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Dependence of Fire Time of Concern on Package Location for a 1 PWR Transport Package

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ABSTRACT

The fire time of concern for a component within a spent nuclear fuel (SNF) transport package is the time after fire ignition when that component reaches its temperature condition of concern. In this work a legal weight truck (LWT) package that is designed to transport one spent pressurized water reactor (PWR) fuel assembly is assumed to be in proximity to a 12-m diameter jet propellant fuel (JP8) pool fire. Container Analysis Fire Environment (CAFE) simulations are used to predict the fire times of concern for the fuel cladding, seal, lead gamma shield, and liquid neutron shield of the package, for different package locations relative to the fire under no wind conditions. When the package was centered over the pool, the CAFE-predicted time of concern for the cladding to reach its possible burst rupture temperature (750°C) was between 11.8 and 13.3 hours, depending on the modeling parameter values and mesh refinement. As the package was moved away from the pool center, the cladding time of concern increased and its in-fire steady state temperature (reached after being exposed to the fire for a long time) decreased. The cladding did not reach its temperature of concern when the package center was 6 m from the pool center (above the pool edge), even in infinitely-long-lasting fires. This type of analysis can be used to determine a "safe distance" between the pool and package centers, beyond which certain important-to-safety components will not reach their temperature of concern, no matter how long a fire lasts. This will help risk analysts determine which accident scenarios require investigation, and which do not.

INTRODUCTION

SNF assemblies from light water reactors consists of fuel rods held in square arrays along with instrumentation and guide tubes between header and footer structures, and periodic spacer plates [1]. Each fuel rod is a zircaloy cladding tube that contains highly radioactive fuel pellets and high pressure fission product gases. Thick walled transportation packages are used to transport SNF assemblies away from reactor sites. However, before a package can receive a Certificate of Compliance (CoC) from the US Nuclear Regulatory Commission (NRC), Federal Regulations (10CFR71) require its manufacturer to demonstrate that the package will maintain

its containment, shielding and criticality control functions after a sequence of tests for the hypothetical accident conditions (HAC) [2]. These tests 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 (1472°F)-fire for 30 minutes, and water submersion.

Transportation risk studies assess the response of certified packages to all possible types of accidents, some of which may be more severe than the regulatory sequence, as well as the likelihood that packages will be involved in those events [3, 4]. 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 SNF transport packages assuming they were in proximity to specific historically-severe long-duration fires. They considered fires that took place in the Caldecott roadway tunnel near Oakland, California in 1982 [5, 6], and the Howard Street rail tunnel in Baltimore, Maryland in 2001 [7]. These studies were conducted to determine if the fire resistance requirements of the federal regulations are adequate for those accident conditions.

OBJECTIVES

The objective of this work was to predict the fire times of concern for the fuel cladding, seal, lead gamma shield, and liquid neutron shield of the package, for different package locations relative to the fire. In this work, the fire time of concern for a package component has been defined as the time after fire ignition when that component reaches its thermal condition of concern. The aim was to use the fire time of concern of the fuel cladding to determine the "safe distance" between the pool and package centers beyond which the peak fuel cladding temperature will not reach its temperature of concern even for infinitely long lasting fire. This will help risk analysts determine which accident scenarios require investigation, and which do not.

METHODOLOGY

This work predicts the response of the NAC-LWT package to long duration, JP8 fuel fires under no-wind conditions. A three-dimensional (3D) computational model of the NAC-LWT package [8] is developed using ANSYS Parametric Design Language (APDL). Heat transfer inside the package is modeled via conduction within all solid components, and via conduction and surface-to-surface radiation across all gas filled gaps. Steady state simulations subjected to normal conditions of transport (NCT) boundary conditions were performed to determine the package temperature. The NCT temperatures were then used as an initial condition for two types of transient HAC fire simulations. The first simulation used a constant user specified fire temperature (T_F) and emissivity as per 10CFR71. The second set of simulation was performed by linking the ANSYS computational model to Container Analysis Fire Environment (CAFE) [9]. CAFE was used to simulate the response of the NAC-LWT package to a 12-m diameter JP8 fuel pool fire for a range of standoff distances.

During both sets of simulations, the peak temperature of fuel cladding, seal and gamma shield, and the average temperature of neutron shield were determined as a function of time to evaluate the time of concern for these components. For CAFE, simulations were performed for various displacements along and normal to the package axis in order to determine the safe distance at which the peak fuel cladding temperature never reached its temperature of concern.

The temperature of concerns used in this work are 750°C for the fuel cladding [10], 427°C for the seal, 316°C for the lead gamma shield, and 177°C for the neutron shield tank [8].

Container Analysis Fire Environment

Container Analysis Fire Environment (CAFE) is a computational fluid dynamics (CFD) and radiation heat transfer fire simulator code that was developed by Sandia National Laboratory to predict the response of SNF packages to severe accidents. CAFE's fire simulator employs physics-based fuel evaporation, turbulent transport, radiation heat transfer and reaction chemistry models that are based on large-fire behaviors. These models calculate the transport, generation and consumption of air, fuel vapor, intermediate combustion species, soot, products of combustion, momentum, and sensible energy. Parameters of these models (such as the combustion kinetics constants, and spatial variation of the fuel evaporation rate) are determined based on comparison of CAFE simulation results with measured data acquired in large fire experiments [11, 12].

