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October 27, 2005

Allen Hansen, Thermal Engineer
Criticality, Shielding and Heat Transfer Section
Spent Fuel Project Office
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20005-0001

RE: Federal Register Notice of Availability, Documents Regarding Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario

Dear Mr. Hansen:

The State of Nevada Agency for Nuclear Projects requests a 60 day extension of the public comment period for review of Documents Regarding Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario, as published in the Notice of Availability, Federal Register, September16, 2005.

Our agency continues to study the implications of the July 2001 Baltimore Tunnel Fire for spent nuclear fuel transportation. With this email, we are sending, for your information, a recent memorandum summarizing our study approach. We are also sending you a paper prepared by one of our contractors evaluating truck cask response to a severe fire patterned after the Baltimore Tunnel Fire. We previously provided these documents to the National Academy of Sciences committee which is preparing a report on spent fuel transportation.

We intend to submit detailed comments on your draft report and on your supporting documents when our contractors complete their reviews. At this time we note for the record that your draft report (NUREG/CR-Draft PNNL-15313) fails to reference our previous analyses of the Baltimore Tunnel Fire. Your draft report also fails to reference the discussion of the Baltimore Tunnel Fire in the U.S. Department of Energy Final Environmental Impact Statement for a Geologic Repository at Yucca Mountain as well as a number of relevant recent studies of shipping cask response to severe fire environments.

Thank you for your consideration.

Sincerely,

Robert R. Loux
Executive Director

RRL/cs
Attachments
cc Governor Guinn
Nevada Congressional Delegation
Earl Easton, NRC

Attachments

Attachment 1

Date: July 14, 2005
To: Bob Loux, Executive Director, Nevada Agency for Nuclear Projects
From: Bob Halstead, Transportation Advisor
Subject: Update on Baltimore Tunnel Fire Studies

Almost four years to the day (July 18, 2001) since a CSX freight train derailed and caught fire in the Howard Street Tunnel, Baltimore, Maryland, the cause of the derailment and the details of the resulting fire are not fully known, and the implications for nuclear waste transportation safety are still a matter of heated debate. At least five papers on this subject will be presented at a technical conference in Denver next week.

Our consultants believe that the burning tripropylene tanker in the tunnel created a fire environment at least equivalent to an engulfing, regulatory fire (30 minutes at 1475°F or 800°C) for a period of three to six hours. Such a fire, according to Sandia National Laboratories (NUREG/CR-6672, Section 6) could cause truck casks, and some rail casks, to fail (defined as significant elastomeric seal degradation at 350°C, and fuel rod failure by burst rupture at 750 °C), allowing release and dispersion of radioactive material to the environment. The principal concern in such a fire is the thermal failure of the cask lid seal, creating a pathway for radioactive cesium (Cs-134, Cs-137) to escape in a respirable aerosol, and the subsequent dispersion of radioactive cesium in the plume of smoke from the fire.

The 2001 analysis prepared by Radioactive Waste Management Associates for the State of Nevada estimated that a spent fuel cask subjected to the Baltimore fire could have released more than 70,000 curies of Cs-134 and Cs-137. A release of that magnitude could cause hundreds to thousands of latent cancer fatalities, contaminate an area of about 82 square kilometers, and cost $13.7 billion to cleanup. The 2002 DOE Final EIS for Yucca Mountain identifies the conditions reported for the Baltimore fire as "similar to the conditions for a Case 20 accident," the maximum reasonably foreseeable rail accident evaluated in the FEIS, which results in release of radioactive material and 5 latent cancer fatalities in an average urban area. (FEIS, J-59, CR8-388)

For the past three years, Nevada consultant studies have focused on analysis of cask performance in long-duration fires, rather than on the Baltimore fire itself, and on cask testing. We did this for two reasons. First, we were waiting for the National Transportation Safety Board (NTSB) to complete its investigation of the Howard Street Tunnel fire, thus providing an "official" report on the fire. Secondly, we wanted to demonstrate how cask failure thresholds should be evaluated in full-scale testing, preferably as part of the U.S. Nuclear Regulatory Commission (NRC) Package Performance Study (PPS).

At least five government agencies have studied the July 2001 CSX freight train derailment and fire, in the Howard Street Tunnel: the State of Nevada Agency for Nuclear Projects; the NRC; the U.S. Department of Transportation (DOT), Intelligent Transportation Systems Office and Volpe National Transportation Center; the Federal Emergency Management Agency (FEMA) U.S. Fire Administration; and the NTSB.

Following an extensive investigation, NTBS issued its final statement (R-04-15 & 16), a safety recommendation, on January 5, 2005. NTSB "could not find convincing evidence to provide a probable cause for the accident … ." A New York Times article (January 14, 2005, A13) by Mat Wald reported that NTSB could not make a determination "because the evidence had been destroyed by fire, a flood from a broken water main and the heavy equipment that cleaned up the mess." The NTSB also declined to provide a detailed fire history. Thus there is not, and probably never will be, an "official" report on the cause and history of the fire. (However, additional studies may be conducted to support litigation between the City of Baltimore and CSX.)

The NRC analysis of the Baltimore fire, directed by Chris Bajwa, was published in 2002 and presented to the Commission in January, 2003. (SECY-03-0002) The NRC developed its own estimate of the fire characteristics, using a model developed by the National Institute of Standards and Technology (NIST). The NRC estimate of the fire differs from ours in several important respects that determine the final analysis of cask performance: NRC concluded that the peak temperatures of 800°C had a maximum duration of about three hours; NRC concluded that the peak temperatures were restricted to a small region of the tunnel, directly over the hottest region of the fire, where flames were directly impinging upon the tunnel ceiling and walls; and NRC concluded that the cask would have to be at least 5 meters (16.4 feet) distant, and most likely 20 meters (65.6 feet) distant, from the hottest region of the fire. Nevada's fire experts have identified deficiencies in the fire model used by NRC (this was the model developed by NIST under circumstances that led to the NRC Inspector General inquiry) and have challenged other NRC assumptions and conclusions.

