Response of a Spent Nuclear Fuel Transportation Package to Regulatory Format Thermal Events

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INTRODUCTION

The objective of this work is to compare the response of intact and damaged versions of the 125-ton Multi-Purpose Canister (MPC) rail package conceptual design (OCRWM 1993) to a range of regulatory format fire/post-fire events. In this work we determine the critical fire duration which causes the spent fuel cladding to reach a containment-integrity temperature limit for a relevant range of fire temperatures and external neutron shield damage levels (Fischer et al. 1987). The sensitivity of these critical-duration versus fire temperature envelopes to differing assumptions regarding the fuel region effective thermal conductivity, and the fuel cladding containment-integrity critical temperature, is also determined. The resulting performance envelopes are compared to the conditions of the half-hour, 800^0C regulatory fire specified in 10-CFR.71 (US NRC 1992).

COMPUTATIONAL MODEL

Figure 1 shows the finite element model of an intact 125-ton MPC rail package used in this work. This cask is configured to carry 21 spent pressurized water reactor fuel assemblies. This two-dimensional, pie-shaped region represents one-eighth of the round package cross section. The horizontal and diagonal edges represent lines of symmetry within the package. The curved surface is the outer skin of the package, and the left hand corner is the package center.

The left-hand portion of the model represents the MPC. It includes a stainless steel/borated aluminum fuel basket, spent fuel, and a stainless steel shell. The outer transportation cask consists of a stainless steel inner liner, depleted uranium and lead gamma shield, a thick stainless steel shell, a neutron shield with radial stainless-steel and copper fin/stiffeners, and an outer stainless steel skin. Helium gas fills the void spaces between the fuel and fuel basket, the basket manufacturing gaps, between the fuel basket and the MPC shell, and between the MPC shell and transportation cask inner liner.

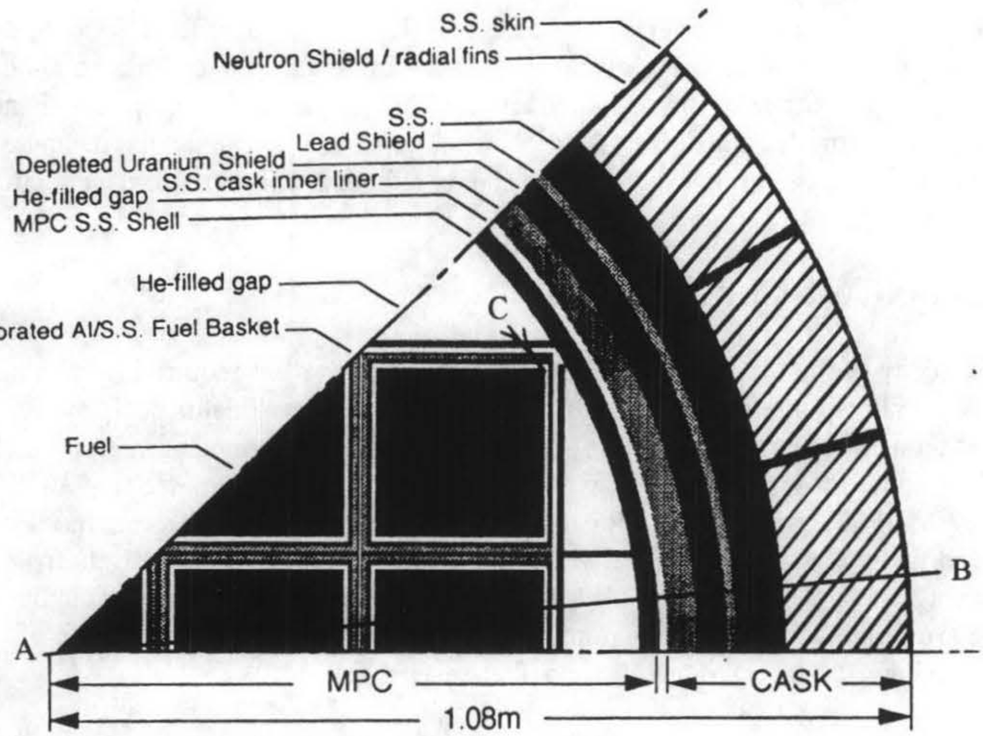

Figure 1. Finite element model of an intact 125-ton MPC rail package configured for 21 spent pressurized water reactor fuel elements.