CAFE uses a Rosseland effective conductivity to calculate participating-media radiation heat transfer within the heavily sooty regions of a fire [13], and view factor radiation to calculate radiation heat transfer across the non-participating regions outside the heavily sooty fire regions. The Rosseland effective conductivity is calculated as $k_R = 16n^2\sigma T^3/3\beta_R$, where n is the media's refractive index, σ is the Stefan-Boltzmann constant, T is the local temperature, and β_R is the media's extinction coefficient. CAFE incorporates an additional correction factor that allows the correct heat transfer and effective radiation conductivity to be calculated as a function of fire optical depth. The correction factor extends the range of solution validity to optically-thin media. It has been validated against exact solutions to the kernel approximation solution of the radiation transport equation.

Large-scale outdoor fire tests have been performed to acquire data to find appropriate values of the model parameters used in CAFE [14, 15]. In those experiments, truck and rail-package-sized pipe calorimeters were centered over round JP8 fuel fires. However, in the current work simulations are performed with the package at different standoff distances from the pool center. The experiments were not performed using that configuration. CAFE's accuracy in calculating heat transfer to objects and fuel evaporation rates has not been evaluated when the objects are not centered above the pool.

In this work, CAFE has been linked with ANSYS to predict the thermal response of the NAC-LWT package to a 12-m diameter JP8 pool fuel fire. CAFE fire model and ANSYS finite element (FE) model use separate computational meshes, and they do not run simultaneously. The CFD code runs for a user defined period, 0.05 seconds in this work, to calculate the fire behavior and interaction with the package surface. Using the heat transfer data calculated by CAFE, the FE code then runs for another user defined period to predict the thermal response of the package to the fire. The new FE package surface temperature is then used to update the package temperature boundary condition of the fire simulation. The two components run alternately until the simulation is complete.

The user defined period for which CAFE and ANSYS run do not need to be the same. If the fire conditions are changing slowly, accurate results may be achieved even when the CFD step is much shorter than the FE-step. This can result in relatively short computational times. There are two parameters that control how often CAFE calculates fire behavior. The first parameter is elapsed FE model time, 60 seconds in this work, and the second parameter is change in surface temperature, 100°C in this work. This means that CAFE calculations are run upon elapse of

every 60 seconds of ANSYS time or change of 100°C on package surface, whichever occurs first.

COMPUTATIONAL MODEL

A three dimension model (3D) of the NAC-LWT package was developed using APDL. Figures 1a and 1b show axial-section and cross-section views of the material regions of the NAC-LWT package used in this work. Most of the model dimensions used in this work were taken from the axisymmetric HEATING5 thermal model and drawings presented in the NAC-LWT's safety analysis report (SAR) [8]. The square cross sections of the fuel block and basket insert opening were taken from PNNL's Caldecott Tunnel Fire report [16]. In this work the fuel block generates a total of 2500 W [8] over the active fuel length with a normalized peaking factor of 1.2. The heat generation rate varies axially along the fuel, and for a given axial location, heat is generated uniformly across the block cross section.

The NAC-LWT package model used 243,180 ANSYS SOLID70 brick elements for different material regions of the model. SURF152 surface effect elements were used to capture convection and radiation heat transfer between the package surface and environment. MATRIX50 elements were used to model surface-to-surface radiation heat transfer across the helium-filled gaps. MATRIX50 elements were also activated in the neutron shield and overflow tanks once air replaced the 56% ethylene glycol/water solution in the tanks during the fire.

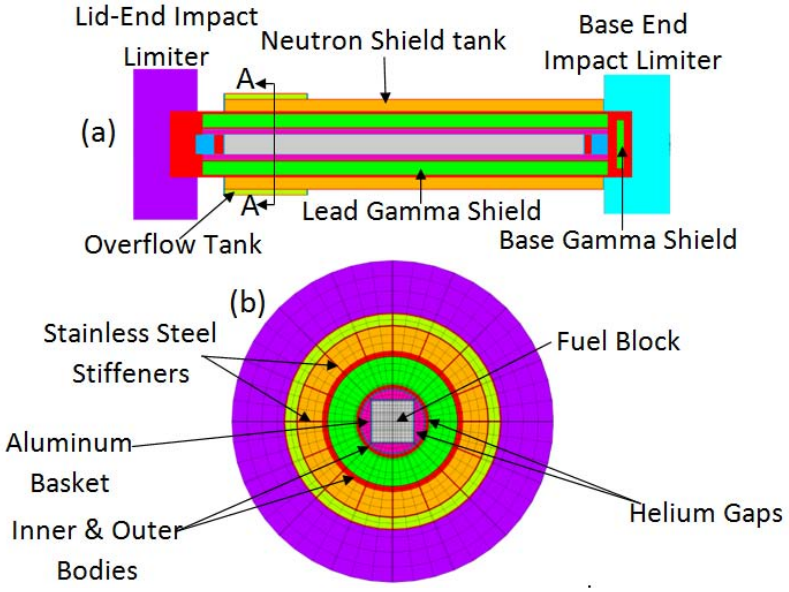

Figure 1: Material regions of the NAC-LWT package model. (a) Axial cross section. (b) Transverse cross section view A-A as seen in part (a).

This model uses temperature dependent material and effective properties presented in [16, 17 and 18]. An effective conductivity was used for the neutron shield and overflow tank to account for natural convection associated with the 56% ethylene glycol solution in the tanks. This conductivity was calculated and updated after each time step in ANSYS by user defined APDL macros.

