-thick stainless steel skin, encircles the package. Stainless steel and copper radial fins both of thickness 0.6 cm support the outer skin.

SPENT NUCLEAR FUEL

Figure 2 represents a transverse cross-section of a Babcock and Wilcox 15x15 pressurized water reactor (B&W 15x15 PWR) fuel assembly [1]. The square around the tubes represents the inner surface of a basket cell for PWR assemblies. As described with regard to Fig. 1, the length of each side of the cells is \( L_B = 22.35 \) cm.

The B&W 15x15 PWR assembly is a square array of \( N_T = 15 \) rows and columns of zircaloy tubes. Two-hundred-eight (208) of these tubes are spent fuel rods. The outer diameter and thickness of their zircaloy cladding are \( D_R = 10.92 \) mm and \( T_R = 0.673 \) mm, respectively. They contain spent uranium dioxide (\( \text{UO}_2 \)) fuel pellets of diameter \( d_P = 9.36 \) mm. The other 17 zircaloy tubes are instrument sheath and guide thimble tubes. Their outer diameter and thickness are 13.46 mm and 0.406 mm, respectively. The tube center to center pitch is \( p = 14.43 \) mm.

For this assembly and basket, the distance between the basket wall and the center of the nearest tube is \( W = 16.38 \) mm. This assumes the fuel is centered within the cell opening. The center of the sheath and guide tubes, the gap between the fuel pellets and cladding, and the void between the tubes and the basket walls, are all assumed to be filled with helium gas.

FUEL ASSEMBLY/BACKFILL GAS MODELS

Thermal models of the fuel assembly/backfill gas region of transport package have been developed by several investigators [1, 3, 5, and 7]. These models are used to
calculate heat transfer in the direction normal to the fuel pin axes. Four of these models are described in this section.

**Manteufel and Todreas**

Manteufel and Todreas [1994] developed an analytical model for one-dimensional conduction and radiation within a rectangular array of heated fuel rods immersed in stagnant gas. They used this model to calculate an effective thermal conductivity for the interior of a fuel/backfill gas region \( k_i(T) \), which is dependent on the local temperature \( T \). This model is for the interior of an assembly. They also developed an edge region thermal conductance model \( h_i(T_E,T_W) \) for the band between the assembly and the basket wall. The conductance is dependent on temperatures of both the basket wall \( T_W \) and the edge of the interior region, \( T_E \). It is based on one-dimensional radiation and conduction heat transfer.

The Manteufel and Todreas neglect possible effects of natural convection, two-dimensional heat transfer at the corners, and the unheated hollow tubes. They compare simulations using this thermal conductivity to measurements performed in spent fuel dry storage packages. The simulations consistently over-predict the measured maximum cladding temperature. This is conservative with regard to calculations used to design dry storage packages.

To model the B&W 15x15 assembly in the MPC rail package using the Manteufel and Todreas model, the interior effective thermal conductivity model \( k_i \) is applied to square regions of edge length \( L_i = P \times N_f = 21.65 \text{ cm} \) within each basket opening. Heat generated by the assembly is applied uniformly to this region. The width of the edge region between the interior and basket is \( W_i = \left( L_B - L_i \right) / 2 = 0.35 \text{ cm} \). The edge conductance is applied to this region as another temperature dependent thermal conductivity \( k_E(T_F) = W_E h_E(T_E,T_W) \). In this expression, the edge region conductivity is a function of the average film temperature \( T_F = (T_E + T_W) / 2 \).

Manteufel and Todreas [1994] give effective thermal conductivity/conductance results for a generic 15x15 PWR assembly without the unheated instrument sheath and guide thimble tubes shown in Fig. 2. The rod pitch, cladding outer diameter and cladding thickness for that model are \( p = 14.23 \text{ mm} \), \( d = 10.7 \text{ mm} \) and \( t = 0.615 \text{ mm} \). These values are similar but not identical to those of the Babcock and Wilcox 15x15 PWR described earlier.

