From: "Adkins, Harold E" <Harold.Adkins@pnl.gov>
To: Christopher Bajwa <CSB1@nrc.gov>
Date: Tue, Dec 9, 2003 9:50 AM
Subject: RE: The Latest Version

The ".doc" some how got stripped off of the file. I believe that if you replace, it will work fine.

However, attached is an additional copy just in case.

Harold

-----Original Message-----
From: Christopher Bajwa [mailto:CSB1@nrc.gov]
Sent: Tue 12/9/2003 5:33 AM
To: Adkins, Harold E
Cc:
Subject: RE: The Latest Version

Harold,

I can't read this document. It is not a .doc

-Chris

>>> "Adkins, Harold E" <Harold.Adkins@pnl.gov> 12/09/03 12:23AM >>>
Chris,

Attached is the latest. You did a good job with the recent additions/modifications.

[ ] Ex. 5

Take care,

Harold

-----Original Message-----
From: Christopher Bajwa [mailto:CSB1@nrc.gov]
Sent: Mon 12/8/2003 1:08 PM
To: Adkins, Harold E
Cc:
Subject: The Latest Version

Harold,

The highlighted italicized section on page 5 is something that you originally wrote, and I'm not sure what you were trying to say.

It's still pretty rough, but it is getting there. I'll look forward to a revised version tomorrow.

I should submit this to my management with a note that it is a draft that will be finalized in February, just so they know we are submitting something for the ANSYS conference.

Portions withheld - Ex 5 B/10

-Chris

Analysis of the Thermal Response of Various Spent Nuclear Fuel Transportation Cask Designs to the 2001 Baltimore Tunnel Fire Event

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Pacific Northwest National Laboratories
Christopher S. Bajwa, P.E.
United States Nuclear Regulatory Commission

Abstract

On July 18, 2001, a train carrying hazardous (non-nuclear) materials derailed and caught fire in the Howard Street railroad tunnel in downtown Baltimore, Maryland. The U.S. Nuclear Regulatory Commission (NRC), who is responsible for evaluating the performance of spent fuel transportation casks under accident conditions, undertook an investigation of the response of spent fuel cask designs to the Baltimore tunnel fire event.

The staff of the NRC, in cooperation with the National Institute of Standards and Technology (NIST) and Pacific Northwest National Labs (PNNL), among other agencies, has performed an analysis to determine the thermal conditions present in the Howard Street tunnel fire, as well as analyze the effects that such a fire would have on various spent fuel transportation cask designs. Utilizing the Fire Dynamics Simulator (FDS) code, developed by NIST, in conjunction with the ANSYS® and COBRA-SFS thermal codes, the staff evaluated cask designs for thermal performance. This paper describes the analytic models used in the assessment and presents the staff's results.

Ex. 5

Introduction

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

This paper will briefly recount factual information surrounding the Baltimore tunnel fire event as well as describe analyses done by the National Institute of Standards and Technology (NIST) and the Center for Nuclear Waste Regulatory Analysis (CNWRA) to quantify the thermal (fire) environment that existed during the event. This paper will also describe the analyses performed to assess the performance of three spent nuclear fuel transportation cask designs subjected to thermal conditions that could have been experienced in the Howard Street tunnel, as calculated by NIST and validated by CNWRA.

The Howard Street Tunnel Fire Event

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

The train had a total of 60 cars, including boxcars and tank cars, and was powered by 3 locomotives. The train carried paper products and pulp board in boxcars and hydrochloric acid, liquid tripropylene, and other hazardous materials in tank cars. While passing through the tunnel 11 of the 60 rail cars derailed. A tank car containing almost 28,600 gallons (108,263 liters) of liquid tripropylene (see Figure 1) was punctured by the brake mechanism during the derailment. Tripropylene leaking from the punctured tank car was the most likely source of the fire. The hole in the tank car was approximately 1.5 inches (3.81 centimeters) in diameter.

The exact duration and temperature of the fire that ensued is not known. Based on interviews with NTSB, emergency responders indicated that the most severe portion of the fire lasted approximately 3 hours. Other, less severe fires burned for periods of time greater than 3 hours. Approximately 12 hours after the fire started, firefighters were able to visually confirm that the tripropylene tank car was no longer burning.