The NRC selected for its performance evaluation a large rail cask (similar to the HOLTEC HI-STAR) with the spent fuel contained in a welded multipurpose canister (MPC) inside the cask. This was an inappropriate selection for two reasons. First, an MPC transporter system is inherently less vulnerable to fire damage than other casks, because the welded canister provides an additional (and extra-regulatory) barrier to any release of radioactive material. Other NRC-certified casks would be expected to lose containment much more quickly in a severe fire. Second, DOE has repeatedly stated that no welded canisters of spent nuclear will be accepted at Yucca Mountain. NRC, therefore, evaluated a cask design that DOE says will not be used for Yucca Mountain shipments. Additionally, DOE used a two-dimensional cask model in its thermal analysis, and focused on the short-term thermal limit for fuel cladding (570°C) as its failure mode.

The first round of NRC analyses concluded, not surprisingly, that there would have been no release of radioactive materials from the rail cask with MPC subjected to the Baltimore fire. NRC has prepared more analyses of different cask designs. We are preparing to review these analyses after they are presented at the 2005 ASME Pressure Vessels and Piping Conference in Denver next week. During FY 2006 our consultants will prepare a detailed critique of the NRC body of work on the Baltimore fire.

The current status of the NRC PPS is unclear. According to a presentation by Larry Camper at Waste Management 05, the NRC has decided against any full-scale fire testing as part of the PPS. However, the documents cited by Camper are not presently available on the NRC PPS website. Our cask performance studies continue to support regulatory testing (sequential drop, puncture, fire, and immersion tests) of each cask design prior to NRC certification or DOE procurement; and extra-regulatory fire testing of selected casks and components, coupled with additional computer simulations, to determine cask failure thresholds.

The prepublication paper (attached) by Prof. Miles Greiner, et al, reports temperatures of concern for key components (seal, gamma shield, basket, and fuel) of a NAC-LWT truck cask subjected to a three-hour duration fire. Prof. Greiner and his associates will soon begin a similar analysis of the GA-4 truck cask in a three-hour fire. As funds become available we hope to sponsor comparable studies of at least two rail casks.

Thermal analysis of legal-weight truck (LWT) casks in three-hour fires is timely, considering the recent interest in shipping spent fuel to Yucca Mountain in LWT casks on railcars. This is another reason for extra-regulatory fire testing. LWT casks could encounter longer duration fires in rail accidents than in highway accidents.

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THERMAL PROTECTION PROVIDED BY IMPACT LIMITERS TO CONTAINMENT SEAL WITHIN A TRUCK PACKAGE

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ABSTRACT

The Container Analysis Fire Environment computer code is used to simulate the response of a truck package designed to transport one PWR fuel assembly to 7.2-m-diameter pool fires. Simulations are performed with the package centered over the fire, and offset axially from that location by 1 and 2.5 m. In all simulations the package body is 1 m above the fuel pool. The simulations predict the package containment seal exceeds its temperature of concern for all three package locations. Simulations of a no-impact-limiter version of the package are also performed to quantify the level of thermal protection provide by the limiter. The minimum fire duration that causes the seal to reach its temperature of concern is determined for each configuration. When the center of the no-impact limiter package is within 2.5 m of the pool center, fires shorter than 0.7 hour are capable of causing the seal to reach its temperature of concern. By contrast, the intact package protects the seal in fires that last roughly 2 hours. These results will help risk analysts better understand the effect of package position and the role of the impact limiters on accident consequences.

INTRODUCTION

Federal regulations require packages that transport large quantities of radioactive materials (Type B packages) to withstand a test sequence consisting of a 10-m drop onto an unyielding surface, a 1-m drop onto a puncture pin, and a 30-minute fully-engulfing fire [10CFR71, U.S. Nuclear Regulatory Commission, 2000]. Damage sustained from each event is not repaired before initiation of the subsequent event. At the conclusion of this sequence, the containment, shielding and criticality functions of the package must be maintained. This sequence is estimated to be more severe than 99.4% of all transportation accidents [Fischer et al., 1987]. However risk assessment studies must consider both more and less severe accident scenarios that are possible during transport campaigns [Sprung et al., 2000].

The performance of packages under severe conditions is evaluated by both testing and analysis. Analyses typically monitor the temperatures of the containment seal, gamma shield, fuel cladding, and other important components during and after a simulated fire to determine if they reach temperatures of concern. The results of these simulations are somewhat dependent on the package and fire models employed in the calculations.

The 10CFR71 regulations specify a simple model for large, fully-engulfing fires. This model employs a specified fire temperature of 800°C and effective fire emissivity of 0.9 [U.S Nuclear Regulatory Commission, 2000]. This type of model is easily linked to finite element models of a package, and the linked package response calculation produces results with relatively short computer turnaround times. However, this type of model generally does not include the effects that wind, the engulfed package itself, or other objects have on the fire.

The three-dimensional Container Analysis Fire Environment (CAFE-3D) computer code was developed at Sandia National Laboratories to simulate the response of transport packages to large hydrocarbon pool fires [Lopez et al., 2003]. CAFE-3D links a computational fluid dynamics (CFD) fire simulator to commercial finite element (FE) programs such as PATRAN or Ansys. CAFE-3D's fire simulator is identical to the Isis-3D CFD code [Greiner and Suo-Anttila, 2005]. It calculates the fire behavior and the heat transfer from the fire to the package. The FE code calculates the response of the package to the heat transfer. This includes the package surface temperature, which is used as a boundary condition for the fire simulator. To reduce computational time the fire simulator does not run continuously for the full fire duration. CAFE-3D only calls it to run for short durations to update the fire heat transfer at specified intervals.

The fire simulator (Isis-3D) is a general-purpose three-dimensional computational fluid dynamics code that is capable of utilizing highly refined computational meshes. However, it is also capable of employing semi-empirical combustion chemistry and radiation heat transfer models [Greiner and Suo-Anttila, 2005]. These models have been developed so that the code gives engineering-level accurate heat transfer results for large hydrocarbon pool fires even when relatively course computational grids are employed [Greiner and Suo-Anttila, 2004b]. Moderate-resolution Isis-3D simulations (less than 60,000 nodes) are relatively fast running. Risk and design studies require relatively fast running codes because they consider a large number of accident scenarios.