NORMAL CONDITIONS OF TRANSPORT

During NCT, it was assumed that solar heat fluxes of 194 W/m^2 and 97 W/m^2 were incident on all curved and vertical flat surfaces [2]. Heat transfer from the package surface to the 38°C

environment was determined using a convection coefficient of 5.06 W/m^{2}K [8], and radiation heat transfer with a thermal emissivity, ϵ_S = 0.8, of the outer package surface [19]. Figure 2 shows the NAC-LWT surface temperature contours for the NCT. The surface temperature varies from 54°C near the Lid-End Impact Limiter to 72°C near the package mid-plane. Figure 3a shows the temperature contours on the vertical axial-section of the package. The maximum temperature of the package during NCT is 210°C. Figure 3b shows the temperature contours on cross-section plane that includes the maximum temperature. The r-coordinate system shown in this figure is located at the cross section of the peak fuel temperature, with the origin at the fuel center.

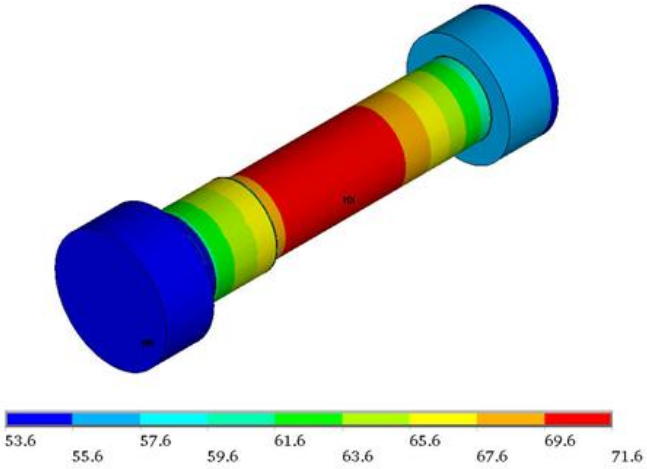

Figure 2: Surface temperature contours in °C for the NAC-LWT model under NCT

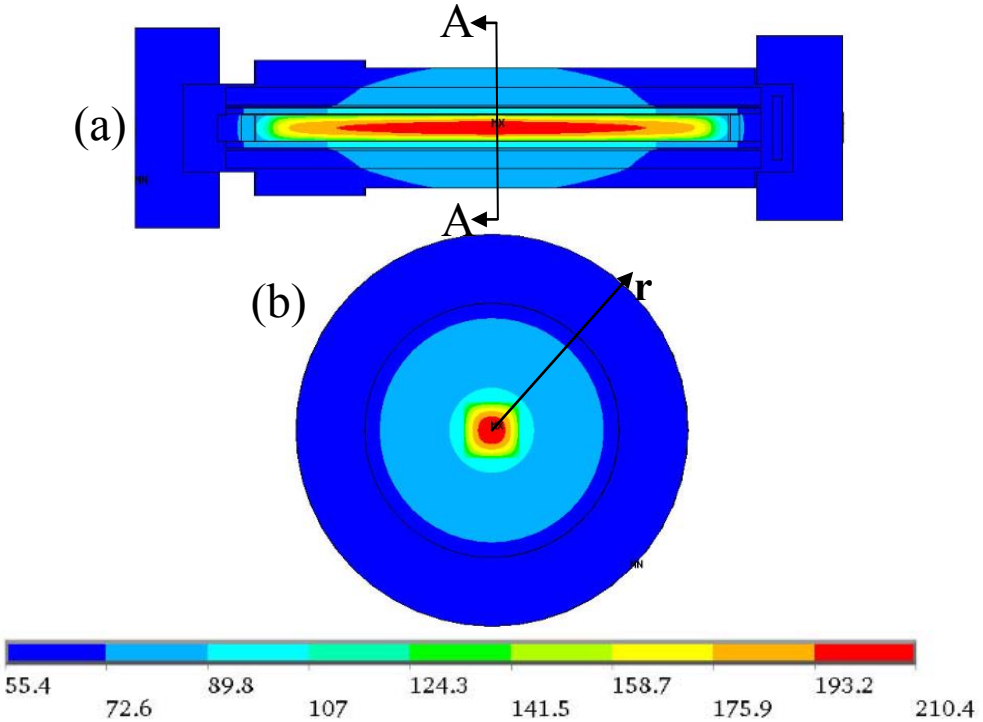

Figure 3: Temperature contours in °C predicted for NAC-LWT package under NCT. (a) Axial cross-section. (b) Transverse cross-sectional

Figure 4 shows the temperature along r-axis versus radial distance from the package center. The temperature along this axis was found in good agreement with the results predicted by PNNL [18] as shown in the figure. The temperatures predicted by the current simulations are within 2°C of those predicted by PNNL along the r-axis. Fig. 4 shows that there is a large temperature gradient across helium gas filled regions as compared to the nearly uniform temperature in the aluminum basket, stainless steel shells, and lead gamma shield. This is attributed to higher thermal conductivities of the metal components.

