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Analysis of Spent Fuel Transportation Cask Response to a Tunnel Fire Exposure

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ABSTRACT

The U.S. Nuclear Regulatory Commission's Spent Fuel Project Office is responsible for enforcing regulations that ensure that transportation of radioactive materials within the United States is conducted in a safe manner. Included in this responsibility is the assessment of the impacts of transportation events on radioactive material shipments, including the shipment of spent nuclear fuel.

On July 18, 2001, a freight train carrying hazardous (non-nuclear) materials derailed and caught fire in the Howard Street tunnel in Baltimore, Maryland. The staff of the Spent Fuel Project Office (SFPO) was tasked with assessing the consequences of this event on the transportation of spent nuclear fuel. This paper details the staff's actions related to the investigation and analysis of the Baltimore tunnel fire event.

This paper describes the staff's coordination with the National Transportation Safety Board (NTSB) to determine the details of the train derailment and fire, and includes details of the staff's technical analysis, which was completed with assistance from the National Institute of Standards and Technology (NIST), Pacific Northwest National Laboratory (PNNL), and the Center for Nuclear Waste Regulatory Analysis (CNWRA).

A fire model of the Howard Street tunnel fire was created by NIST, based on details of the fire event provided by NTSB. The CNWRA provided analyses of materials removed from the tunnel after the fire to confirm the temperature results of the NIST fire model. SFPO staff, with the assistance of PNNL, created a finite element model of a spent fuel transportation cask, and applied boundary conditions derived from temperature and flow results of the NIST fire model to analyze the spent fuel cask under the Howard Street tunnel fire conditions. This work provides a demonstration of the robust design of a rail cask used to ship spent nuclear fuel. This paper presents the results of the staff's analysis and the staff's conclusions on the ramifications of the Baltimore tunnel fire event on the transportation of spent nuclear fuel.

INTRODUCTION

Following the July 18, 2001, derailment and fire involving a CSX freight train inside the Howard Street tunnel in Baltimore, Maryland, the staff of the Nuclear Regulatory Commission's Spent Fuel Project Office (SFPO) was tasked with investigating the incident and determining what impact this type of fire event might have on a spent fuel transportation cask.

This paper will discuss the pertinent facts surrounding the Baltimore tunnel fire event; describe the analytic tunnel fire model developed by the National Institute of Standards and Technology (NIST), and the material property analyses performed by the Center for Nuclear Waste Regulatory Analysis (CNWRA) to quantify the thermal conditions that the rail cars experienced during the event. This paper will also describe an analysis performed to assess the performance of a spent fuel transportation cask design when subjected to the thermal conditions experienced in the tunnel, as calculated by NIST and validated by CNWRA. The staff's conclusions regarding the possible radiological consequences of this event will also be presented.

THE HOWARD STREET TUNNEL FIRE EVENT

The Howard Street tunnel is a single track rail tunnel, 2.7 kilometers (1.65 miles) in length, with an average upward grade of 0.8% from the west portal to the east portal of the tunnel. The tunnel is constructed of concrete and refractory brick, and has a manually activated ventilation system. The tunnel has vertical walls with a cylindrical ceiling measuring approximately 6.7 meters (22 feet) high by 8.2 meters (27 feet) wide, but the dimensions vary slightly along the length of the tunnel.

The train that derailed in the tunnel had 60 cars, including both boxcars and tank cars, and was pulled by 3 locomotives. The train was carrying paper products, hydrochloric acid, liquid tripropylene, pulp board and other cargo. As the train traveled through the tunnel 11 of the 60 rail cars derailed. A tank car containing approximately 108,263 liters (28,600 gallons) of liquid tripropylene (see Figure 1) was punctured during the derailment and the leaking tripropylene was ignited. The hole punctured in the tank car was approximately 3.81 centimeters (1.5 inches) in diameter.

The exact duration of the tripropylene fire is unknown; however, reports from emergency responders indicate that the most severe portion of the fire lasted approximately 3 hours. Approximately 12 hours after the fire started, conditions in the tunnel were such that firefighters were able to enter the tunnel and visually confirm that the tripropylene tank car was no longer burning.