The combustion chemistry and radiation heat transfer models are theoretically based but employ parameters. The values of these parameters are determined from measurements in fires whose conditions are "relatively close" to those for which the models are used. The combustion chemistry model employs four separate reactions, two of which produce radiating soot. Reaction rate and soot production parameter values for this model are determined [Greiner and Suo-Anttila, 2005] by comparing Isis-3D simulations with experimental time dependent measurements of soot temperature and soot volume fraction at one location within a 6 m square JP8 pool fire under low wind conditions [Gritzo et al., 1998].

At each time step, the heat transfer model divides the computational domain into the diffusely radiating fire (which moves with time) and its non-participating environment. A minimum soot volume fraction parameter $f_{S,m}$ is used to define the edge of the fire zone. The version of Isis-3D that employs these combustion chemistry and heat transfer models is therefore only valid for fire from smoky fuels, such as liquid hydrocarbons in pools with diameters greater than 2 meters [Murphy and Shaddix, 2004].

Two large-scale fire tests were performed to acquire data to select the soot volume fraction parameter for the radiation heat transfer model [Kramer et al., 2003]. In that experiment a pipe calorimeter whose dimensions were roughly the same size as a legal-weight-truck package was suspended 1 m above the center of an outdoor 7.2-m-diameter hydrocarbon pool. The test facility was surrounded by a porous barrier to reduce the effect of wind. This type of wind fence is typically employed during regulatory testing. The calorimeter temperature and the wind conditions at two locations outside the wind fence were measured as functions of time during the 30-minute fire.

Are, Greiner and Suo-Anttila [2005] and Greiner and Chalasani [2004] performed simulations of the tests and developed a computational model of the wind fences. They determined that simulations employing the value $f_{S,m} = 0.5\times10^{-6}$ (0.5 ppm) gave results that agreed with the experimental measurements.

Greiner et al. [2004a] used the version of CAFE-3D with $f_{S,m} = 0.5\times10^{-6}$ to simulate the response of a generic truck package in different fires. The package dimensions and properties are similar to a currently-licensed legal weight truck package designed to transport one spent pressurized water reactor (PWR) fuel assembly [NAC International, 2000]. Simulations were performed with the package over the center of the fire, and shifted transverse to the package axis by 1 meter. In all simulations the package was placed at ground level. The ground level elevation and offset between the centers of the package and fuel source were considered more likely accident conditions than those specified in the 10CFR71 regulations. That study considered 30-hour fires to observe both the transient and steady state response of the package. That work estimates the time after the fire begins when the temperatures of the containment seal, gamma shield and fuel reach their respective temperatures of concern for each fire sizes and package locations.

In the current work CAFE-3D is used to simulate the response of the same truck package considered in the earlier Greiner et al. [2004a] work to three-hour fires. The package is suspended 1.07 m over the center of a 7.2-m-diameter hydrocarbon fuel pool. These are roughly the same elevation and pool size as the experiment used to determine the soot volume fraction parameter $f_{S,m}$ [Kramer et al., 2003]. The surrounding wind conditions and wind barriers of that experiment are also modeled in the current simulations. The pool size is larger than those considered by Greiner et al. [2004a], and nearly as large 10CFR71 specifies for regulatory testing of this package.

A sequence of simulations is performed for an intact package for normal transport, fire and post-fire conditions. To evaluate the effect of package location, simulations are performed with the package offset axially from that location by 1 and 2.5 m. For each configuration, the minimum fire duration that causes the containment seal to reach its temperature of concern is estimated. The simulations are repeated for a package whose impact limiters are not present. Events capable of removing an impact limiter are considered to be highly unlikely. However, these simulations are performed to evaluate the level of protection the limiters provide to the containment seal.

TRANSPORT PACKAGE MODEL

Figure 1 shows three-dimensional finite element (FE) models of intact and no-impact-limiter versions of a generic legal weight truck package. The intact package dimensions and material properties are similar but not identical to those of a currently licensed package [NAC International, 2000]. This

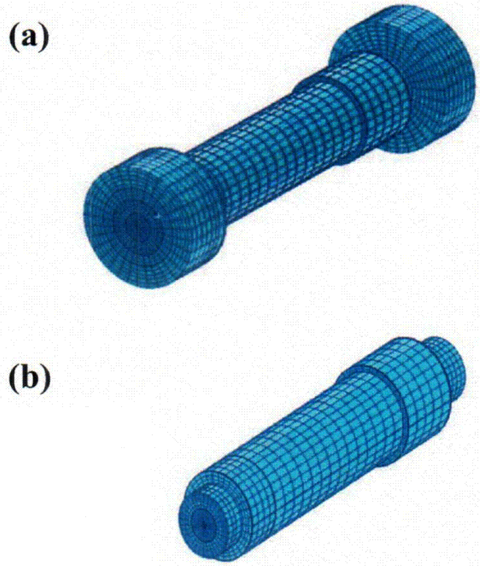


Fig. 1 Three dimensional package finite element models (a) Intact Package (b) No Impact Limiter Package

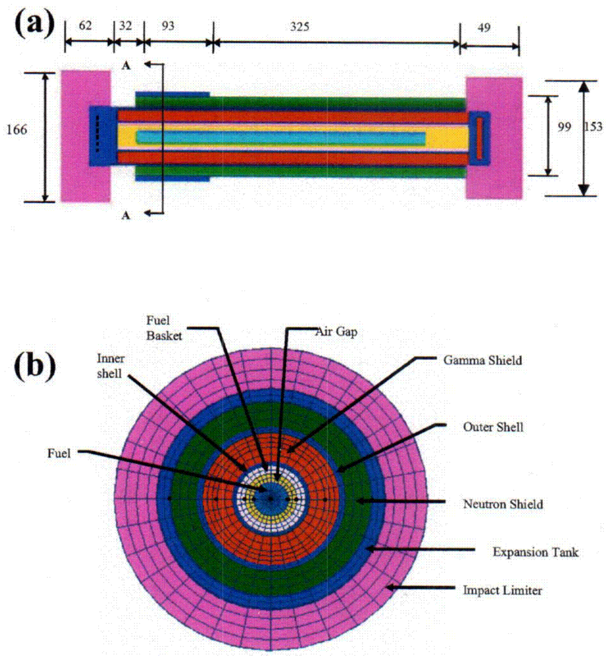


Fig. 2 (a) Axial and (b) Cross-sectional slice views of the intact package models. All dimensions are in centimeters. Material color code: blue = stainless steel, red = lead, green = glycol/water mixture or air, yellow = air, Cyan = Fuel, Dusty pink = Aluminum, Magenta = Honeycomb-Aluminum.