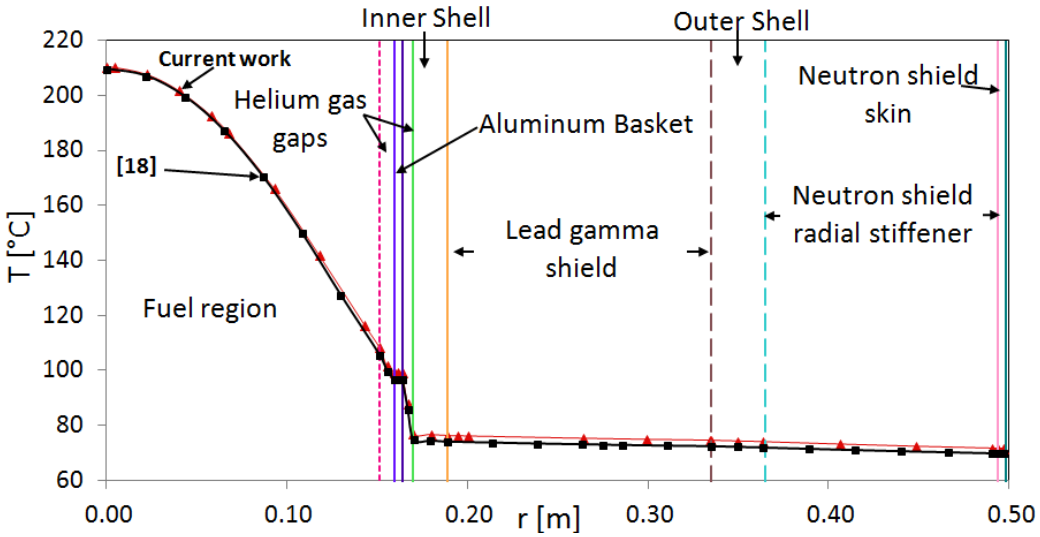

Figure 4: Temperature versus distance for package centerline along the r-axis shown in Fig. 3. Results from the current work are compared to results presented in [18].

FIRE ACCIDENT SIMULATIONS

The NCT simulation results were used as an initial condition for two types of fire simulations. The first set of simulations is based on 10CFR71 regulations that uses heat transfer from the package outer surface to a user specified fire temperature environment. Fire temperatures of 800°C and 1000°C were used in this work. The second set of simulation is based on CAFE which uses temporally and spatially dependent fire motion to determine heat transfer to the package.

Regulatory-Format Fire Simulations

10CFR71 regulations require that a fully engulfing fire should be used to evaluate the response of the package [2]. It specifies that the fire temperature must be at least $T_F = 800°C$, and the fire and package surface effective emissivities must be at least $\epsilon_F = 0.9$ and $\epsilon_S = 0.8$, respectively. In this work two different fire temperatures, $T_F = 800°C$ and $1000°C$ were used with $\epsilon_F = 0.9$ and $\epsilon_S = 0.8$. The effect of convection heat transfer was assumed to have negligible effect as compared to radiation heat transfer, and is not included.

Figure 5 shows the peak fuel cladding temperature (T_{PC}) versus time after fire ignition, t. The cladding temperature rises more quickly when $T_F = 1000°C$ as compared to $T_F = 800°C$ because of higher heat transfer rates associated with the higher fire temperature. As a result, the time of concern of the fuel cladding (t_C) is 5.1 hours when $T_F = 1000°C$, and 15.4 hours when $T_F = 800°C$, as shown in Table 1. This is the time at which the peak fuel cladding temperature reaches the burst rupture temperature $T_{BR} = 750°C$.

The times of concern for the seal (t_S), liquid neutron shield (t_{NS}) and lead gamma shield (t_{GS}) to reach their respective temperatures of concern are also included in Table 1.

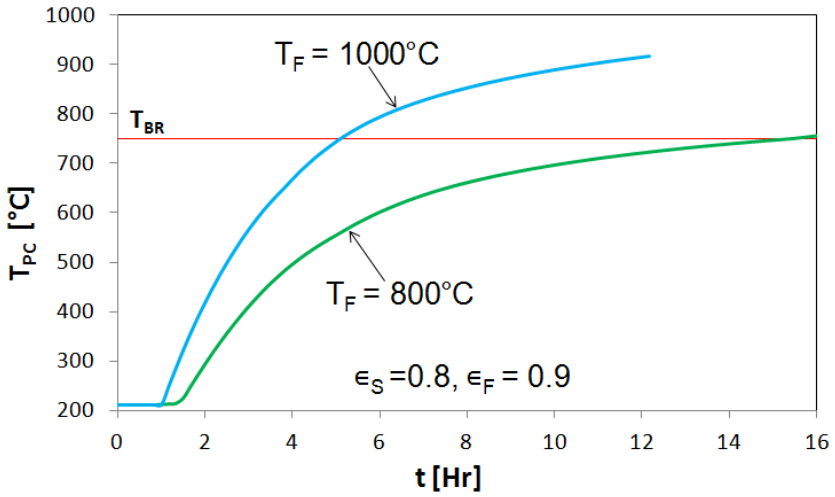

Figure 5: Peak component temperatures comparison for long duration-regulatory-format fires calculated using ANSYS with $T_F = 800°C$ and $T_F = 1000°C$, $\epsilon_S = 0.8$ and $\epsilon_F = 0.9$

Table 1: Package location (S_X,S_Z), parameter values (xwm, F_{PC}), mesh node count (N) and times of concern comparison for different package locations.