The following thermal boundary conditions define the "regulatory format" fire and post-fire thermal events which are used in this paper. Initially, the package is assumed to operate at steady state under normal conditions of transportation (38^{0}C ambient air, 388 W/m^2 insolation). It is then exposed to a fully engulfing thermal radiation environment for a specified duration and with a given temperature. This environment is assumed to have an effective emissivity of 0.9, and the cask skin is assumed to have an absorptivity of 0.8. After the fire period, the external boundary conditions return to the initial environment. These regulatory format conditions are an extension of the regulatory half-hour, 800^{0}C fire test in that simulations are performed for a range of fire durations and temperatures.

Simulations are also performed for a cask whose external neutron shield and skin are completely destroyed moments before the thermal event begins. In these damaged-cask simulations, the same finite element model shown in Figure 1 is used except that the neutron shield, radial fin/stiffeners, and outer skin are removed. The initial temperature distribution determined for the intact package is used in the remaining regions of the cask. The regulatory format thermal boundary conditions are applied directly to the outer surface of the thick stainless steel shell.

Transient thermal conduction in the package solid structure and helium-filled regions is simulated using the commercial finite element computer code ANSYS (Swanson Analysis Systems 1993). Radiation heat transfer across the interior helium spaces is included in the simulations, but natural convection is neglected. Heat of fusion effects for potential melting and solidification phase change within the aluminum and lead cask components are neglected. The change in thermal conductivity of these materials with phase change is included in the model. Each fuel assembly is modeled as a smeared solid having uniform volumetric heat generation (3620 W/m^3) and an effective, temperature-dependent thermal conductivity.

MODELING ASSUMPTIONS

The majority of the temperature dependent material properties required to calculate the cask thermal response under regulatory format events are well defined. However, the critical temperature at which zircaloy fuel cladding loses containment integrity under accident conditions is not well known. Values in the literature vary from 593^{0}C (OCRWM 1993) to 740^{0}C (Sandoval et al. 1986). Furthermore, different models of the smeared fuel region produce different effective thermal conductivities. Data from E-MAD dry storage tests (Unterzuber et al. 1982) give temperature-dependent conductivities which are roughly four times greater than those from the analytical evaluation of Manteufel and Todreas (Manteufel and Todreas 1994).

In this work, the following assumptions are employed for evaluating baseline thermal performance envelopes of intact and damaged MPC rail packages: (1) the effective fuel region thermal conductivity is evaluated from the Manteufel and Todreas model, and (2) the higher, 740^{0}C, zircaloy cladding critical temperature is employed. To evaluate the sensitivity of the cask performance envelopes to these modeling assumptions, alternate envelopes are calculated using the E-MAD effective thermal conductivity, and the lower, 593^{0}C, critical cladding temperature.

THERMAL SIMULATIONS

Line A-B in Figure 1 passes through each cask component from the center of the cask to the edge. Figure 2 shows two temperature profiles calculated along this line. Both profiles are for normal conditions of transportation, but they employ the two different fuel region effective thermal conductivity models. We see that for both models, the maximum cask temperature resides at the center of the fuel region. Both profiles have three humps which correspond to the three fuel regions which are traversed by line A-B. The temperature profiles decrease rapidly in the large helium-filled gap between the fuel basket and MPC shell. It decreases more slowly in the metal portions of the MPC and outer package, and then decreases rapidly in the low thermal conductivity region of the neutron shield.