package model is identical to the one considered by Greiner et al. [2004a]

Figures 2a and 2b show axial and cross sectional slices through the intact package. The location of the cross section slice in Fig. 2b is shown in Figs. 2a as section AA. Regions in the figure are colored according to their material. Some interior components in the physical package have rectangular cross sections. However, they have been made round in the current work to allow the use of an axis-symmetric model.

The innermost cylinder with outer radius 8.5 cm and length 3.66 m represents the spent fuel payload. Its sides are surrounded by an aluminum basket with inner radius 12.7 cm and thickness of 4.1 cm. The gap on the sides and ends of the fuel are filled with air. A stainless steel containment vessel surrounds these components. The side wall thickness of this vessel is 1.9 cm. The vessel sides are surrounded by a 14.5 cm thick lead gamma shield. A 4.8 cm thick stainless steel cask body surrounds this shield. A 12.7 cm thick neutron shield tank surrounds the outer shell. This tank does not cover a 22.9 cm region on the left-hand-side of the containment vessel. The outer skin of the neutron shield is constructed of 0.635-cm-thick stainless steel.

The neutron shield tank contains an ethylene glycol/water solution during normal transport conditions before the fire simulation. During the fire and post-fire simulations this tank is assumed to contain only air. This is a standard practice for package analysis based on the likelihood of a puncture during accident conditions. It may also conservatively over predict the maximum temperatures experience by the package components. The outermost region of the main package body is an expansion tank for the neutron shield fluid. The tank is 5.7 cm thick, and its outer skin is constructed of 0.635 cm thick stainless steel.

A spent nuclear fuel assembly is loaded into the package by removing the impact limiter and bolted closure on the left-hand side of Fig. 2a. The massive stainless steel cylinder on this "closure" end consists of two parts. The first is a circular flange that is permanently attached to the package body. The second is a closure that is bolted to the flange. The axial location of a 45.2-cm-diameter elastomer gasket that seals the interface between the flange and this closure is shown in Fig. 2a using a dotted line. The cylindrical steel-lead-steel sandwich structure on the right-hand-side of Fig. 2a is permanently attached to the package body. This structure has a 7.6 cm thick, 52.8 cm diameter cylinder of lead encapsulated in a 26.7 cm thick, 72.6 cm diameter stainless steel cylinder.

Conduction heat transfer within the solid steel, lead and aluminum components and the air employ standard computational methods and material properties [Incropera and DeWitt, 1996]. Thermal effects of phase change (heat of fusion) are modeled for the lead gamma shield and the aluminum basket. The possible effects of flowing molten metal are not included. The impact limiters are made of aluminum honeycomb. Honeycomb properties vary significantly depending upon its density and cell configuration. We implement the honeycomb material properties used in the safety analysis report of another transport package [Westinghouse Electric Company, 2000].

The spent fuel region properties are based on one pressurized water reactor (PWR) fuel assembly. This fuel type is chosen because its maximum heat generation rate is 2.5 kW, which is the greatest of any payload considered in the NAC LWT transport package Safety Analysis Report [NAC International, 2000].

Under steady and quasi-steady state conditions, heat generated within the spent fuel assembly elevates its cladding temperature above that of the surrounding basket structure. This temperature rise is dependent on the heat generation rate and the thermal transport properties of the fuel assembly and backfill gas region. The transport properties are affected by both thermal radiation and natural convection. The radiative properties depend on the emissivity of the fuel cladding and basket walls, and the geometric configuration of the fuel pins. The backfill gas thermal properties and pressure as well as the fuel pin geometric configuration affect natural convection.

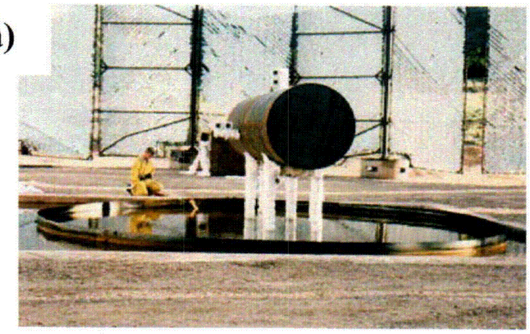
A highly simplified method for evaluating the temperature within the fuel/backfill gas region is employed in this work. The fuel region is modeled as a homogenous cylinder whose dimensions are similar to that of a pressurized water reactor (PWR) fuel assembly (see Fig. 2). The volume fractions of fuel, cladding and air within the fuel/backfill gas region were calculated. The effective density, specific heat and thermal conductivity for the cylinder are volume fraction averages of these three components. The total fuel heat generation rate is applied uniformly throughout the cylindrical volume.

The volume-averaged properties model some aspects of conduction heat transfer in the fuel/backfill-gas region. It is not currently known if this approach under- or over-predicts the conduction heat transfer rates. However, this analysis completely neglects the effect of natural convection and thermal radiation. Development of an accurate thermal model for spent nuclear fuel is outside the scope of this work. Further analysis is needed to more accurately understand and model heat transfer in this region [Manteufel and Todreas, 1994; Bahney and Lotz, 1996].

Under normal transport conditions, natural convection heat transfer in the liquid filled neutron shield tank is modeled as conduction using an effective thermal conductivity of 16.17 W/m-K [NAC International, 2000]. Air fills the gap between the fuel and the aluminum basket. Air also fills the interior of the neutron shield tank during the fire. Heat transfer across these air gaps is modeled as a combination of conduction through stagnant air and view factor radiation from surface to surface. The emissivity of the fuel region is 0.8, while the emissivity of the metal surfaces is 0.36 [NAC International, 2000].