The interior and edge region thermal conductivities determined by Manteufel and Todreas [1994] for this configuration are plotted in Fig. 3. This model assumes the backfill gas is helium and the cladding surface and package basket wall emissivities are 0.8 and 0.2 respectively. Moreover, the effect of conduction within the fuel pellets is neglected.

The effective thermal conductivities both increase with temperature as the contribution of radiation to the total heat transfer increases. The interior region conductivity is significantly higher than that at the edge due to the effect of the zircaloy tube conductivity.

**E-MAD**

Experiments at the Engine Maintenance Assembly and Disassembly (E-MAD) facility measured temperatures within a spent fuel dry storage package [3]. As part of that program, simulations of the test conditions were performed using an effective thermal conductivity model for the fuel/backfill gas region. A plot presented in the report indicates the effective thermal conductivity increases from \( 2.6 \times 10^6 \) to \( 10.4 \times 10^6 \) \( \text{W/m}^2\text{C} \) as the temperature increases from 200 to 570°C. These conductivities are several orders of magnitude greater than those developed by Manteufel and Todreas [1994], but they have been used in the preliminary design report of a package [9]. Neither the method for determining the effective thermal conductivity nor the source of those values is described in the report.

In the current work, we assume the exponent on the conductivity values was an error and use values that range from 2.6 to 10.4 \( \text{W/m}^2\text{C} \). The resulting effective thermal conductivity versus temperature is plotted in Fig. 3 in the curve marked E-MAD (modified). Even though the E-MAD conductivity is reduced by six orders of magnitude relative to the plot in the report, it is still significantly higher than that form the Manteufel and Todreas model.

In the current work the E-MAD effective thermal conductivity and fuel heat generation rate are applied to the same size square region (\( L_s = 21.65 \text{ cm} \)) at the center of each basket opening used in the Manteufel and Todreas calculations. Heat transfer across the gap between the surface of this square and the basket surface is modeled within the finite element simulations using thermal radiation across the gap and conduction through stagnant helium. The emissivities of the fuel and basket surfaces are 0.32 and 0.57, respectively.
Bahney and Lotz
Bahney and Lotz, [1996] performed two-dimensional finite element simulations of radiation and conduction heat transfer in fuel assembly/backfill gas regions using the ANSYS commercial finite element package. These simulations considered several PWR and BWR assemblies, including the Babcock and Wilcox 15x15 PWR. Based on these simulations they developed a temperature dependent thermal conductivity model for the entire fuel assembly/backfill gas region (including the gap around the assembly). Their results are included in Fig. 3. Those results are close to the Manteufel and Todreas interior effective thermal conductivity.

GA-4
The Safety Analysis Report for the GA-4 transport package [3] gives temperature dependent thermal conductivities for the interior and edge regions for a PWR fuel assembly. No information is given on how this model was developed, the type of PWR assembly for which it can be used, and no reference is mentioned. The temperature dependent interior and edge conductivities are included in Fig. 3. They are close to the values determined by Manteufel and Todreas.

NORMAL TRANSPORT CONDITIONS
In this section the Manteufel and Todreas [1994] and modified E-MAD [5] fuel assembly/backfill gas models are implemented within the basket openings shown in Fig. 1. Manteufel and Todreas is representative of three of the models described in the last section. The E-MAD model is used to determine how the results depend on the fuel/backfill gas model. As mentioned earlier, the goal of this work is not to determine which heat transfer model is more accurate. Rather, it is to determine the sensitivity of the allowable heat generation rate and basket wall temperature on different fuel region models that have been employed in past analyses.

