ANSYS DRAFT 4

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

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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), the agency responsible for evaluating the performance of spent fuel transportation casks under accident conditions, undertook an investigation of the hypothetical 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 Laboratory (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 2 separate cask designs for thermal performance. This paper describes the analytic models used in the assessment and presents the staff's results.

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 typical spent fuel transportation cask. This paper will briefly recount factual information surrounding the Baltimore tunnel fire event as well as describe analyses performed by the National Institute of Standards and Technology (NIST) and confirmed through metallurgical studies through the Center for Nuclear Waste Regulatory Analysis (CNWRA), to quantify the thermal (fire) environment that existed during the event. This paper will also describe analyses conducted to assess the performance of two spent nuclear fuel transportation rail 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 derailed 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, as shown in Figure 1, was punctured by the car's brake mechanism which failed during the derailment. Tripropylene

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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 conducted by 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. Firefighters were able to visually confirm that the tripropylene tank car was no longer burning approximately 12 hours after the fire started.

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.[1,2] 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.

To validate FDS for tunnel fire applications, NIST developed fire models in FDS based on the geometry and test conditions 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.[3] 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 (56°C) of the recorded data.[4]

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. This is shown in 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).[4]

CNWRA Materials Exposure Analysis

Staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA), along with staff from NRC and NIST, examined railcars and tank cars removed from the Howard Street tunnel approximately one year after the fire. The examination of physical evidence provided the staff with further insight into the fire environment that existed in the tunnel during the accident. Staff from CNWRA also collected material samples from the box and tank cars inspected. By performing different metallurgical analyses 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 CNWRA was able to estimate exposure time and temperature for the samples tested. The material time/temperature exposures determined by the CNWRA's analyses were consistent with the conditions predicted by the NIST FDS tunnel fire model.[5]

Transportation of Spent Nuclear Fuel

NRC regulations require that spent fuel transportation casks be evaluated for a series of hypothetical accident conditions that include a 30 foot (9 meter) drop test, a 40 inch (1 meter) pin puncture drop 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.[6]

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 two different NRC-approved spent fuel transportation cask designs. These include the HOLTEC HI-STAR 100 and Transnuclear TN-68 rail transportation casks. The ANSYS finite element analysis (FEA) code[7] was used to model the HI-STAR 100, and this model will be discussed in detail. The TN-68, modeled using the COBRA-SFS finite-difference thermal package, will be discussed briefly.

HOLTEC HI-STAR 100 Cask

This design utilizes a welded multi-purpose canister (MPC), to contain spent fuel. The MPC has an integral fuel basket that accommodates 24 spent Pressurized Water Reactor (PWR) fuel assemblies, with a maximum total decay heat load of 20.0 kW. The MPC is placed into the transportation cask (or overpack) for shipment after it has been loaded with spent nuclear fuel and the closure lid 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 carbon steel stiffening fins. The outer shell of the cask is fabricated of 0.5 inch (1.27 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 event of a cask drop accident and to provide insulation in the event 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.

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 carbon 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. This cask was analyzed with COBRA-SFS, a code that has been developed by Pacific Northwest National Laboratory and has been successfully validated in blind validation studies using data collected from spent fuel cask testing with actual spent fuel assemblies.[8,9,10]

Procedure

The staff utilized ANSYS to analyze the HOLTEC HI-STAR 100 cask. Data derived from the NIST model was used to develop the boundary conditions for the casks that were analyzed. The model utilized both temperature and flow data from the NIST Howard Street tunnel fire model. A three dimensional ANSYS FEA model was developed for the HI-STAR 100 with its accompanying support cradle and is shown in Figure 5, respectively. The model developed for the HI-STAR 100 utilized 120,412 SOLID70 and 1,542

SHELL57 thermal elements for conduction, two groups of 13,573 SURF152 surface effect elements for handling both convection states during the pre-fire and fire event, and 288 highly structured AUX-12 generated MATRIX50 superelements for radiation interaction constructed with the use of SHELL57 elements. Solar insolation loading was assigned via heat generation to the first group of 13,573 SURF152 surface effect elements per regulatory requirements.[6]

The material properties from the cask vendor's Safety Analysis Reports (SARs) were verified and then used in the analyses.[11] The models explicitly represented the geometry of the cask, including the internal geometry of the fuel basket, all gaps associated with the basket, as well as the integral neutron absorber plates for the HI-STAR 100.