In this work the temperature of several interior package locations are monitored during and after the simulated fire. The temperature of the seal is monitored at its top, bottom and both sides. The temperatures of several other components are monitored at the package midplane, roughly halfway between the two ends. The dots in Fig. 2b show the radial locations of the midplane temperature probes at the fuel center, fuel edge, fuel basket inner surface, gamma shield centerline and the neutron shield cover.

(a)



(b)

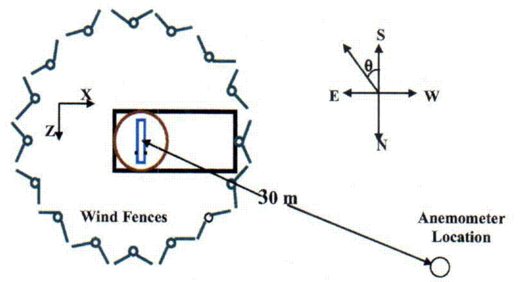


Fig. 3 Test facility (a) Calorimeter, fuel pool and wind fences before fire test. (b) Plan-view showing wind fences, anemometer location, compass direction, and wind direction coordinate system [Kramer et al. 2003].

Package Temperatures of Concern In this work the temperature of concern for spent fuel cladding is 866 K (593°C, 1100°F) [Office of Civilian Radioactive Waste Management, 1993] and for the elastomer seal is 664 K (391°C, 735°F) [NAC International, 2000]. The temperatures of concern for the lead gamma shield and aluminum basket were 601 K (328°C, 662°F) and 855 K (582°C, 1080°F), respectively. These temperatures are the melting points of the component materials [Incropera and DeWitt, 1996].

The properties of the gamma shield, basket, fuel cladding and seal change at their temperatures of concern. This paper does not evaluate whether these property changes affect the performance of a component. Moreover, packages generally employ multiple components for containment, criticality and shielding safety. This paper does not evaluate whether malfunction of a single component affects the performance of the entire package system.

LARGE-SCALE CALORIMETER FIRE TESTS

A large-scale fire test was performed to simulate the conditions of a truck-sized transport package in a regulatory fire [Kramer et al., 2003]. In the current work we simulate the response of a generic truck package to the conditions of that fire. This section describes the experimental facility and the ambient wind conditions of that test.

Figure 3a shows a carbon steel pipe calorimeter suspended 1-m above the center of a 7.2-m-diameter pool of JP8 fuel before the test. The fuel floats on top of a 1-m deep water pool. A sheet metal dam contains the fuel so that it forms a circle. The pipe diameter, length and wall thickness are 1.22 m (4 ft), 4.57 m (15 ft) and 2.54 cm (1 inch),

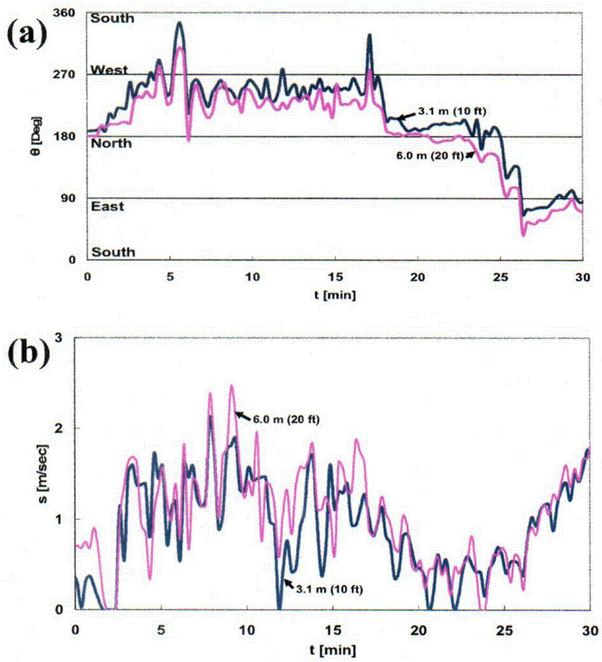


Fig. 4 Wind conditions versus time measured by two anemometers 3.1 and 6.0 m above the ground during the 30-minute burn. (a) Wind direction (indicates direction to which the wind blew, see Fig. 1b). (b) Wind speed [Kramer et al. 2003].

respectively, and it has 2.54 cm (1 inch) thick caps on each end. It is roughly the size of a legal weight truck package. However, it does not have the "dumbbell" shape that is typical of packages with impact limiters (Fig. 1a). The fuel pool size and calorimeter location comply with the conditions specified in the 10CFR71 regulations base on the calorimeter size.

Figure 3b shows a plan view of the test facility. The calorimeter, water pool, fuel dam and compass directions are show. The test facility is surrounded by a series of wind fences, which are also seen in Fig. 1a. There are gaps between these fences to allow the natural indraft of air toward the fire, but reduce the effect of wind. The calorimeter interior temperature is measured at 47 locations, mostly on four rings. The wind speed and direction are measured outside the barriers at the location shown in Fig. 3b. Figure 4 shows the wind speed and direction measured during the test. During the first 17 minutes of the test the wind blew toward the northwest (to the lower right in Fig. 3b) with an average speed of 1 m/s (2.2 mi/hr). The wind speed was low between t = 17 and 27 min. After that time it blew toward the east (to the left in Fig. 3b) with increasing speed.

PACKAGE RESPONSE SIMULATIONS

Simulation Sequence The 10CFR71 regulations specify that under normal conditions of transport the package receives 193.8 W/m^2 of insolation, and transfers heat to a 38°C surrounding by radiation and natural convection. Steady

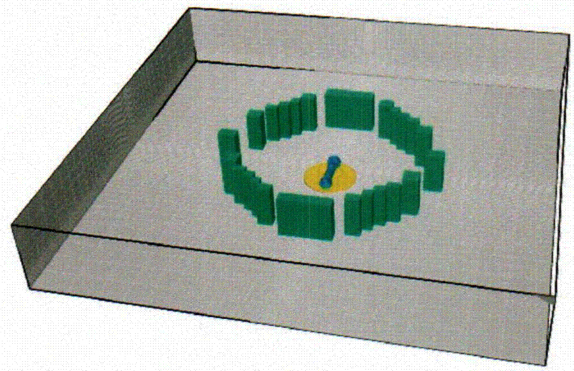


Fig. 5 CAFE-3D computational domain fire simulations

state simulations of these conditions are performed first to determine the package temperature distribution before the fire. The package outer surface emissivity is assumed to be 0.36 [NAC International, 2000]. Under these conditions heat generated within the spent fuel causes the interior components to be hotter than the exterior ones.