	T_F [°C]	S_X	S_Z	N	xwm	F_{PC}	Non-Nominal Condition	t_C [hr]	t_S [hr]	t_{NS} [hr]	t_{GS} [hr]
10 CFR 71	800	0	0	-	-	-	-	15.4	1.54	0.32	0.46
	1000	0	0	-	-	-	-	5.1	1.30	0.16	0.19
CAFE	-	0	0	85272	0.25	0.08	(f)	13.3	1.48	0.33	0.50
		0	0	85272	0.25	0.1	-	12.9	1.47	0.32	0.50
		0	0	39780	0.25	0.1	(-)	11.8	1.46	0.19	0.50
		0	0	177840	0.25	0.1	(+)	12.8	1.40	0.13	0.43
		1.9	0	85272	0.25	0.1	-	15.8	1.46	0.15	0.38
		3.4	0	89148	1	0.08	(f,x)	24.3	2.90	0.24	0.69
		3.4	0	85272	0.25	0.1	-	21.2	1.52	0.21	0.42
		3.9	0	85272	0.25	0.1	-	29.4	2.16	0.21	0.59
		4.4	0	85272	0.25	0.1	-	50.5	1.52	0.20	0.10
		5.4	0	89148	0.25	0.1	-	-	1.94	0.27	0.16
		6.4	0	69768	1	0.08	(f,x)	-	3.59	0.45	0.33
		6.4	0	69768	0.25	0.08	(f)	-	3.35	0.37	0.28
		6.4	0	69768	0.25	0.1	-	-	3.00	0.35	0.26
		0	1.5	88616	0.25	0.1	-	18.7	1.45	0.17	0.57
		0	3	86944	0.25	0.1	-	21.9	1.50	0.21	0.57
		0	5	90288	0.25	0.1	-	29.4	1.39	0.32	0.22
		0	6	93632	0.25	0.1	-	-	1.38	0.50	0.17

CAFE Fire Simulations

Preliminary CAFE simulations with a range of pool diameters showed that a 12-m-diameter pool fire engulfed the package when it was centered above the pool with the package outer body at a height of 1 m. Figure 6 shows the CAFE computational domain mesh with the package centered above the pool. The domain is 40m x 40m x 12m with the 12-m-diameter fuel pool centered in the domain.

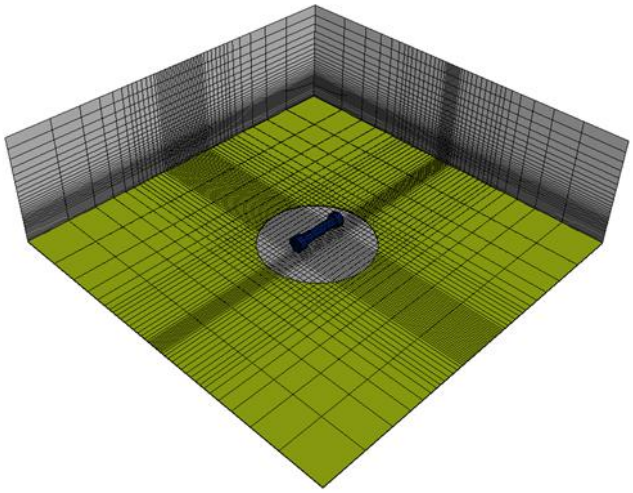

Figure 6: CAFE computational domain and mesh with the package centered over the 12-m-diameter fuel pool. The domain outer dimensions are 40 m by 40 m by 12 m, and it contains 85,272 mesh points.

In this work, the fuel pool comprises of two regions. A central disk of 8-m-diameter consists of JP8 fuel vapor being injected into the domain at a rate of 0.01 kg/m^2s. The outer 2-m-wide ring has fuel being injected in at a rate of 0.12 kg/m^2s. The higher fuel injection rate is a result of higher heat transfer to that region from the fire, resulting in a higher rate of evaporation. These fuel flow rates are based on comparing CAFE simulations [20] with temperature measurements of a rail-package-sized calorimeter suspended over a JP8 pool fire [15]. This fuel evaporation rate is used for all calculations in this work. However, its accuracy has not been evaluated when objects are not centered over the pool.

There is no flow though the bottom of the domain outside of the fuel pool. Hydrostatic pressure boundary conditions are applied to the sides and top of the domain. This allows air to flow in from the domain sides, and products of combustion, along with air, unburned fuel, soot and intermediate species, to flow out of the top surface. Wind boundary conditions could also be used, but in this work only no-wind conditions were investigated.

In this work, simulations were performed with the package centered above the pool, and at various offset locations along and normal to the package axis. Figure 7a shows a plan view of the NAC-LWT package model over the fuel pool. This figure shows the x,z coordinated system with its origin located at the center of the pool, and the package center at $(x,z) = (S_X, S_Z)$. In this work, all the calculations were performed with the package axis parallel to the z-axis. Simulations were performed with the package offset along the x-axis ($S_Z = 0$ and $S_X > 0$) and offset along the z-axis ($S_X = 0$, and $S_Z > 0$). Figure 7b shows snapshot of the fire surface and exposed package surfaces.