Spent fuel assemblies in the model were 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.[12]

Analysis

The normal conditions for transport described in 10 CFR 71.71 were used as initial conditions for each analysis.[6] The casks were subjected to an ambient temperature of, 100°F (38°C), with solar insolation (energy) accounted for as well. For pre-fire conditions, the cask surface was given an emissivity value representative of its surface finish (e.g., 0.3 for stainless, 0.85 for painted surfaces). Thermal radiation transfer to the ambient was accounted for using the defined surface effect elements (SURF152).

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To model the decay heat of the fuel, heat generation equivalent to decay heat loads of 68,240 BTU/hour (20kW) for the HOLTEC HI-STAR 100 and 72,334 BTU/hour (21.2kW) for the TN-68, were applied. Conduction was modeled through all components of the casks, including the fuel region, with the use of the SOLID70 elements. The models also included radiation between all plate-to-plate gaps and across purge gas regions present in the model. The MATRIX50 superelements were employed for this task. The fuel region models account for radiation and convection within the assembly 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.[11] Normal condition temperatures distributions for the HI-STAR 100 are provided in Figure 6.

The staff then evaluated the HI-STAR 100 cask response to the tunnel fire environment as predicted by the NIST model. The evaluation had the cask oriented horizontally with one end of the cask facing the fire source. The evaluation 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.[13]

Convective boundary conditions were calculated for the cask models using temperature and flow data from the NIST model, which predicts the flow field present in the tunnel. Tunnel wall temperatures were also obtained from the NIST model. During the fire duration and applicable portion of the post fire duration the convective boundary conditions were based on forced convection correlations that were applied to each cask model in three "zones." The upper portion of the cask was exposed to the maximum temperature and flow that existed in the upper region of the tunnel; the middle portion of the cask was exposed to the maximum temperatures and flow that existed at the mid-height region of the tunnel; and the bottom portion of the cask, including the shipping cradle (if applicable), was exposed to the maximum temperature and flow conditions along the lower elevations of the tunnel.

The impact limiter skins were assumed to remain in place and retain their general shape for the entire fire duration as they are fabricated of stainless steel. The emissivity of the cask body was set to 0.9 for the fire duration to simulate sooting with 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 the NIST model, to determine the cask time/temperature response.

Analysis Results & Discussion

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Conclusion

While the exact duration and temperatures of the actual fire that occurred in the Howard Street tunnel may never be known 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, after considering their response to the tunnel fire environment. Based on the results of the analyses to date, the staff concludes that, had a rail cask similar to the ones analyzed been involved in a fire similar to that experienced in the Baltimore tunnel, the public health and safety would have been protected.