The pre-fire simulation for the intact version of the package includes the impact limiter. The pre-fire calculation of the no-impact limiter version does not. The no-impact-limiter simulations therefore model situations where the impact limiter is removed a long time before the fire begins.

CAFE-3D is used to simulate the response of the package to a 7.2-m-diameter pool fire for fire durations of D = 3 hr = 180 min (six times the regulatory duration). The package temperature distribution at the end of the fire is used as the initial condition for post-fire simulations. The post-fire simulations use the normal conditions of transportation environment.

Computational Domain Figure 5 shows an Isis-3D computational domain used for an intact package fire simulation. The fuel pool and wind fence model used to model the pipe calorimeter experiments [Kramer et al., 2003] are included within the Isis-3D domain [Are et al 2005, Greiner and Chalasani 2004]. The outer surface of an intact package is centered over the pool. CAFE-3D links this package surface to the outer surface of the finite element model in Fig. 1. The finite element model calculates the response of the calorimeter to the fire heat flux.

The measured wind conditions presented in Fig. 4 are applied to the side boundaries of this domain. The wind condition time scale is re-scaled so that the 30-minutes of wind data are applied during the entire 180-minute package response simulation. We did not re-run the measured wind conditions six times to cover the 180-minute fire simulations. We do not know how this would affect the simulation results.

Six different configurations are considered in this work. In all six the outer surface of the neutron shield expansion tank is 1.07 m above the fuel pool. Configurations 1, 2 and 3 are for an intact package. In Configuration 1 the package is centered over the fuel pool (see Fig. 5). In that case, the

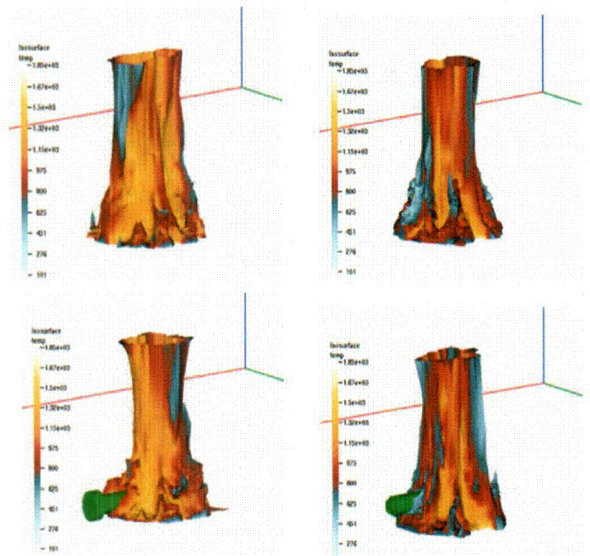


Fig. 6 Typical simulated fire surface snapshots for Configurations 1, 3, 4 and 6.

horizontal offset distance between the centers of the package and pool is $Y_{Off} = 0$. In Configuration 3 the containment seal is centered over the pool. The center of the package is offset from the center of the pool by a distance $Y_{Off} = 2.5$ m. In Configuration 2 $Y_{Off} = 1$ m. Configurations 4, 5 and 6 examine the no-impact-limiter version of the package with $Y_{Off} = 0$, 1 and 2.5 m, respectively.

SIMULATION RESULTS

Fire Surface Figure 6 shows snapshots of the fire surface from simulations of four of the six configurations. It shows the fire outer surfaces, which are the locations where the soot volume fraction equals $f_{s,m} = 0.5$ ppm. These surfaces are colored according to their local temperature. The fire surface moves with time during each simulation. However, these surfaces are representative of the fire shape for each configuration. In Configurations 1 and 4 the packages are centered over the fuel pool and they are almost entirely engulfed in flames. In Configurations 3 and 6 the packages are offset axially by $Y_{Off} = 2.5$ m and the un-engulfed ends are seen on the left sides of the fires.

Intact Package Centered Over Pool Figure 7 shows the temperature response of the fuel, basket, gamma shield and the neutron shield cover at the package midplane. These results are for Configuration 1 (intact package centered over the fuel pool), with three-hour fire duration. The vertical line shows the time when the fire is extinguished and the post fire conditions begin. The simulations monitor the temperature of each component at multiple locations. Figure 7 shows the maximum of these temperatures.

The neutron shield cover temperature rises rapidly at the beginning of the fire, oscillates with fire motion, and decreases rapidly when the fire is extinguished. The interior components are more thermally massive and further away from the fire. As a result they respond more slowly to changes in the fire. The gamma shield, basket, and fuel temperatures continue to increase after the fire is extinguished. This is

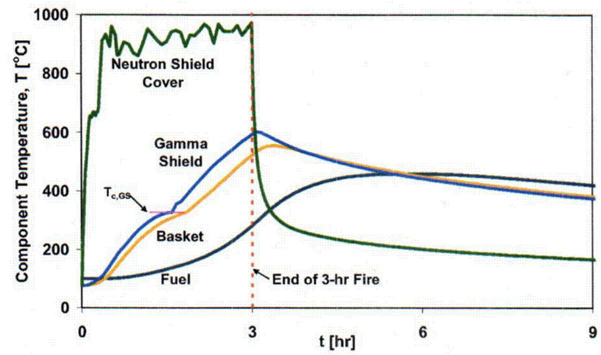


Fig. 7 Mid-plane component temperatures for Configuration 1 (intact package $Y_{OFF} = 0$) during and after a 3 hr fire.

because heat continues to diffuse to these interior components from the hotter exterior regions of the package.