NIST Tunnel Fire Model

In order to predict the range of temperatures present in the Howard Street tunnel during the fire, experts at the National Institute of Standards and Technology (NIST) were contracted to develop a model of the tunnel fire using the Fire Dynamics Simulator (FDS) code.

FDS is a computational fluid dynamics (CFD) code that models both 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 for any given fire.

As part of a validation effort for FDS, NIST developed tunnel fire models in FDS and compared their results 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] NIST modeled both a 6.83×10^7 BTU/hr (20 MW) and a 1.71×10^8 BTU/hr (50 MW) unventilated fire test from the Memorial Tunnel Test Program, and achieved results using FDS that were within 100°F, (50°C) of the recorded data.[2]

The full length 3-dimensional (3D) representation of the Howard Street tunnel model developed by NIST included railcars positioned as they were found following the derailment. The source of the fire was a pool of burning liquid tripropylene positioned below the approximate location of the hole punctured in the tripropylene tank car. (see Figure 2)

Maximum temperatures calculated in the FDS model were 1800°F, (1000°C) in the flaming regions of the fire. The model indicated that the hot gas layer above the railcars, within three rail car lengths of the fire, was an average of 900°F, (500°C). Temperatures on the tunnel wall surface were calculated to be 1500°F, (800°C) 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, was 750°F, (400°C).[2]

CNWRA Materials Exposure Analysis

NRC staff, along with staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA) examined several railcars removed from the Howard Street tunnel approximately a year after the fire. The physical evidence examined gave the staff further insight into the environment that existed in the tunnel during the fire. CNWRA staff analyzed the paint and metal samples removed from box cars, as well as components removed from the tripropylene tank car. In order to estimate exposure time and temperature for the samples, 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 time/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

NRC regulations require that spent fuel transportation casks be evaluated for a series of hypothetical accident conditions (HACs) that include a 30 foot (9 meter) drop test, a pin puncture test, and a fully engulfing fire with an average flame temperature of 1475°F, (800°C) for a period of 30 minutes. These tests are followed by the immersion of an undamaged cask under 50 feet (15 m) of water.[4]

The cask certification process must include either an open pool fire test or an analysis of the cask for a fire exposure meeting the aforementioned criteria. Casks must maintain shielding and criticality control functions throughout the sequence of hypothetical accident conditions.

The staff investigated how a fire similar to the Howard Street tunnel fire might affect three different NRC-approved spent fuel transportation cask designs including the HOLTEC HI-STAR 100 and Transnuclear TN-68 rail transportation casks [redacted] Ex 5

The HI-STAR 100 [redacted] will be discussed in detail as these two casks were modeled using the ANSYS® FEA package. The TN-68 was modeled using the COBRA-SFS finite-difference thermal package.

HOLTEC HI-STAR 100 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 is placed into the transportation cask (or overpack) for shipment after it has been loaded and seal welded shut. A diagram of the HI-Star 100 cask system (MPC and overpack) is provided in Figure 3. The overall outer diameter of the cask is 96 inches (244 cm). The stainless steel cask inner shell is 2.5 inches (6.35 cm) thick. The gamma shield is comprised of 6 layers of carbon steel plates a total of 6.5 inches (16.51 cm) thick. The next layer is 4.5 inch (11.43 cm) thick polymeric neutron shield, strengthened by a network of stainless steel stiffening fins. The outer shell of the cask is fabricated of 0.25 inch (0.635 cm) thick carbon steel.

Impact limiters, made of aluminum honeycomb material with a stainless steel skin, are installed on the ends of the cask prior to shipping. Impact limiters serve to prevent damage to the cask, specifically protecting 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 4 shows a rendering of this cask design with impact limiters installed and secured to a transportation railcar. This cask weighs 277,300 lbs (125,781 kg) when loaded for transport.