Grids within the basket openings of Fig. 1 are used to implement the fuel assembly/backfill gas models. For both the Manteufel and Todreas and E-MAD models, the interior effective thermal conductivity is applied only to the center of each region in a square of dimensions $L_I \times L_I$. Volumetric heat generation is applied uniformly to that region at a rate $q = QP/L^2$. In this expression, $Q$ is the assembly heat generation rate, and $L_A$ is the active fuel rod length. The assembly peaking factor $P$ describes the ratio of the heat generation at the center of the fuel assembly to the average rate. In this work, the values $P = 1.25$ and $L_A = 3.601$ m [OCRWM 1993] are used. The Manteufel and Todreas edge region effective thermal conductivity presented in Fig. 3 is used for the edge gap for that model. Conduction and radiation across that gap are calculated by the finite element simulation for the E-MAD simulations.

Normal conditions of transport thermal boundary conditions are applied to the exterior surfaces of the package [4]. These conditions include a constant and uniform insolation [387 W/m$^2$] on all package surfaces (future simulations may consider more realistic conditions, such as applying this flux for half of each day, and/or only to the top of the package). The normal conditions of transport also include natural convection and thermal radiation to still air at an environment temperature $T_E = 38^\circ C$. For these calculations, the package surface emissivity is $\varepsilon_{surf} = 0.2$, and its absorptivity is 0.57.

The natural convection heat transfer coefficient $h$ between the package surface and its surroundings is determined based a
standard Nusselt number correlation for a horizontal cylinder in stagnant air [10]:

\[
Nu = \frac{hd}{k} = \left[ 0.6 + \frac{0.387 \times Ra^{1/6}}{1 + \left( \frac{0.559}{Pr} \right)^{9/16}} \right]^{2/5}
\]

In this expression, package diameter is \( d = 2.172 \, \text{m} \), and \( k \) is the thermal conductivity of air. The Rayleigh number is \( Ra = \left( g \times \beta (T - T_e) \times d^3 \right) (\nu \times \alpha) \). The local skin temperature is \( T \) and \( g \) is the acceleration of gravity. For air, \( \nu \) is the kinematic viscosity, \( \alpha \) is the thermal diffusivity, and \( \beta \) is the isobaric expansion coefficient.

All open gaps are assumed to be filled with atmospheric pressure helium (He) gas. Conduction heat transfer is modeled in all solid and gas filled elements using temperature dependent thermal conductivities. Gap radiation is modeled across all gas filled regions. For these calculations, the emissivity of stainless steel and borated aluminum are assumed to be \( \varepsilon_{SS} = 0.3 \) and \( \varepsilon_{BA} = 0.5 \).

**SIMULATION RESULTS**

Figure 4 shows steady state temperature contour plots in the MPC Rail Package cross section. The heat generation rate for each assembly is \( Q = 800 \, \text{W/assembly} \), resulting in a total package rate for the 21 assemblies of \( Q_e = 16.8 \, \text{kW} \). Figure 4a and 4b show results from simulations using the Manteufel and Todreas model and the modified E-MAD fuel assembly/backfill gas models, respectively.

The convective and radiation heat transfer conditions in these simulations are applied uniformly around the package circumference. The package geometry and mesh in Fig. 1 exhibit symmetry about horizontal, vertical and diagonal lines through the package center. As a result, the temperature contours are symmetric about these lines. The temperature contours in the MPC shell and Cask body are similar for both simulations. This is because both models employ the same material properties in those regions.

For both simulations the hottest fuel is located at the middle of the center spent fuel assembly. The fuel temperatures from the modified E-MAD simulation are more uniform than those from the Manteufel and Todreas calculation. This is due to the higher effective thermal conductivity of the E-MAD model. This also makes the maximum fuel clad temperature form the Manteufel and Todreas model (392°C) hotter than that from the E-MAD calculation (367°C). Both these temperatures are below the allowed limit for normal transport of 400°C [4].

Figure 5 shows the package temperature versus radial location \( R \) from the modified E-MAD and Manteufel and Todreas simulations. These results are for the bold horizontal line in Fig. 1. This line passes through several components. Within the MPC it passes through portions of three different fuel/backfill gas regions, the basket structures that surround them, a helium filled open region between the basket and MPC wall, and finally the MPC wall itself. Then passes though the helium filled gap between the MPC and cask inner liner. In the cask, it passes through the stainless steel inner liner, the depleted uranium and lead portions of the gamma shield, the stainless steel cask outer body, along the line between the stainless steel and copper plates of the radial fin stiffener, and finally through the stainless steel outer skin.