The horizontal line segment in Fig. 7 marked $T_{C,GS}$ shows the gamma shield temperature of concern, which is the melt temperature for lead. As shown in Fig. 4b, the gamma shield temperature is monitored halfway between its inner and outer radii. At that location the gamma shield reaches its temperature of concern at t = 1.58 hr. Just before this time the rate of temperature change (slope) decreases due to constant melting that takes place in the outer regions of the gamma shield. The slope increases abruptly after the monitored location melts. The aluminum fuel basket also exhibits a slope discontinuity. While it does not melt, its temperature is affected by melting of the lead gamma shield. Possible effects of flowing molten lead are not included in these simulations.

The gamma shield temperature is only monitored at two midplane locations. More extensive monitoring is required to determine what fraction of the gamma shield melts during the fire. Neither the fuel nor the basket reach their temperature of concern at their monitored locations. However, the current simulations do not determine if these components reach these temperatures at other locations.

Figure 8 shows the seal temperature versus time for Configuration 1. The simulations monitor it at its top, bottom and on both sides. The results in this figure show the maximum of these temperatures. The horizontal dashed line marked $T_{C,Seal} = 391^0C$ shows the seal temperature of concern.

The line marked *CAFE-3D, D = 3 hr* shows results from the CAFE-3D simulation of a three-hour fire duration, D = 3 hr. The seal reaches its temperature of concern at t = 2.25 hr. It reaches its maximum temperature of $T_{S,Max} = 496^0C$ at t = 3.15 hr, 0.15 hr after the fire is extinguished. In this work we define the temperature excess as the maximum amount the seal temperature exceeds its temperature of concern $\Delta T_E = T_{S,Max} - T_{C,Seal}$. For this configuration the temperature excess is $\Delta T_E = 106^0C$. The excess time is the total amount of time the seal temperature exceeds it temperature of concern. For this configuration $\Delta t_E = 4.4$ hrs.

The predicted seal response is dependent on the fire model used in the simulation. For comparison the line in Fig. 8 marked *10CFR71, D = 3 hr* shows the maximum seal

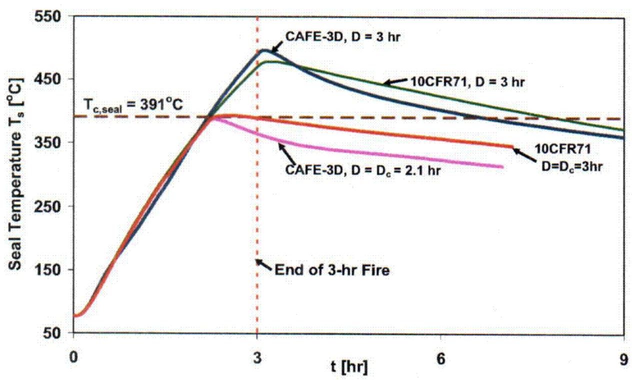


Fig. 8 Maximum seal temperature for Configuration 1 (intact package $Y_{OFF} = 0$) during and after 3-hr and duration-of-concern fires.

temperature calculated using the simplified fire model described in the 10CFR71 regulations. That simulation uses the same pre-fire and post-fire conditions as the CAFE-3D simulations. It indicates that seal first reaches its temperature of concern at t = 2.26 hr, which is essentially the same as the CAFE-3D result. However the seal exceeds its temperature of concern by a maximum of $\Delta T_E = 87^0C$, which is 19°C less than the CAFE-3D simulation. However it spends a total of $\Delta t_E = 5.7$ hrs above the temperature of concern, which is 1.3 hrs longer than the result from the other simulations.

The fire duration of concern for the seal D_C is the minimum duration capable of causing the seal to reach its temperature of concern. In the current work the duration of concern is determined by running CAFE-3D simulations with different fire durations. As discussed earlier, the seal temperature continues to rise after the fire is extinguished. As a result, the seal does not reach its temperature of concern until the post fire period. The CAFE-3D simulations indicate that the duration of concern is $D_C = 2.1$ hr. The 10CFR71 simulations give a slightly larger value of $D_C = 2.2$ hr. The maximum seal temperature from these simulations are shown in Fig. 8 as the curves marked *CAFE-3D, D =* D_C *= 2.1 hr* and *10CFR71, D =* D_C *= 2.2 hr.*

Effect of Position and Impact Limiter The response of intact and no-impact limiter packages to three hour fires were simulated for offset distances of $Y_{Off} = 0$, 1 and 2.5 m. For all six configurations the seal exceeds its temperature of concern before the end of the fire. Figures 9a and 9b show the temperature excess (maximum amount the seal temperature exceeds its temperature of concern, $\Delta T_E = T_{S,Max} - T_{C,Seal}$) and excess time (total time the seal spends above its temperature of concern) versus offset distance for both packages. Solid symbols represent results from CAFE-3D simulations. These results are connected by straight lines for clarity, but the actual trends between the data points may be different. Results from the simplified fire model in the 10CFR71 regulations are presented for a fully engulfing fire with $Y_{Off} = 0$ using open symbols.

The CAFE-3D simulations indicate that for the intact package centered over the pool ($Y_{off} = 0$) the seal exceeds its