NIST TUNNEL FIRE MODEL

During the event, no temperature readings were taken in the tunnel. Thus, the precise temperature at which the fire burned was unknown. In order to better predict what the temperatures in the tunnel could have been during the event, fire modeling experts at the National Institute of Standards and Technology (NIST) developed a model of the Howard Street tunnel fire using the Fire Dynamics Simulator (FDS) code.

The FDS code is a computational fluid dynamics (CFD) code that models combustion and the flow of hot gasses in fire environments. FDS solves the mass, momentum, and energy equations for a given computational grid, and is also able to construct a visual representation of smoke flow from a given fire.

In order to demonstrate the capability of FDS to accurately model tunnel fires, NIST developed tunnel fire models to validate FDS against data taken from a series of fire experiments conducted by the Federal Highway Administration and Parsons Brinkerhoff, Inc. as part of the Memorial Tunnel Fire Ventilation Test Program.[1] These tests were conducted in an abandoned West Virginia highway tunnel to study tunnel fire response to various tunnel ventilation schemes. The data from these tests were reviewed by NIST, and used to validate the FDS code. NIST modeled both a 20

MW (6.83×10^7 BTU/hr) and a 50 MW (1.71×10^7 BTU/hr) unventilated fire test from the Memorial Tunnel Test Program, and achieved results using FDS that were within 50°C, (100°F) of the recorded data.[2]

THE HOWARD STREET TUNNEL FIRE MODEL

The Howard Street tunnel model developed by NIST is a full length 3-dimensional (3D) representation of the tunnel that included railcars positioned as they were found following the derailment (see Figure 2). The model simulated the burning of a pool of liquid tripropylene positioned below the approximate location of the puncture hole on the tripropylene tank car. The railcars were all modeled as thin-walled rectangular boxes that were allowed to heat up as the fire progressed.

The initial Howard Street tunnel fire simulation in FDS was run for 30 minutes.[2] At this time, the surface of the tunnel walls, the hot gas layer above the railcars, and the metal skins of the railcars had reached a relatively constant temperature. In subsequent simulations the fire is allowed to burn for 7 hours, followed by a 23 hour cool down period. The fire duration is based on a burn time calculation for the controlled burn of over 108,263 liters (28,600 gallons) of liquid tripropylene fuel in a circular pool with an area of 63.6 m^2 (685 square feet). This fire duration is conservative given the tripropylene that spilled was not contained in a pool. In addition, vents are added to the tunnel walls in the model to allow air to enter the tunnel at locations other than the portals. These vents do not exist in the actual Howard Street tunnel. Because of the increased ventilation, the predicted fire in the tunnel did not become oxygen limited and burned at full power for 7 hours.

In order to determine temperatures, the FDS code allows placement of thermocouples at precise locations within the model. Temperatures calculated in the FDS model were as high as 1100°C, (2000°F) in the flaming regions of the fire. The maximum temperatures reported were localized and limited to the most intense portions of the fire. The model indicated that the hot gas layer above the railcars, within three rail car lengths of the fire, is an average of 600°C, (1100°F). Temperatures on the tunnel wall surface were calculated to be a max of 900°C, (1650°F) where the fire directly impinged on the top of the tunnel. The average tunnel ceiling temperature, within a distance of three rail cars from the fire, is 500°C (900°F).

Figure 1. Tripropylene Tank Car

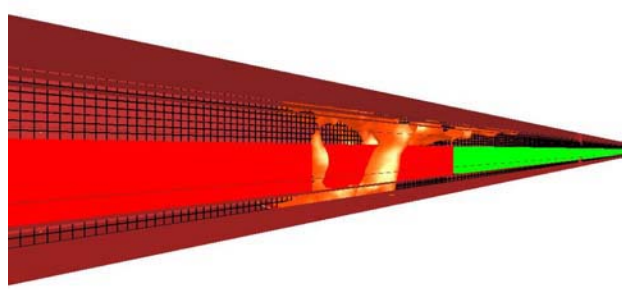

Figure 2. Howard Street Tunnel Fire Model (Image Courtesy of NIST)