[redacted] Ex. 5

TransNuclear TN-68 Cask

The TN-68 spent fuel shipping cask is similar in construction to the Hi-Star 100, however, it is designed to transport up to 68 BWR spent fuel assemblies, with a maximum total decay heat load of 21.2 kW. The TN-68 also differs in the fact that it does not utilize a separate canister to contain spent fuel. The spent fuel assemblies are contained within a basket structure consisting of 68 stainless steel tubes, with aluminum and borated aluminum (or boron carbide/aluminum composite) neutron poison plates sandwiched between the steel tubes. The basket structure is supported by aluminum alloy support rails which are bolted to the inner carbon steel cask shell, which also serves as the inner gamma shield. This inner steel shell is shrink-fitted within an outer carbon steel shell that also serves as the outer gamma shield. The gamma shielding is surrounded by the neutron shielding, which consists of a 6.0 inch (15.24 cm) thick ring of aluminum boxes filled with borated polyester resin. The outer shell of the cask is stainless steel, 0.75 inch (1.91 cm) thick. The overall outer diameter of the cask is 98 inches (249 cm). The cask bottom plate is 8.25 inch (21.0 cm) thick carbon steel, with a 1.5 inch (3.81 cm) thick inner shield plate. The cask lid is 5 inch (12.7 cm) thick carbon steel plate with an inner top shield plate 4.5 inch (11.43 cm) thick. During transport, the ends of the cask are capped with impact limiters, made of redwood and covered in 0.24 inch (6 mm) thick steel plate. As stated previously, this cask was analyzed with COBRA-SFS, a code that has been developed by Pacific Northwest National Laboratories and has been successfully validated in blind validation studies using data collected from spent fuel cask testing with actual spent fuel assemblies.[5,6,7]

Procedure

The staff utilized the ANSYS® finite element analysis code[8] to analyze two of the casks described above. The models utilized both temperature and flow data from the NIST Howard Street tunnel fire model. Data derived from the NIST model was used to develop the boundary conditions applied to the casks that were analyzed.

Three dimensional models of each of the casks described above were developed (See Figure 5.) The models utilized SOLID70 thermal elements for conduction, SURF152 surface effect elements for convection, and SURF152 elements in conjunction with AUX-12 generated Matrix 50 superelements for radiation interaction. The material properties from the cask vendor's Safety Analysis Reports (SARs) were verified and then used in the analyses.[9,10] The models explicitly represented the geometry of each cask, including the internal geometry of the fuel baskets, all gaps associated with the baskets, as well as the integral neutron absorber plates (HOLTEC HI-Star) [redacted] Ex. 5. Fuel assemblies are homogenized (represented by a volume with an effective thermal conductivity) in order to reduce the number of elements. The effective thermal conductivity applied to these regions was calculated utilizing a correlation based on data.[11] [redacted] Ex. 5

Analysis

The normal conditions for transport described in 10 CFR 71.71 were used as a starting point for each analysis. The casks were subjected to an ambient temperature of 38°C, (100°F), with solar insolation accounted for as well. For pre-fire conditions, the cask surface was given an emissivity value representative of its surface finish (i.e., 0.3 for stainless, 0.85 for painted). Thermal radiation transfer to the ambient is modeled using surface effect elements (SURF152). Convection from the surface of the cask is modeled with a similar set of surface effect elements. Natural buoyant convection correlations were used to simulate the convective heat transfer at the cask surface.

To model the decay heat of the fuel, heat generation equivalent to a decay heat loads of 20kW (68,240 BTU/hour) for the HOLTEC HI-Star 100, [redacted] Ex. 5, and 21.2kW (72,334 BTU/hour) for the TN-68, were applied. Radial conduction was modeled through all components of the casks, including the fuel region. The models also include radiation between all gaps present in the model. The fuel region models account for radiation and convection in the formation of an effective thermal conductivity.

A steady state normal condition temperature distribution for each cask was obtained. The normal condition temperature distribution was verified against the results reported in each SAR, and was found to be in good agreement with those results. [redacted] Ex. 5

The staff then evaluated each cask response to the tunnel fire environment as predicted by the NIST model. The evaluations had the casks oriented horizontally with one end of the cask facing the fire source. The evaluations located the center of each cask 65.6 feet (20 meters) from the fire source. This 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.[12]

Convective boundary conditions were calculated for the cask models utilizing temperature/flow data from the NIST model, which predicts the flow field present in the tunnel due to the fire. Tunnel wall temperatures were also assigned based on results yielded from the NIST model. The convective boundary conditions are based on forced convection correlations that are applied to each 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 at mid-height of the tunnel; and the bottom third of the cask, including the shipping cradle (if applicable), is exposed to the maximum temperature and flow conditions along the lower elevations of the tunnel.