Acknowledgments

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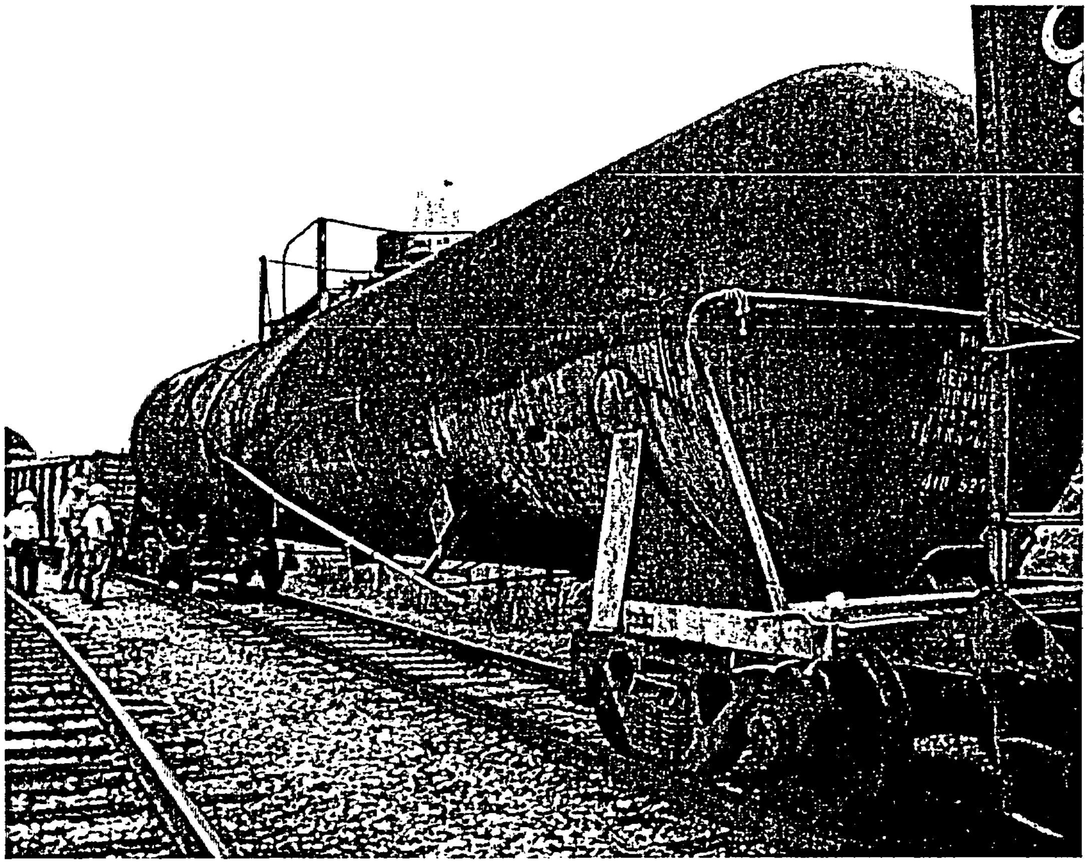

Figure 1. Tripropylene Tank Car

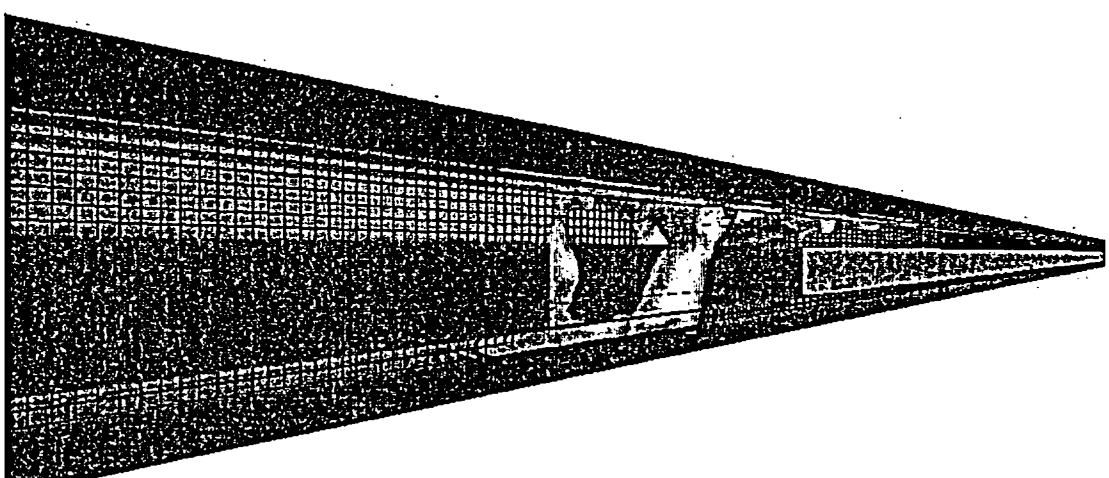

Figure 2. Howard Street Tunnel Fire Model (Image Courtesy of NIST)