The maximum fuel cladding temperature from the simulation employing the Manteufel and Todreas model is 270^{0}C, while the maximum from the E-MAD data is 257^{0}C. Both of these cladding temperatures are well below the allowable temperature of 340^{0}C for transporting fuel stored for 10 years. The fuel basket borated aluminum has a thermal conductivity which is 50 to 200 times larger than either of the two fuel region models, and

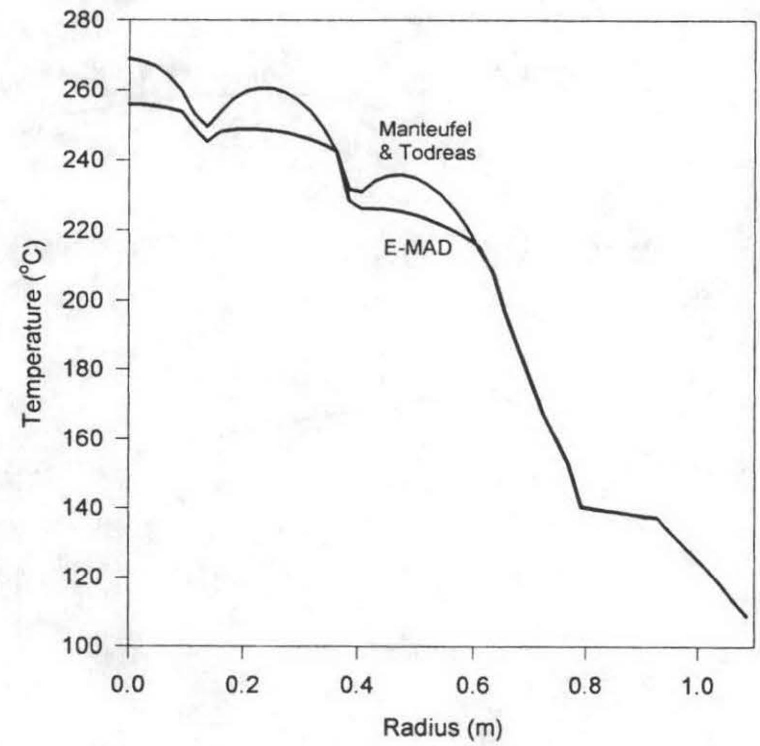

Figure 2. Normal conditions of transportation temperature profiles calculated along Line A-B in Figure 1. Profiles are calculated using the two different fuel region thermal conductivity models discussed in this paper.

therefore dominates the effective thermal conductivity of the fuel/fuel basket mixed region. Despite the factor of four difference in fuel region effective thermal conductivity from these two models, the choice of fuel model has a very small effect on the resulting maximum temperature under normal conditions of transportation.

We now consider the transient cask response to a regulatory half-hour, 800^0C fire. Figure 3 shows the temperatures of the fuel region center (left hand corner of Figure 1, labeled "A") and at the upper right-hand corner of the fuel region (labeled "C"), as functions of time, during and after the fire. A vertical line indicates the duration of the fire. We see that the center and corner fuel temperatures in this massive cask are unaffected during the fire. In the post-fire period, the corner temperature is seen to respond first and the center temperature begins to climb at a later time. For the regulatory test, the maximum temperature experienced within the fuel region is located at the center of the cask, and occurs 17.8 hours after the fire is extinguished. The maximum temperature is 304^0C, which is well below the baseline critical value of 740^0C.

Simulations are run for longer lasting 800^0C fires to determine the minimum duration which causes the fuel cladding temperature to reach 740^0C. Using a trial and error technique, we find that this fire must last 22.1 hours for the cladding to reach 740^0C.