The fire source was conservatively modeled as a "wall of flame" with the same dimensions as the tunnel cross section, and given a temperature of that reported for the top (hottest) convective zone, based on the NIST calculations. Radiation from the fire source to the cask body was captured by radiation view factors that were calculated for the cask, taking into account that the impact limiters are in place at the beginning of the fire. The impact limiter skins are assumed to remain in place and retain their general shape for the entire fire duration as they are fabricated with stainless steel. The emissivity of the cask bodies were set to 0.9 for the fire duration to simulate sooting by combustion by-products. 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) was accounted for in the evaluations.

The analysis was carried out for a 7 hour fire and 23 hour post-fire cool-down duration, as predicted by NIST, to determine the cask time/temperature response.

Ex.5

Ex. 5

Conclusion

While the exact duration and temperatures of the actual fire that occurred in the Howard Street tunnel may never be know with certainty, the FDS model developed by NIST provided insight into what the fire could have been like based on the facts surrounding the event, as we currently know them.

The robust nature of these spent fuel transportation cask designs is evident, based on their response to the tunnel fire environment. Based on the results of these analyses, the staff concludes that, had these types of spent fuel casks been involved in a fire similar to the Baltimore tunnel fire, the public health and safety would have been protected.

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1) Bechtel/Parsons Brinkerhoff, Inc., *Memorial Tunnel Fire Ventilation Test Program, Comprehensive Test Report*, Prepared for Massachusetts Highway Department and Federal Highway Administration, November 1995.

2) McGrattan K. B., Hammins, A., National Institute of Standards and Technology, *Numerical Simulation of the Howard Street Tunnel Fire, Baltimore, Maryland, July 2001*, NUREG/CR-6793, February 2003.

3) Garabedian, A.S., Dunn, D.S., Chowdhury A.H., Center for Nuclear Waste Regulatory Analysis, *Analysis of Rail Car Components Exposed to a Tunnel Fire Environment*, NUREG/CR-6799, March 2003.

4) Title 10, Code of Federal Regulations, Part 71, *Packaging and Transportation of Radioactive Material*, Jan. 1, 2003, United States Government Printing Office, Washington, D.C.

5) Rector, D. R., Wheeler, C.L., Lombardo, N.J., *COBRA-SFS:A Thermal-Hydraulic Analysis Computer Code: Volume I: Mathematical Models and Solution Methods*, Richland, Washington: Pacific Northwest National Laboratory, 1986. PNL-6049 Vol. I

6) Rector, D. R., et. Al., *COBRA-SFS:A Thermal-Hydraulic Analysis Computer Code: Volume II: User's Manual*, Richland, Washington: Pacific Northwest National Laboratory, 1986. PNL-6049 Vol. II

7) Lombardo, N. J., et. Al., *COBRA-SFS:A Thermal-Hydraulic Analysis Computer Code: Volume III: Validation Assessments*, Richland, Washington: Pacific Northwest National Laboratory, 1986. PNL-6049 Vol. I

8) ANSYS, Inc., "ANSYS Users Guide for Revision 7.1," ANSYS, Inc., Canonsburg, PA, USA. 2003.

9) NRC Docket Number 72-1008, *Final Safety Analysis Report for Holtec International Storage Transport and Repository Cask System* (HI-STAR 100 Cask System), Holtec Report HI-210610, Volumes I and II, March 30, 2001.

10) Ex. 5

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12) Title 49, Code of Federal Regulations, Subchapter C, *Hazardous Materials Regulations*, Oct. 1, 2002, United States Government Printing Office, Washington, D.C.

Standard

13) Johnson, A.B., Gilbert, E.R., *Technical Basis for Storage of Zircalloy-Clad Spent Fuel in Inert Gases*, Pacific Northwest Laboratory, PNL-4835, September 1983.

14) J.L. Sprung, et. Al., Sandia National Laboratories, *Reexamination of Spent Fuel Shipment Risk Estimates*, NUREG/CR-6672, March 2000

15) ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, American Society of Mechanical Engineers, 1995.