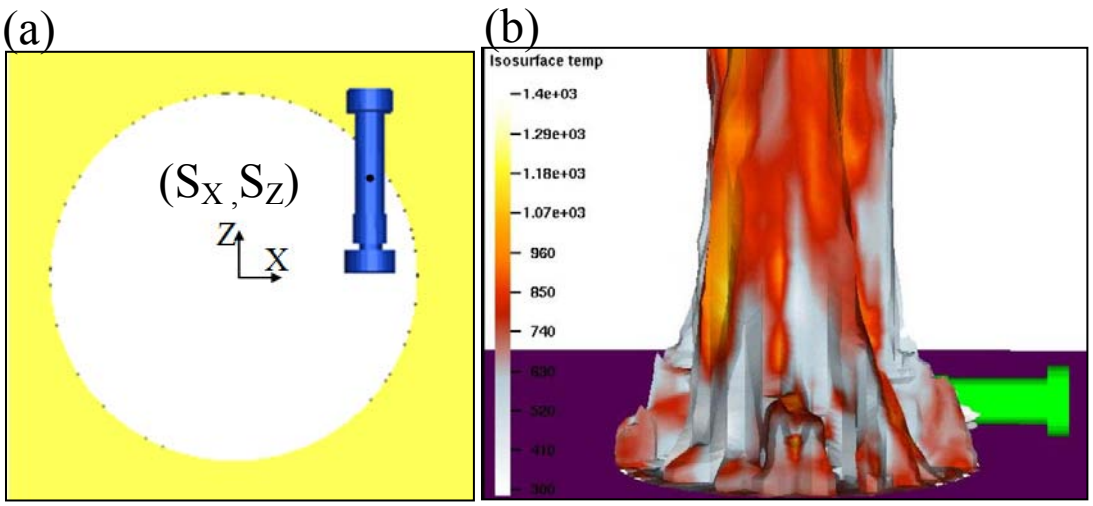

Figure 7: Plan view of the NAC-LWT package model over a 12-m diameter fuel pool. The origin of the x,z-coordinate system is at the center of the pool. The coordinate of the package center is (x,z) = (S_X, S_Z). (b) Representative steady state fire surface (colored according to temperature) and NAC-LWT package surface from CAFE simulations.

CAFE provides user with the ability to control various parameters to establish the fire environment. Simulations were performed for a range of CAFE parameters to determine how much they affect the results. These parameters are:

- F_{PC}: CAFE uses Rosseland effective conductivity to calculate radiation heat transfer in the highly sooty regions of the fire, where the mass fraction of products of combustion is above a user-defined value, F_{PC}. Benchmarking studies conducted in the past [15, 20 and 21] suggested that a value of 0.08 is appropriate for F_{PC}. In the current work, the nominal value of F_{PC} is considered to be 0.1. Simulations have also been performed with F_{PC} = 0.08 to determine the sensitivity of CAFE results to this parameter.
- xwm: The cross wind momentum factor limit (xwm) affects the solution of the momentum equations. CAFE uses a Total Variation Diminishing (TVD) scheme to calculate the fraction of upwind differencing and second-order-accurate central differencing that will be used to calculate momentum transfer inside the CAFE domain. xwm determines the maximum fraction of upwind differencing which will be used. The normally-suggested value is xmw = 1. However, in this work 0.25 is considered a nominal value of xwm because it causes the CAFE simulated fire to exhibit the puffing behavior exhibited by real-world fires. Simulations have also been performed with the suggested value of xmw = 1 to determine the sensitivity of CAFE results to this parameter.

Table 1 summarizes important parameters that were used for the two 10CFR71 simulations and 17 CAFE simulations performed for this work. The third and fourth columns specify the location of the package relative to the pool center. The fifth column shows the number of node points that were used for each CAFE mesh. As the package location changes, this parameter varies. In this work, simulations with CAFE node points (N) within 20% of 85,272 are considered to have a "nominal" refinement. When the package was located at the center, simulations were also performed with twice and half as many node points as in nominal refinement to evaluate the sensitivity of CAFE results to mesh refinement. The sixth and seventh column show the value of xwm and F_{PC} used in each CAFE calculation.

In table 1, the symbol "f" is used when a non-nominal value of $F_{PC} = 0.08$ is used, "x" is used when a non-nominal value of xwm = 1 is used, and "+" or "-" is used when number of nodal points are more or less than the nominal value, respectively.

Fig. 8a shows the peak cladding temperature (T_{PC}) versus time for three package locations at S_X = 0, 3.4 and 6.4 m, with $S_Z = 0$. Results marked with "n" are for nominal parameters (F_{PC} = 0.1, xwm = 0.25) and mesh refinement (N = 85,272 ± 20%). Fig. 8a shows that variation in the mesh refinements and parameters affect the calculated peak cladding temperature versus time. When the package is centered over the fuel pool, the predicted value of t_C is between 11.8 and 13.3 hours. As listed in table 1, t_C is 12.9 hours for nominal conditions, and decreases by 0.1 and 1.1 hrs, respectively, when a coarse (-) or fine (+) mesh is used. Decreasing F_{PC} to 0.08 increases t_C by 0.4 hr. Symbols "f" and "x" are used for non-nominal parameter values of F_{PC} and xwm, and "+" and "-" are used for non-nominal mesh refinement in Fig. 8a.

The time of concerns calculated using regulatory format fire simulation with fire temperatures T_F = 800°C (t_C = 15.4 hours) and T_F = 1000°C (t_C = 5.1 hours) suggests that an effective fire temperature between 800°C < T_F < 1000°C is required in order to predict the same cladding time of concern as the CAFE calculations.

Fig. 8a shows that for S_X = 3.4 and 6.4 m, the peak fuel cladding temperature rises slower than when S_X=0. This is expected as package surface engulfed in fire becomes less as S_X increases. For S_X = 3.4 m, the peak fuel cladding temperature reaches T_{BR} at 21.2 hours for nominal parameter values. Whereas for S_X = 6.4 m the peak cladding temperature appears to plateau at approximately T_{PC} = 500°C after around 25 hours. This suggests that the cladding will not reach its temperature-of-concern at this location, no matter how long the fire lasts.