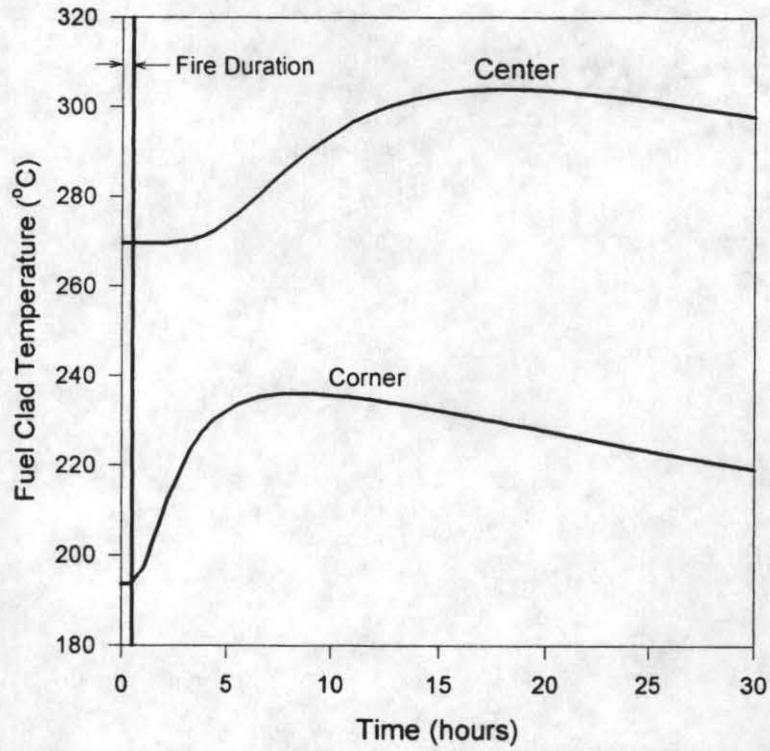

Figure 3. Center and corner fuel cladding temperatures versus time during and after a regulatory 800^{0}C, half-hour regulatory fire test.

PERFORMANCE ENVELOPES

The trial and error search technique described in the last section is used to determine the critical fire duration for a range of fire temperatures. In Figure 4, the curve marked "Intact" and "T_C = 740^{0}C" shows the performance envelope for an intact cask assuming the cladding critical temperature is 740^{0}C. As expected, very low temperature fires are not capable of causing the fuel cladding temperature to reach its limit, no matter how long they last. A steady-state thermal analysis is used to determine the maximum temperature reached by the fuel cladding during "infinitely long" lasting fires. This analysis is performed for a range of fire temperatures, and it shows that a regulatory format fire must have a temperature of at least 657^{0}C to cause the cladding in an undamaged cask to reach 740^{0}C. The critical fire duration decreases rapidly as the fire temperature increases above the asymptotic value of 657^{0}C. For example, a 1300^{0}C fire causes the fuel cladding to reach 740^{0}C it if lasts 7.0 hours.

The curve in Figure 4 marked "Damaged" and "T_C = 740^{0}C" shows the performance envelope of an MPC whose neutron shield is destroyed moments before the thermal event begins. A fire must have a temperature of at least 675^{0}C to cause the fuel cladding to reach its critical temperature. The critical duration of a 1300^{0}C fire is only 1.4 hours, roughly five times less than for the intact package. We see that the intact package provides far better cladding protection (exhibits larger critical durations) against high