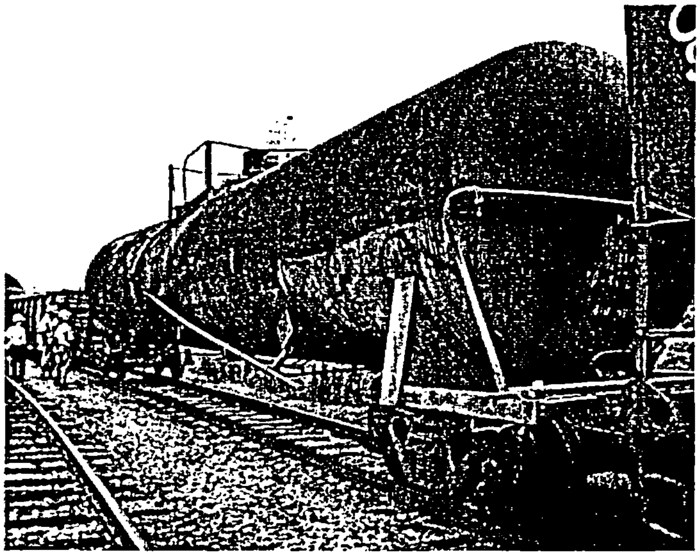

Figure 1. Tripropylene Tank Car

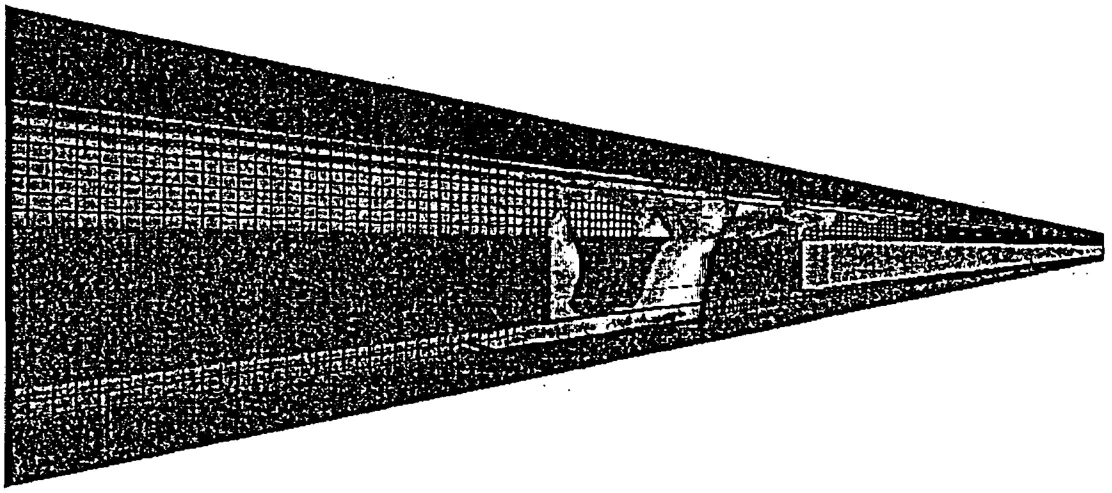

Figure 2. Howard Street Tunnel Fire Model (Image Courtesy of NIST)