Figures 8b and 8c show the peak fuel cladding temperature versus time for package shifted normal and parallel to package axis, respectively. The cladding time of concern t_C increases as the package center moves away from the pool center. These calculated values of time of concern for each simulation have been listed in Table 1.

Figure 9a shows the cladding time of concern versus standoff distance between the fuel pool and package centers, $S = \sqrt{S_X^2 + S_Z^2}$. Circles have been used to indicate calculations performed for package offsets normal to its axis ($S_Z = 0$), and triangles have been used for package offset parallel to its axis ($S_X = 0$). Solid symbols have been connected with lines to represent results for simulations performed with nominal mesh and parameter values, and open-symbols with labels (x,f,+ or -) have been used to indicated non-nominal values. Figure 9a shows that non-nominal parameter values affect the cladding time of concern by less than 2 hours.

The cladding time of concern increases as the package is moved away from the center. In this work, safe distances, W_X and W_Z, are the minimum values of S_X and S_Z for which the fuel does not reach its burst rupture temperature (T_{BR}) in an infinitely long-lasting fire. Calculations performed in this work predict that for a 12-m-diameter fuel pool, the cladding safe distance is $W_X \leq 5.4$ m, and $W_Z \leq 6$ m. Based on these simulations, if the package center is 6 m from the pool center (near the pool perimeter), then this fire will not cause the cladding to reach its temperature of concern, no matter how long the fire lasts.

(a)

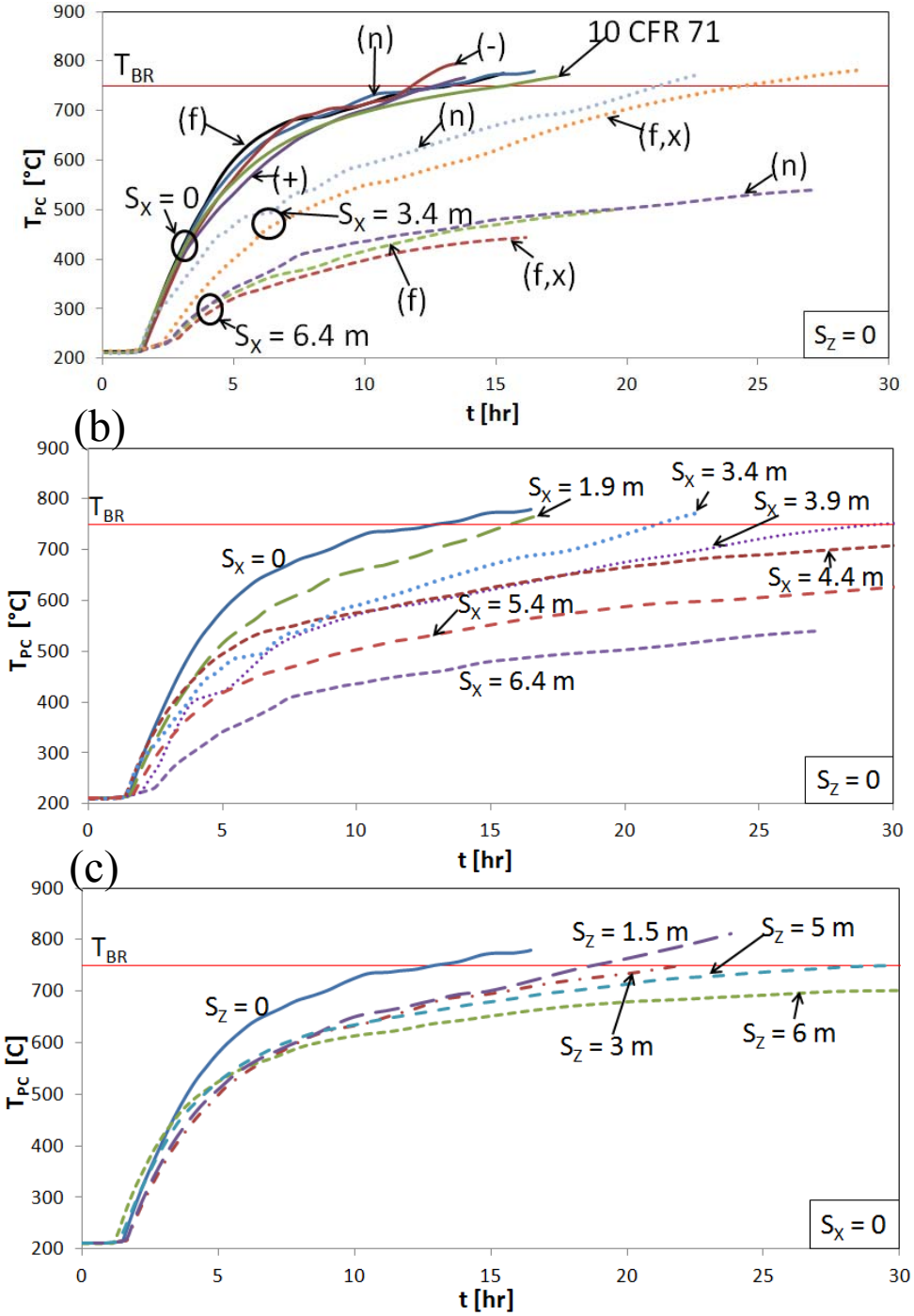

Figure 8: Peak fuel cladding temperature response to CAFE fires (a) Temperature versus time for $S_X = 0$, 3.4 and 6.4 m ($S_Z = 0$), for nominal and non-nominal parameter values and mesh refinements. (b) Temperature versus time for different values of S_X ($S_Z = 0$), for nominal parameter values and mesh refinements. (c) Temperature versus time for different values of S_Z ($S_X = 0$), for nominal parameter values and mesh refinements.