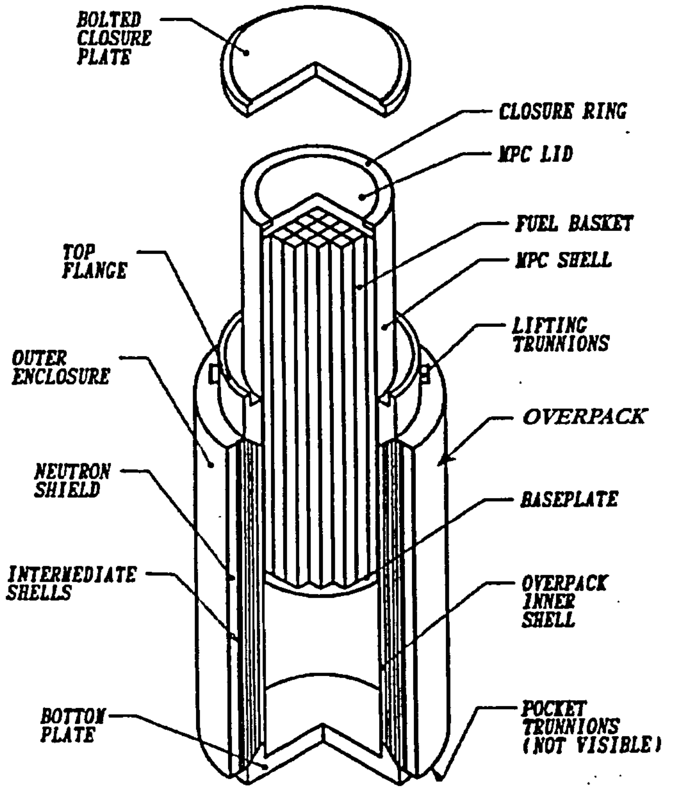

Figure 3. HOLTEC HI-STAR 100 Spent Fuel Cask

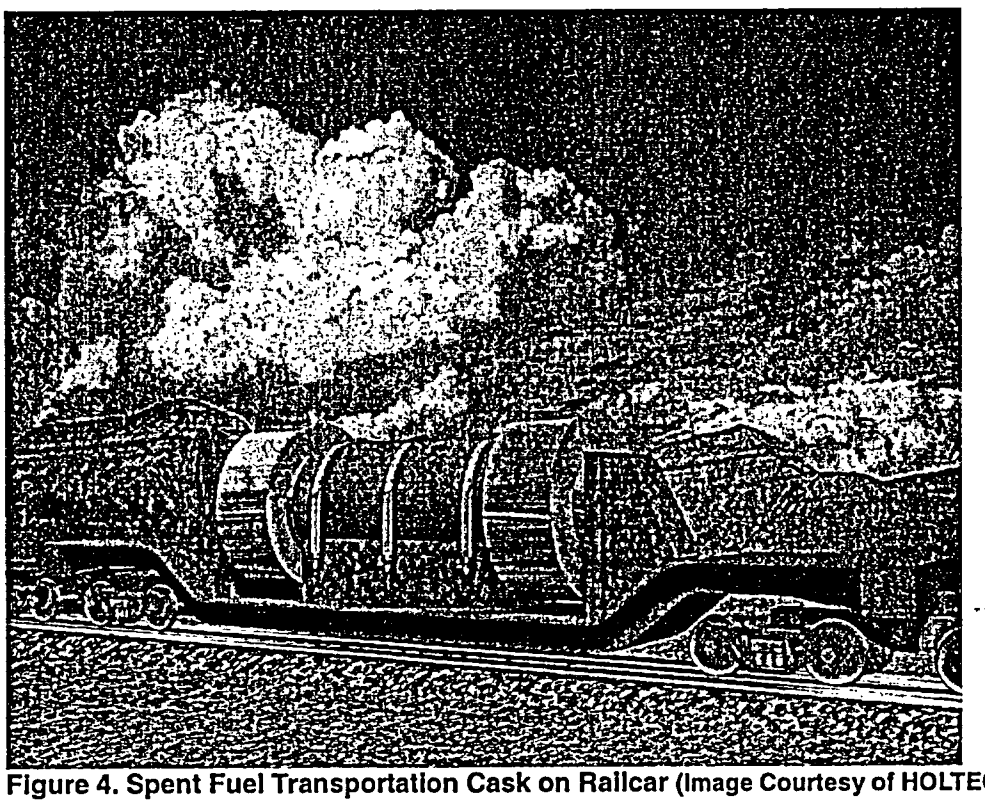

Figure 4. Spent Fuel Transportation Cask on Railcar (Image Courtesy of HOLTEC International)