MATERIALS EXPOSURE ANALYSIS

SFPO staff was given access, through CSX Corporation, to the railcars that were removed from the Howard Street tunnel, following the fire. The staff examined the railcars along with staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA) who provided expertise in fire modeling, fire testing, and materials analysis. The physical evidence examined was used by the staff to gain further insight into the environment that may have existed in the tunnel during the fire. CNWRA staff analyzed the condition of paint, metal samples removed from box cars, and components removed from the tripropylene tank car during the staff's examination of the cars. In order to estimate the time and temperature of exposure for these samples, several different metallurgical analyses were performed on the material samples collected, including sections of the boxcars exposed to the most severe portion of the fire, and an air brake valve from the tripropylene tanker car. The temperature exposures estimated by the CNWRA's analyses were consistent with the conditions predicted by the NIST tunnel fire model.[3]

TRANSPORTATION OF SPENT NUCLEAR FUEL

In recent years, a great deal of focus has been placed on the safe transportation of spent nuclear fuel. The licensing and operation of a long term waste disposal facility is a possibility in the foreseeable future. The occurrence of the Baltimore tunnel fire placed a spotlight on a type of accident that could have an effect on the safe shipment of spent nuclear fuel by rail. Current NRC regulations require that spent fuel transportation casks be evaluated for a hypothetical accident condition that includes a fully engulfing fire with an average flame temperature of 800°C, (1475°F) for a period of 30 minutes.[4]

In order for transportation cask designs to be certified by the NRC, cask designs must either be subjected to an open pool fire test or analyzed for a fire event meeting the aforementioned criteria. Cask designs must maintain shielding and criticality control functions throughout a sequence of hypothetical accident conditions, which include a 9 meter (30 foot) drop test and a pin puncture test, prior to the fire event.

SPENT FUEL TRANSPORTATION CASK

The staff investigated what impact the Howard Street tunnel fire might have on an NRC approved spent fuel transportation cask design. The design chosen for this evaluation is the HOLTEC HI-STAR 100 transportation cask. This design utilizes a welded multi-purpose canister (MPC), to hold spent fuel. The MPC has an integral fuel basket that accommodates 24 spent Pressurized Water Reactor (PWR) fuel assemblies. The MPC, after it has been loaded and seal welded, is placed into the transportation cask (or overpack) for shipment. The outer shell of the cask is fabricated of 0.635 centimeter (0.25 inch) thick carbon steel. The next layer is a 11.43 centimeter (4.5 inch) thick polymeric neutron shield, strengthened by a network of stainless steel stiffeners. The gamma shield is comprised of 6 layers of carbon steel plates a total of 16.51 centimeters (6.5 inches) thick. The stainless steel cask inner shell is 6.35 centimeters (2.5 inches) thick.

Impact limiters, fabricated from aluminum honeycomb material with a stainless steel skin, are installed on the ends of the cask immediately prior to shipping. The impact limiters serve two functions: to prevent damage to the cask, its closure lid, MPC, fuel basket, and contents in the case of a cask drop accident and to provide insulation in the case of a fire exposure. Figure 3 shows a model of the HI-Star 100 cask system, with impact limiters installed, secured to a transportation railcar.

DESCRIPTION OF ANALYSIS APPROACH AND CASK MODEL

The staff analysis of the transportation cask utilized both temperature and flow data from the NIST Howard Street tunnel fire model. The data derived from the NIST model was used to develop boundary conditions for the cask analysis model developed by the staff.

A two dimensional cross section model of the cask in the horizontal transport position, including the transport cradle, was developed in the ANSYS® finite element analysis code.[5] (See Figure 4.) The model utilized PLANE55 thermal elements for conduction, SURF151 surface effect elements for convection, and SURF151 elements in conjunction with AUX-12 generated Matrix 50 superelements for radiation. The material properties from the cask vendor's Safety Analysis Report (SAR) were verified and then used in the analysis.[6] The analysis model explicitly represented the geometry of the cask, including the internal geometry of the basket, all gaps associated with the basket, as well as the integral neutron absorber plates. The fuel assemblies are homogenized in order to reduce the number of elements. The effective thermal conductivity applied to these regions was calculated utilizing a correlation based on data.[7] The analysis model is comprised of over 28,300 elements.