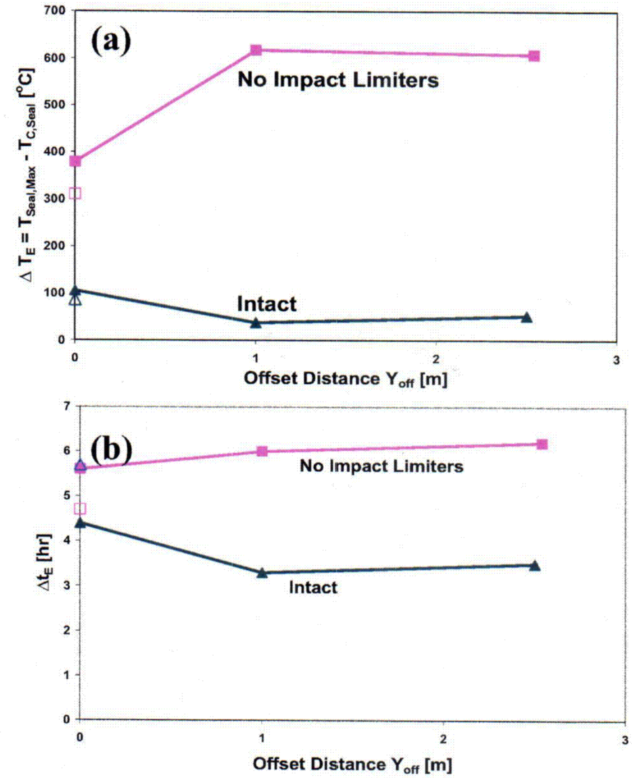


Fig. 9 Seal response to three-hour-fire/post fire simulations. CAFE-3D results are presented with solid symbols, and 10CFR71 results are reported with open symbols. (a) Maximum temperature excess $\Delta T_E = T_{MaxSeal} - T_{C,Seal}$. (b) Excess time (total time seal spends above its temperature of concern during and after fire).

temperature of concern by a maximum amount of $\Delta T_E = 106^0C$, and the seal spends a total of $\Delta t_E = 4.4$ hrs above that temperature. When the intact package is offset by $Y_{off} = 1$ and 2.5 m, the temperature excess and excess time both decrease to roughly $\Delta T_E = 46^0C$ and $\Delta t_E = 3$ hrs. The seal end of the intact package is protected by the impact limiter. A large fraction of the heat reaching the seal from the fire must conduct through the package body. As Y_{Off} increases the fraction of the package engulfed in flames decreases. This decreases the heat transfer to the seal and reduces ΔT_E and Δt_E compared to $Y_{off} = 0$.

The temperature excess and excess time are both significantly larger for the no-impact-limiter package than for the intact package. This is because the impact limiter insulates the seal end of the package from the fire.

For the intact package, ΔT_E and Δt_E are both smaller when the package is not centered over the pool than they are for $Y_{Off} = 0$. However, the opposite trend is observed for the no-impact-limiter package. When the impact limiter is removed heat from the fire is able to transfer directly to the exposed end of the package to the seal. The seal end is nearer the center of the fire for $Y_{Off} = 1$ and 2.5 m than for $Y_{Off} = 0$, and the central region may be hotter than the edge. This may be the reason ΔT_E and Δt_E are higher.

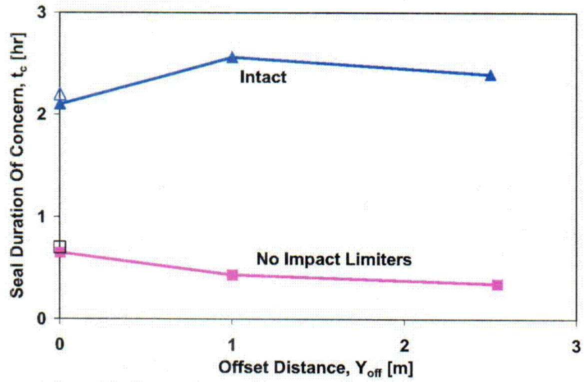


Fig. 10 Duration of concern of the seal versus offset distance for intact and no-impact-limiter packages. CAFE-3D simulations results are presented with solid symbols, 10CFR71 calculation results are reported with open symbols.

The10CFR71 calculation for the intact package gives a smaller temperature excess but a longer excess time than the CAFE-3D simulation. For the no-impact limiter package, the 10CFR71 calculation again gives a smaller temperature excess but a shorter excess time.

Figure 10 shows the fire duration of concern versus offset distance for both the intact and no-impact-limiter packages. Results calculated by CAFE-3D are once again presented using solid symbols connected by straight lines. Results from the 10CFR71 fully engulfing fire model for $Y_{Off} = 0$ are presented using open symbols. The results from the two fire models are in fair agreement for $Y_{Off} = 0$. For the intact package the duration of concern is 2.1 hours when it is centered over the fuel pool, and it is higher for $Y_{Off} = 1$ and 2.5 m. For the no-impact-limiter package the duration of concern is 0.65 hrs when it is centered over the pool, and it decreases as Y_{Off} increases.

We do not know if the value of D_C is minimized at a certain values of Y_{Off}. A series of simulations that consider more values of Y_{Off} are required to determine this. However, for both the intact and the no-impact-limiter packages, we expect D_C to increase significantly once Y_{Off} is large enough so that the package is not appreciably engulfed in the fire. Future simulations will evaluate the minimum "safe" distance. This is the minimum distance between the fire and package for which an infinitely long lasting fire will not cause the seal to reach it temperature of concern.

The difference between the Intact and No Impact Limiter curves in Figs. 9 and 10 quantifies the level of thermal protection provided by the impact limiter to the seal end of the package. For example, the presence of the impact limiter increases the duration of concern by over one hour compared to the no impact limiter package. This result, however, is dependant on the impact limiter thermal properties used in the simulations [Westinghouse Electric Company, 2000].

SUMMARY

A finite element model of an intact legal-weight-truck package is constructed and linked to the CAFE-3D fire model. Simulations of the package response to 3-hour fires from a 7.2-m-diameter hydrocarbon pool are performed with the package centered over the pool, and offset axially from that location by 1 and 2.5 m. In all simulations the body package is 1-m above the fuel pool.

The simulations predict the package containment seal exceeds its temperature of concern for all three package locations. Simulations of a no-impact-limiter version of the package are also performed to quantify the level of thermal protection the impact limiter provides. The minimum fire duration that causes the seal to reach its temperature of concern is determined for each configuration. When the center of the no-impact-limiter package is within 2.5 m of the pool center, fires of duration less than 0.7 hr are capable of causing the seal to reach its temperature of concern. By contrast, the intact package protects the seal in fires that last roughly 2 hours. These results will help risk analysts and package designers better understand the dependence of package position and the role of the impact limiters on accident consequences.

Future simulations work will employ new versions of CAFE-3D with improved fuel evaporation models. They will also consider a wider variety of offset locations. This will help determine the package position that minimizes the duration of concern. This will also help determine the minimum "safe" distance between the package and fire for which an infinitely long fire will not cause the seal to reach its temperature of concern.

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