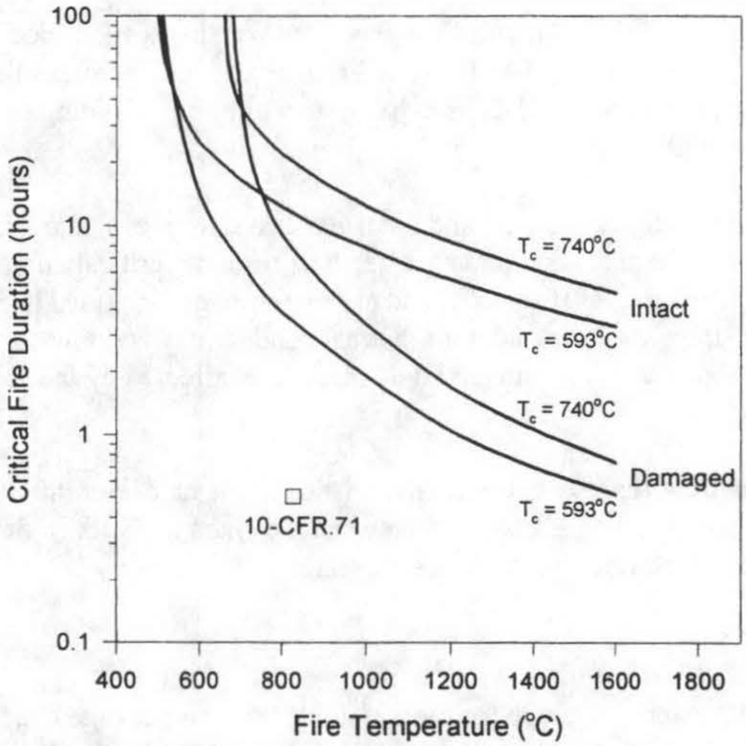

Figure 4. Critical fire duration versus fire temperature for intact and damaged versions of the 125-ton MPC rail package conceptual design subject to regulatory format thermal events. These performance envelopes are presented for cladding containment-integrity critical temperatures of 740^{0}C and 593^{0}C, and employ the Manteufel and Todreas fuel region thermal conductivity model.

temperature fires than the damaged package. This is expected since the neutron shield insulates the package from the incoming fire heat flux.

We note that the intact and damaged performance envelopes cross at a temperature of roughly 700^{0}C. At first it may seem surprising that the damaged package actually provides longer lasting cladding protections for fires in the temperature range 657^{0}C to 700^{0}C. To understand this behavior, we note that the forty-or-more-hour critical fire durations at these low fire temperatures bring the cask to near steady-state thermal conditions. Under steady-state conditions, the net heat flow is *out* of the cask. The thermal insulation of the neutron shield inhibits heat flow to the environment, increasing the temperature of the fuel compared to the case if no neutron shield were present.

VARIATION OF MODELING ASSUMPTIONS

The curves in Figure 4 marked "T_C = 593^{0}C" are the calculated thermal performance envelopes of intact and damaged packages assuming the critical temperature is 593^{0}C. Simulations for these curves employ the Manteufel and Todreas fuel thermal conductivity model. For fire temperatures above 800^{0}C, the critical duration for a given fire temperature is decreased by a factor of roughly 1.5. We also see that decreasing the critical cladding temperature by 147^{0}C, from 740^{0}C to 593^{0}C, decreases the asymptotic fire temperature (the minimum which is capable of causing the cladding to reach its critical temperature) by roughly 180^{0}C.

The performance envelopes of intact and damaged casks are reevaluated using E-MAD fuel region effective thermal conductivity data. The resulting critical durations differ from the curves in Figure 4 by less than 15%, and are therefore not included in the figure. As described earlier, the center cask mixture thermal conductivity is dominated by the properties of the borated aluminum, and only marginally affected by the fuel region conductivity.

The square in Figure 4 represents the characteristics of the half-hour, 800^{0}C regulatory fire. A wide margin of safety is observed between the characteristics of the regulatory fire and all the thermal performance envelopes presented in this paper.

CONCLUSIONS

The thermal performance envelope for the 125-ton MPC rail package conceptual design, subjected to regulatory format thermal events, is significantly affected by the presence of the external neutron shield, especially at high fire temperatures. If the assumed fuel cladding containment-integrity temperature limit is decreased from 740^{0}C to 593^{0}C, then the calculated critical fire duration for the cladding to reach its critical temperature decreases by a factor of 1.5 for fire temperatures above 800^{0}C. Furthermore, the minimum asymptotic fire temperature is decreased by roughly 180^{0}C. All of these envelopes are essentially insensitive to the fuel region thermal conductivity model employed. The wide margins of safety between the conditions of the 10-CFR.71 test and all of the performance envelopes indicates that the 125-ton MPC conceptual design adequately protects the fuel cladding under regulatory fire conditions, regardless of the modeling assumptions employed.

The performance of the MPC rail package has been evaluated for *regulatory format* fire and post-fire conditions. These conditions are an extension of the regulatory test to a range of fire temperatures and durations. These conditions are well defined and therefore useful for comparing the performance of intact and damaged packages using different modeling assumptions. However, the fully engulfing condition, as well as the thermal emissivity and absorptivity assumptions of the regulatory format thermal event, may be substantially different from actual conditions encountered in transportation accidents. Caution should therefore be exercised before comparing accident data to the results of the present work.

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