Figure 3. Spent Fuel Cask on Railcar (Image Courtesy of HOLTEC International)

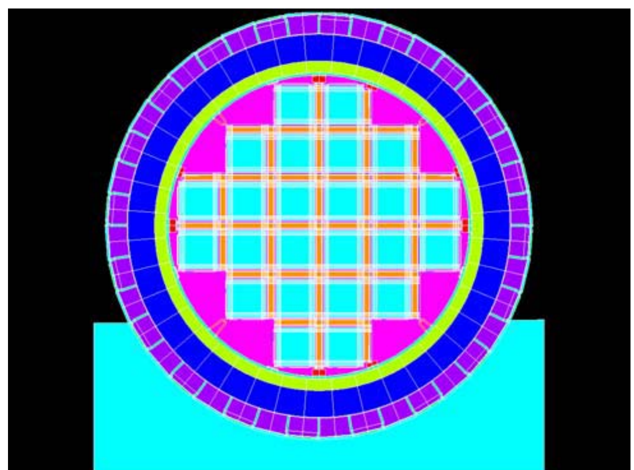

Figure 4. ANSYS® Cask Analysis Model Material Plot

ANALYSIS OF SPENT FUEL TRANSPORTATION CASK

Pre-Fire Boundary Conditions

The normal conditions for transport described in 10 CFR 71.71 were used as a starting point for the analysis. The cask is subjected to an ambient temperature of 38°C, (100°F), with solar insolation accounted for as well. For pre-fire conditions, the surface of the cask is given an emissivity value of 0.85, based on the emissivity value for a painted cask surface. Radiation and convection to and from the cask surface is modeled with surface effect elements (SURF151). The convective heat transfer coefficient applied is calculated, and is based on natural buoyant convection correlations.

To model the decay heat of the fuel, heat generation equivalent to a decay heat load of 20kW (68,258 BTU/hour) is applied. Radial conduction is modeled through all components of the cask, including the fuel region. The model also includes radiation within all gaps present in the model. The fuel region model accounts for radiation and convection in the formation of an effective thermal conductivity value.

A steady state normal condition temperature distribution for the cask was obtained for the model. This temperature distribution was verified against the results reported by the cask vendor, and was found to be in good agreement with those results.

Tunnel Fire Boundary Conditions
The staff completed an evaluation of cask response to the tunnel fire environment, predicted by the NIST fire model, with the cask oriented axially along the length of the tunnel. The center of the cask is located 20 meters (65.6 feet) from the fire source. The 20 meter (65.5 foot) distance is based on Department of Transportation regulations that require railcars carrying radioactive materials to be separated by at least one railcar (a buffer car) from other cars carrying hazardous materials or flammable liquids.[8] A typical railcar is approximately 20 meters (65.6 feet) in length, and based on the width of the Howard Street tunnel, this is a realistic distance to assume between the cask and the fuel source.

A convective boundary condition is calculated for the cask model utilizing flow data from the NIST model, which predicts the flow field present in the tunnel due to the fire. The convective boundary conditions are based on forced convection correlations that are applied to the cask model in three "zones." The upper third of the cask is exposed to the maximum temperature and flow that existed in the upper portion of the tunnel; the middle third of the cask is exposed to the maximum temperatures and flow that existed along the side of the tunnel; and the bottom third of the cask, including the shipping cradle, is exposed to the maximum temperature and flow conditions along the lower elevations of the tunnel.

Although the fire source is conservatively modeled as a "wall of flame" with the same dimensions as the tunnel cross section, and given a temperature of 850°C, (1562°F), based on the NIST calculations, radiation view factors calculated for the cask, for the 20 meter case, are very small and therefore are neglected. Tunnel wall surface temperatures were also taken from the NIST calculations, and radiation from the tunnel walls (which have the most direct view of the cask body) is accounted for as well. The emissivity of the cask is set to 0.9 for the fire duration.