As noted with regard to Fig. 4, the simulations give nearly identical temperatures from the outermost basket wall to the cask outer skin. Moreover, the modified E-MAD simulation gives more uniform and lower temperatures in the fuel and inner basket walls than the Manteufel and Todreas results. The temperature difference between the hottest fuel cladding (at the center of the package, \( R = 0 \)) and the basket wall surrounding it (\( R = 0.11 \, \text{m} \)) is smaller for the modified E-MAD model than for Manteufel and Todreas. Furthermore, the hottest basket wall temperature is also lower in the E-MAD simulations than it is for the Manteufel and Todreas calculation. This is because heat diffuses from the hottest (innermost) basket walls to the environment through both the basket structure and the periphery fuel assembly/backfill gas regions. The thermal resistance in the fuel assembly/backfill gas regions is smaller in the E-MAD simulations than for Manteufel and Todreas.

Table 1 presents important temperatures from both simulations for \( Q = 800 \, \text{W/assembly} \). In both cases the environment temperature is \( T_e = 38^\circ\text{C} \), and the minimum and maximum package outer surface temperatures are \( T_{Surf,Min} = 158^\circ\text{C} \) and \( T_{Surf,Max} = 194^\circ\text{C} \). The maximum package temperature (excluding the fuel), \( T_{P,Max} \), is on the wall of the center basket tube. The value of \( T_{P,Max} \) is 370°C for the Manteufel and Todreas simulation, and 357°C for the modified E-MAD calculation. The maximum fuel clad temperature \( T_{F,Max} \) is 392°C for the Manteufel and Todreas simulation, and 367°C for the E-MAD calculation.
The temperature differences between the environment and package, within the package, and across the center fuel region are, respectively, \( \Delta T_E = T_{\text{surf,min}} - T_e \), \( \Delta T_F = T_{P,\text{max}} - T_{\text{surf,min}} \), and \( \Delta T_F = T_{P,\text{max}} - T_{P,\text{max}} \). The environmental temperature difference \( \Delta T_E \) is the same for both simulations since they involve the same heat loads, thermal boundary conditions and exterior emissivities. The package and fuel region temperature differences \( \Delta T_F \) from the Manteufel and Todreas model are both greater than they are for the modified E-MAD model by 15\(^\circ\)C and 10\(^\circ\)C, respectively. This is due to the lower fuel/backfill gas thermal conductivity of the Manteufel and Todreas model. For this heat generation rate the effect of the fuel/backfill gas model on the package temperature difference \( \Delta T_F \) is 1.5 times larger than it is on the fuel temperature difference, \( \Delta T_F \).

As noted earlier, effective thermal conductivity models have generally been developed assuming a uniform wall temperature. The thermal conductivity in the in the basket cells near the package periphery (where the wall temperatures are not uniform) have a larger effect on the maximum cladding temperature than the conductivity in the central cell. This suggests the effect of non-uniform basket wall temperatures on heat transfer must be quantified in order to accurately predict the maximum fuel clad temperature.

Figure 6 shows the maximum fuel clad temperature as a function of fuel assembly heat generation rate for both the Manteufel and Todreas and modified E-MAD models. A horizontal line shows the maximum allowed long term cladding temperature, \( T_{\text{Clad,L}} = 400\,^\circ\text{C} \) [4]. For a given heat generation rate, the Manteufel and Todreas models predict measurably higher temperatures than the E-MAD model.