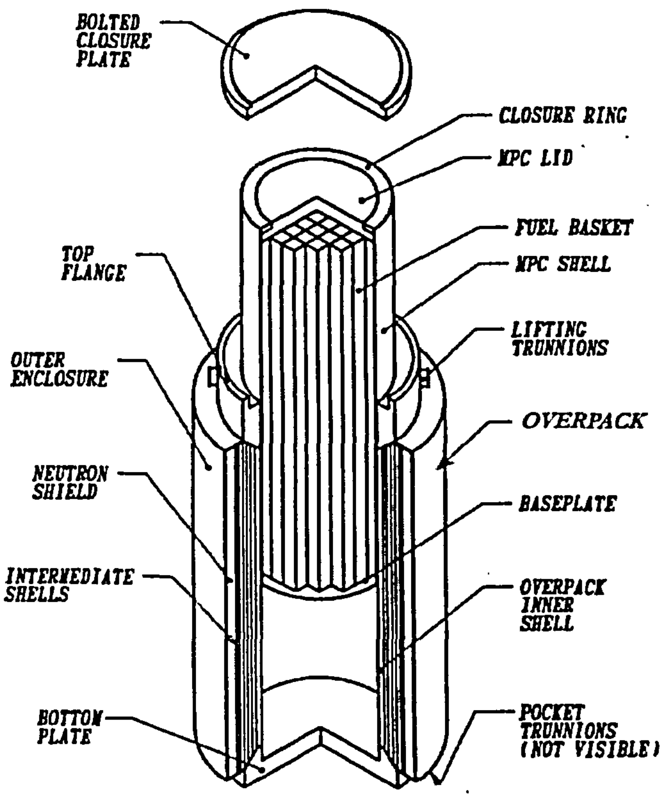

Figure 3. HOLTEC HI-STAR 100 Spent Fuel Cask

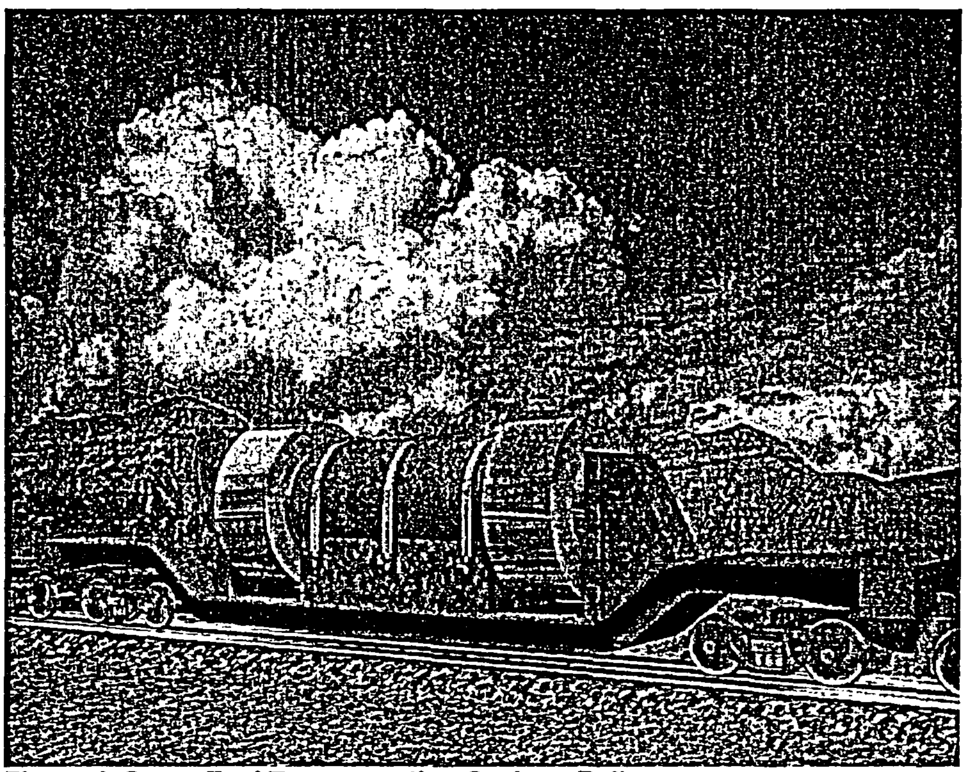

Figure 4. Spent Fuel Transportation Cask on Railcar (Image Courtesy of HOLTEC International)