The time of concern versus standoff distance for the seal, gamma shield, and neutron shield has been shown in Fig. 9(b,c,d). These times of concern are considerably shorter than the times of concern for the cladding. This is because the temperature of concern for the cladding is

significantly higher than those for the other components, and the cladding is much further from the package surface than the other components. The 800°C-regulatory-format simulations predict times of concern that are generally closer to the CAFE results than the 1000°C regulatory-format simulations. A detailed description of the times of concern predicted for the package seal, gamma shield and neutron shield will be included in future work.

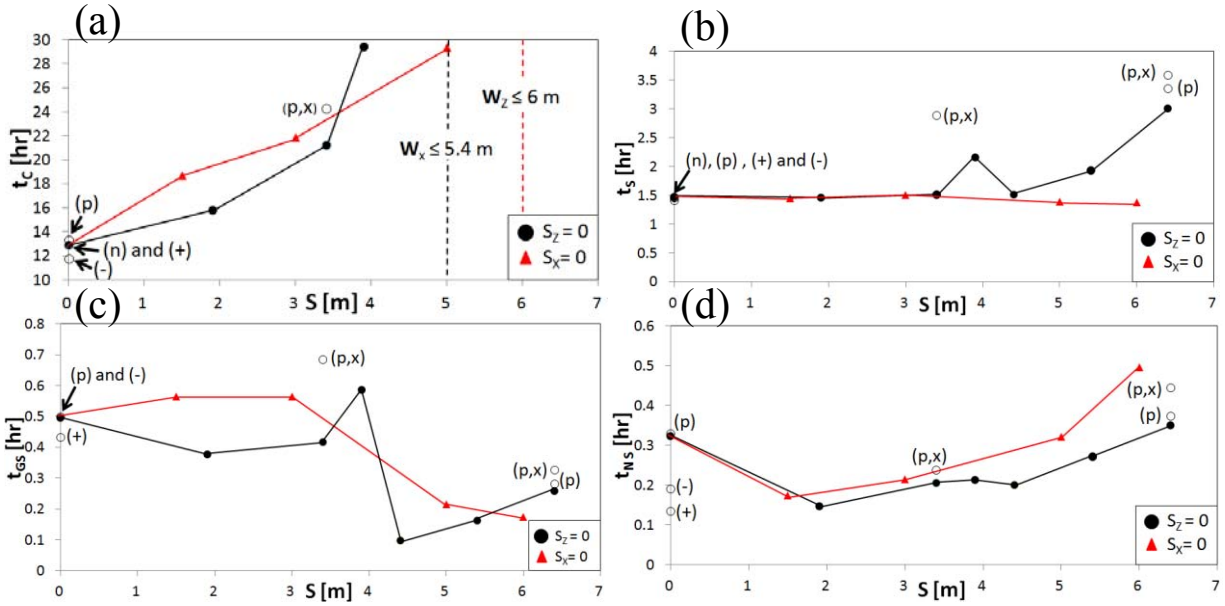

Figure 9: Fire time of concern versus standoff distance for nominal and non-nominal parameters and mesh refinements (a) Fuel cladding (b) Package seal (c) Gamma shield (d) Neutron shield

SUMMARY

The objective of this study was to determine the fire times of concern for the fuel cladding, seal, lead gamma shield, and liquid neutron shield of the SNF transportation package, for different package locations relative to the fire center under no wind conditions. In order to do this, a three-dimensional model of the NAC-LWT model was constructed using ANSYS Parametric Design Language (APDL) to predict the response of package to normal conditions of transport (NCT) and hypothetical accident conditions (HAC). NCT analysis predicted that the package has a maximum temperature of 210°C located at the center of the fuel assembly. The results predicted by this model were in good agreement with PNNL's results. The NCT calculation was used as an initial condition for HAC fire simulations conducted using 10CFR71 regulatory format and CAFE fire simulator code. The regulatory format simulations used a constant fire temperature of 800°C and 1000°C. These calculations predicted that the time of concern of the fuel cladding (t_C) to reach its possible burst rupture temperature (750°C) was 15.4 hrs and 5.1 hrs for these fire temperatures, respectively, assuming a package surface emissivity of 0.8 and fire emissivity of 0.9. The three dimensional model of NAC-LWT package was linked with CAFE to test its response to a 12-m-diameter JP8 pool fire with different package locations with respect to the center of the fuel pool. CAFE simulations predicted that when the package was centered over the pool, t_C was between 11.8 and 13.3 hours, depending on the modeling parameter values and mesh refinement. As the package was moved away from the pool center, t_C increased. Simulations were performed for various displacements normal and parallel to the package axis. It was determined that the cladding did not reach its temperature of concern when the package center was 6 m from the pool center (above the pool edge), even in infinitely-long-lasting fires.

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