The maximum temperatures and flow fields predicted by the NIST fire model were used to define the fire exposure for the entire analysis. The analysis determined how the cask and its contents would heat up in response to this exposure.

ANALYSIS RESULTS

Temperature Results
The analysis indicated that the spent fuel cladding, which is the primary fission product containment boundary, reached a maximum of 404°C, (785°F) roughly 300 hours into the transient. This is below the currently accepted short term fuel temperature limit of 570°C, (1058°F) for Zircalloy clad spent nuclear fuel.[9] This temperature limit is based on creep experiments done on two fuel cladding test samples held at, 570°C, (1058°F), which remained undamaged (i.e., there was no significant

observable damage) for times up to 30 and 71 days. The temperature at which Zircalloy fuel rods actually fail by burst rupture is approximately 750°C, (1382°F).[10] Figure 5 presents cask component temperatures as a function of time.

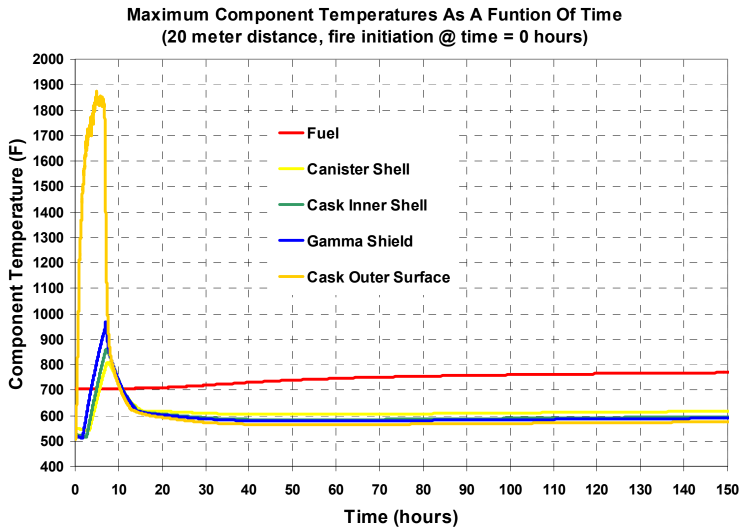

Figure 5. Component Temperature Plot

While the primary boundary preventing release of fission gasses contained in the spent fuel rods is the fuel cladding, the release of these gasses to the environment cannot occur unless the MPC is breached. The vendor for this particular cask design does not take credit for the MPC as a containment boundary, even though it is a seal welded pressure vessel designed to American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, Subsection NB.[11] The MPC has an internal pressure limit for accident conditions of 868 kPa (125 psig). Pressure and stress calculations demonstrated that the canister would remain intact (i.e., there would be no leak path to the environment) in accordance with ASME code, for the entire duration of this fire exposure.

DOSE CONSIDERATIONS

The staff also considered radioactive doses from the cask to first responders after a severe fire accident. The cask's polymeric neutron shield would be damaged under the fire conditions experienced in this analysis. The SAR for this particular cask design demonstrates that even with the neutron shield material completely gone, dose rates in the vicinity of the cask would not exceed the limits prescribed in 10 CFR 71.51.[6] Therefore, a complete loss of the neutron shield, while being a highly improbable event, would not increase doses beyond what is currently allowed by NRC regulations.

CONCLUSION

While the precise duration and temperatures of the actual fire that occurred in the Howard Street tunnel will never be known with certainty, the NIST model has provided insight into what the fire might have been like, taking into account the facts of the event that are known today.

The robust nature of this spent fuel transportation cask design is evident, based on the response of this cask to the tunnel fire environment. Based on the results of this analysis the staff concludes that, had this type of spent fuel cask been involved in a fire similar to the Baltimore tunnel fire, the public health and safety would have been protected.

ACKNOWLEDGMENTS

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