The maximum allowable heat generation rate \( Q_A \) for each model is the value that causes its clad temperature to reach the allowed limit. The results in Fig. 6 indicate that the values predicted form the Manteufel and Todreas and modified E-MAD models are \( Q_{A,M&T} = 828 \text{ W/assembly} \), and \( Q_{A,E-MAD} = 915 \text{ W/assembly} \), respectively, an 11% difference. Another set of simulations was performed using conductivities that were 1.1 times larger than the Manteufel and Todreas values. The results show that a 10% increase in conductivity compared to the Manteufel and Todreas model increases \( Q_A \) by 1%. We note, however, that this result is based on the assumption that the same conductivity model can be used in both the center and periphery basket cells.

### Basket Wall Temperatures

Experimental measurements and computational fluid dynamics simulations must be performed for basket cell and fuel assembly geometries with non-uniform wall temperature profiles to determine how this profile affect radiation and natural convection heat transfer [Araya and Greiner 2005]. These studies require estimates of typical basket wall temperature profiles. In this section, these profiles are presented for the maximum allowed fuel heat generation rate for both the Manteufel and Todreas and modified E-MAD simulations.

Figure 7 shows the wall surface elements (from Fig. 1) of all 21 basket openings. Due to the symmetry of the geometry and boundary conditions, we expect that the temperature profiles along segments of each tube to be identical, to within the numerical uncertainty of the simulation method. In Fig. 7 the tubes are divided into 5 categories, A, B, C, D and E according to their location.

The walls of Tubes A, B, C, D and E are subdivided into segments, again based on symmetry. Tube A at the package center is divided into eight segments, labeled 1 to 8. For each segment, location \( S = 0 \) corresponds to the middle each tube wall and \( S = 11 \text{ cm} \) is the tube corner. The four B tubes in Fig. 7 are above, below and on either side of A. Each of these four segment locations were divided into 5 categories.
The 21 Fuel basket tubes are broken into 5 different categories (A, B, C, D and E) subdivided into segments based on symmetry.

The tubes are divided into two segments, for a total of eight segments. They are labeled 1 to 8. These segments terminate at the middle of the inner (S = 0) and outer tube walls (S = 44 cm). The four C tubes are on diagonals adjacent to A. Once again, these tubes are divided into two segments each, but these segments terminate at the innermost (S = 0) and outermost tube corner (S = 44 cm). The four D tubes are outside the B tubes. They are divided into two segments each, which terminate at the middle of the inner (S = 0) and outer tube walls (S = 44 cm). The eight E tubes share walls with the D and C tubes. Each of the eight E tubes is divided into two segments, for a total of 16. These segments terminate at the innermost (S = 0) and outermost tube corner.

Figure 8 shows simulation results for the temperature profiles around each line segment. Figures 8a and 8b show results from the Manteufel and Todreas simulations and the modified E-MAD calculations, respectively. The results for tube A for each simulation show that the temperatures form all eight segments are essentially identical (and very close to those for portions of tube B).

The Manteufel and Todreas results for Tube A show that the maximum temperature difference from each segment at the same s-location is $E_T = 0.01{}^\circ C$. This is an indication of the numerical error of the simulation technique. The maximum difference for the E-MAD simulation is the same. The average temperature for Tube A from the Manteufel and Todreas simulations is $T_{AVG} = 379{}^\circ C$, while it is $T_{AVG} = 390{}^\circ C$ for the E-MAD simulation. The difference between the minimum and maximum temperature on Tube A is an indication of the non-uniformity of the tube temperature. It is $\Delta T = 1.7{}^\circ C$ from Manteufel and Todreas, and $\Delta T = 1.5{}^\circ C$ for E-MAD.

![Figure 8](image)

**FIGURE 8** Temperature profiles along segments of basket tube versus location (a) Manteufel and Todreas simulation with $Q_A = 828$ W/assembly, and (b) E-MAD calculation with $Q_A = 915$ W/assembly.