Standard

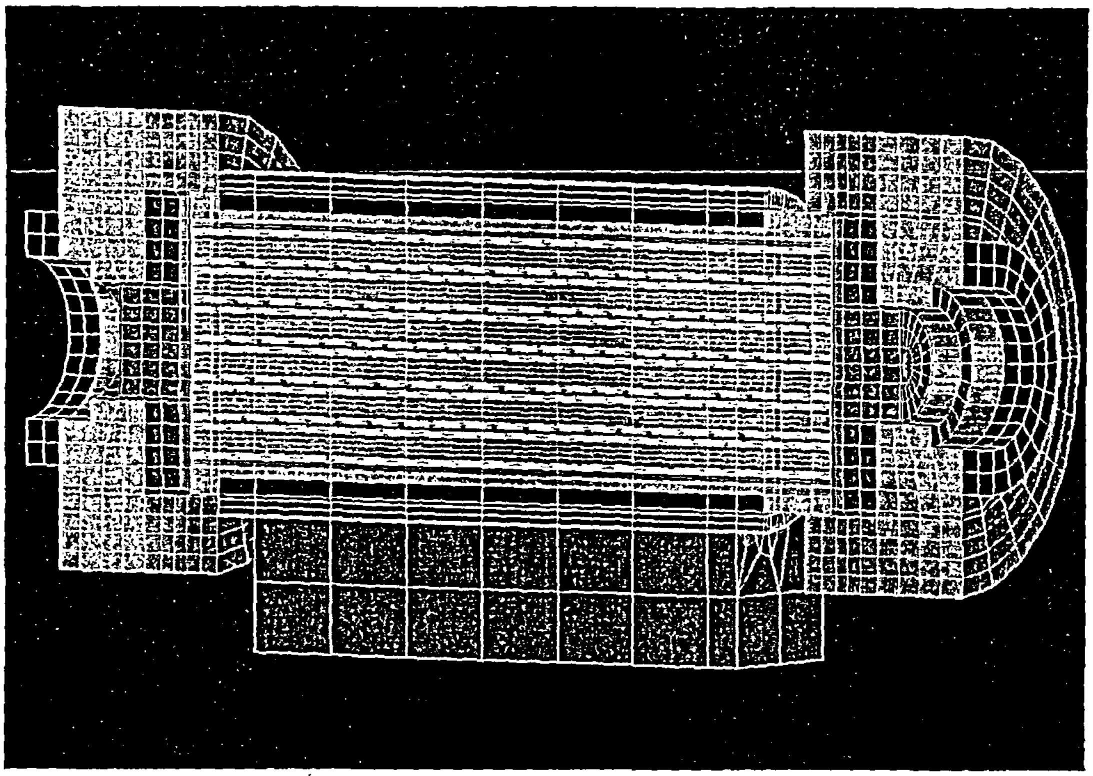

Figure 5. ANSYS® Hi-Star 100 Cask Analysis Model Element Plot

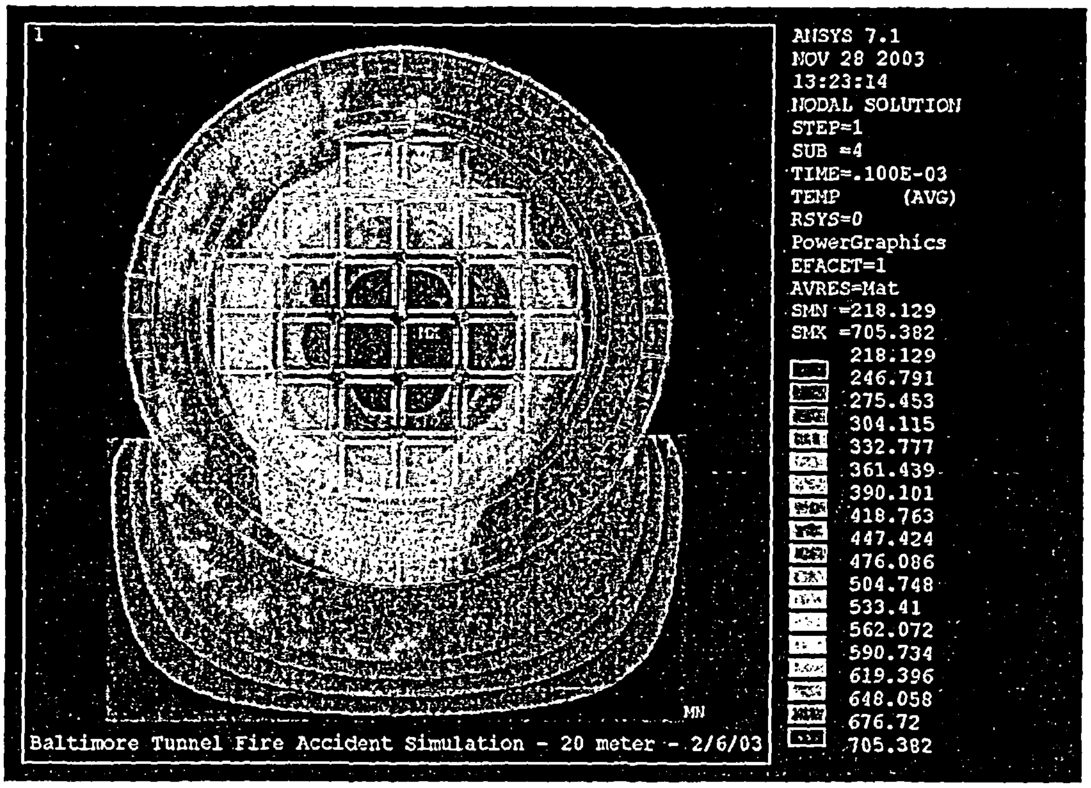

Figure 6. Hi-Star 100 Cask Normal Condition Temperature Distribution

Standard