I. INTRODUCTION

The objective of this work is to evaluate the response of intact and damaged versions of the GA-4 Legal Weight Truck Cask\(^1\) to a range of regulatory format fire/post-fire events. Specifically, we determine the envelopes of fire durations which cause the spent fuel cladding to reach containment-integrity temperature limits for a relevant range of fire temperatures\(^2\). Moreover, the sensitivity of the calculated performance envelopes to different fuel cladding critical temperatures is evaluated. This article is the first of a two part series. Part 2 determines fire conditions which compromise the GA-4 containment seal performance\(^3\).

II. DESCRIPTION OF WORK

Figure 1 shows the finite element model of the 27.5-ton GA-4 Legal-Weight Truck Cask used in this work. This two-dimensional model represents one-quarter of the package cross section. The left-hand and bottom edges are lines of symmetry within the package, and the remaining surfaces are the package outer skin.

The GA-4 is designed to carry four spent, pressurized water reactor (PWR) fuel assemblies. The spent fuel assembly in the quadrant shown in Fig. 1 is represented by the square region located near the bottom left-hand corner. The fuel assembly is surrounded by a helium gap. To the left and below the gap is a stainless steel/B,\(_{\text{C}}\) support structure, while the stainless steel cask inner liner is located above and to the right. Moving outward from the liner (to the right and upward), we see a depleted uranium gamma shield, the stainless steel cask body, a polypropylene-1\% boron neutron shield with aluminum radial stiffeners, and finally, a stainless steel outer skin. In this study, the tubular aluminum stiffeners within the GA-4 neutron shield are replaced by equivalent-volume planar structures to allow the use of a two-dimensional model.

The following thermal boundary conditions are used to evaluate the cask performance. Initially, the package is assumed to operate at steady state under normal conditions of transportation (38\(^\circ\)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 fire 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 10-CFR.71 half-hour, 800\(^\circ\)C regulatory fire test\(^4\) in that simulations are run for a range of fire durations and temperatures. We note that the fully-engulfing conditions and thermal emissivity and absorptivity assumptions of regulatory format thermal events may be substantially different than those of historical or probable transportation accidents.
Simulations are also performed for a cask whose neutron shield and skin are completely destroyed moment before the thermal event begins. These damaged-cask simulations use the same finite element model shown in Fig. 1 except that the neutron shield, radial stiffeners and outer skin are removed. The initial temperature distribution determined from the intact package is used in the remaining regions of the cask.

Transient thermal conduction in the package solid structure and helium-filled region is simulated using the commercial finite element computer code ANSYS®. Radiation heat transfer across the interior helium gap is included in the simulation, but natural convection is neglected. Potential melting within the aluminum stiffeners is neglected in this study. The fuel assembly is modeled as a smeared solid having uniform volumetric heat generation (3620 W/m³) and an effective, temperature-dependent thermal conductivity¹.

The majority of material properties required to calculate the cask thermal performance under regulatory format thermal events are well defined. However, the critical temperature, $T_C$, at which zircaloy spent fuel cladding loses containment integrity is not well known. Values in the literature⁶,⁷ range between 593°C and 740°C. Separate performance envelopes of intact and damaged packages are therefore calculated using both of these critical temperatures.

III. RESULTS

Figure 2 shows the temperatures at the center of the fuel region (bottom left-hand corner of Fig. 1) and at the upper right-hand corner of the fuel, as functions of time during and after a regulatory half-hour, 800°C fire test. A vertical line indicates the duration of the fire. 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 7.1 hours after the fire is extinguished. The maximum temperature is 200°C, which is well below the baseline critical value of 740°C.

Computer simulations are run for longer lasting fires to determine the minimum duration which causes the fuel cladding temperature to reach its limit. Using a trial and error technique, we find that an 800°C fire must last for 10.4 hours. This trial and error technique is repeated for a range of fire temperatures. The curve marked “Intact” and “$T_C = 740^0$C” in Fig. 3 shows the critical fire duration as a function of fire temperature for an intact GA-4, assuming the cladding critical temperature is 740°C. A steady state analysis shows that fires with temperatures below an asymptotic value of 715°C are not capable of causing the cladding to reach 740°C, no matter how long they last. We see from Fig. 3 that the critical duration decreases rapidly as the fire temperature increases above 715°C. The critical duration is only 3.0 hours for a fire temperature of 1300°C.

The curve marked “w/o NS” and “$T_C = 740^0$C” shows the thermal performance envelope for a package whose neutron shield is destroyed moments before the thermal event begins. The critical duration for a 1300°C fire is
only 0.29 hour, roughly ten times less than the intact-cask critical duration at the same fire temperature.

The line marked “MPC” in Fig. 3 is the thermal performance envelope of an intact 125-ton Multi-Purpose Canister (MPC) rail package, assuming the critical cladding temperature is 740°C. This package is configured to carry 21 PWR assemblies. The MPC provides better (longer lasting) cladding protection against high temperature fires than the GA-4 since it is much more massive and therefore has a much slower thermal response for a given thermal input. For fire temperatures below 730°C, however, the GA-4 provides longer lasting fire protection. This is again due to the larger size of the MPC. Steady state conditions are approached in the long duration fires relevant at low temperatures. Under steady state conditions, in a given temperature environment, the innermost fuel elements are hotter in the MPC than they are in the GA-4.

The “Intact” and “w/o NS” curves marked with “Tc = 593°C” are the performance envelopes if the lower critical cladding temperature is assumed. Reducing the critical temperature by 147°C decreases the asymptotic fire temperature (below which a fire cannot cause the fuel cladding to reach its critical temperature) by 155°C. For a fire temperature of 1300°C, the intact and damaged cask critical durations are decreased by roughly one third compared to the critical durations evaluated for Tc = 740°C.

The square in Fig. 3 indicates the characteristics of the half-hour, 800°C regulatory fire. A margin of safety is observed between the characteristics of the regulatory fire and all of the presented GA-4 performance envelopes.

IV. CONCLUSIONS

The calculated thermal performance envelope for the 27.5-ton GA-4 is significantly affected by assumptions regarding the critical fuel cladding temperature and the neutron shield damage level. The margins of safety between the conditions of the 10-CFR.71 test and all of the performance envelopes indicate that the GA-4 adequately protects the fuel cladding under regulatory fire conditions, regardless of the modeling assumptions employed. Part 2 of this series of papers addresses the GA-4 containment seal performance.

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REFERENCES


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