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<th>$T_{AVG}$ [$^\circ C$]</th>
<th>$\Delta T$ [$^\circ C$]</th>
<th>$E_T$ [$^\circ C$]</th>
<th>$T_{AVG}$ [$^\circ C$]</th>
<th>$\Delta T$ [$^\circ C$]</th>
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**TABLE 2** Distance from package center, average, maximum variation, and numerical error temperatures for tubes A, B, C, D and E. Results are presented for both the Manteufel and Todreas [1994] model with $Q = Q_{A,M&T} = 828$ W/assembly, and the modified E-Mad [5] model with $Q = Q_{A,E-MAD} = 915$ W/assembly.

The temperature profiles for the separate segments of Tubes B, C and D are again nearly identical. For Tube E the segments adjacent to Tube C are hotter than those adjacent to Tube D.
For each tube, the distance between its center and the package center is defined as $D$. The value of $D$ for each tube is given in Table 2. The average $T_{AVG}$, maximum variation $\Delta T$, and numerical error $E_T$ temperatures for each tube are also tabulated. Results from both the Manteufel and the E-MAD simulations are included. The values of $T_{AVG}$, $\Delta T$, and $E_T$ are plotted against $D$ in Fig. 9. The average temperature $T_{AVG}$ decreases as the distance between the tube center and package center increases. However, the non-uniformity of the tube temperature $\Delta T$ increases with $D$. The temperature uncertainty $E_T$ increases with $D$, similar to the behavior of $\Delta T$.

In future work, numerical simulations and experimental measurements will be performed that approximate the non-uniform wall temperatures determined in the current work. It may be difficult for experiments to exactly reconstruct the continuously varying temperature profiles exhibited in Fig. 8. It may be easier to construct an apparatus for with each wall has a uniform temperature, but each wall temperature is different. In order to give guidance to such efforts, Table 3 presents the average temperatures on the left, right, top, and bottom walls of tubes A, B, C, D, and E, as calculated by both the E-MAD and Manteufel and Todreas models. The letters within five of the cells in Fig. 7 are circled. The left, right, top, and bottom designations in Table 3 refer to the walls of those cells.

**SUMMARY**

A two-dimensional finite element model of a rail package designed to transport twenty-one spent PWR assemblies was constructed. Fuel assembly/backfill gas region thermal conductivity models were implemented in the basket openings. These models were developed assuming the basket wall temperature is uniform. They are typically used to predict the maximum fuel cladding temperature near the package center for a given fuel heat generation rate. The cladding temperature must not exceed specified limits during transport. This condition limits the number and heat generation rate of fuel assemblies that can be transported.

In this work, normal conditions of transport thermal simulations were performed using the same fuel heat generation rate and thermal conductivity model in all twenty-one basket locations. These simulations show that the wall basket wall temperatures at the periphery of the package were highly non-uniform. Moreover, the thermal resistance of these regions significantly affects the maximum cladding temperature at the package center. These results bring the validity of the fuel assembly/backfill gas region thermal conductivities (developed assuming uniform wall temperature) into question. They also motivate the study of heat transfer between spent fuel assemblies within non-uniform wall temperature baskets. The non-uniform wall temperatures determined in the current simulations will be used in future experimental and computational works. This will be an

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**TABLE 3** Average temperatures of the left, right, top and bottom walls for tubes A, B, C, D and E tubes circled in Fig. 7.

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<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>A</td>
<td>379</td>
<td>379</td>
</tr>
<tr>
<td>B</td>
<td>378.7</td>
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<td>365</td>
<td>332</td>
</tr>
<tr>
<td>E</td>
<td>354.5</td>
<td>317</td>
</tr>
</tbody>
</table>

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FIGURE 9 (a) Average, (b) Maximum variation, and (c) Numerical error temperatures for each tube versus distance from package center. Results are presented for the Manteufel and Todreas [1994] model with $Q_{A,M&T} = 828$ W/assembly, and the modified E-MAD [5] model with $Q_{A,E-MAD} = 915$ W/assembly.
iterative process, since the assembly/backfill model affects the predicted basket wall temperature profiles.

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REFERENCES