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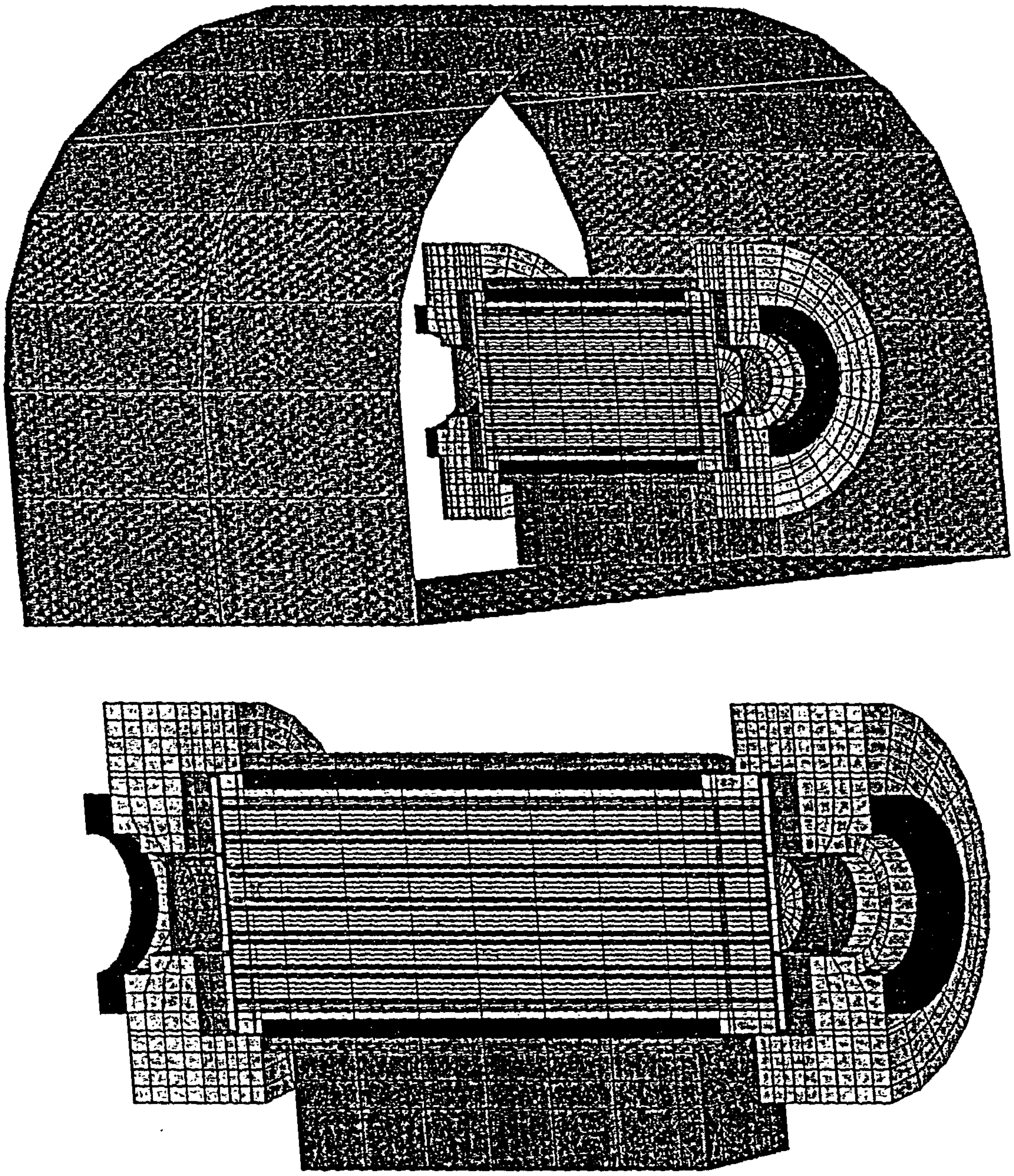

Figure 5. ANSYS HI-STAR 100 Cask Analysis Model Element Plot

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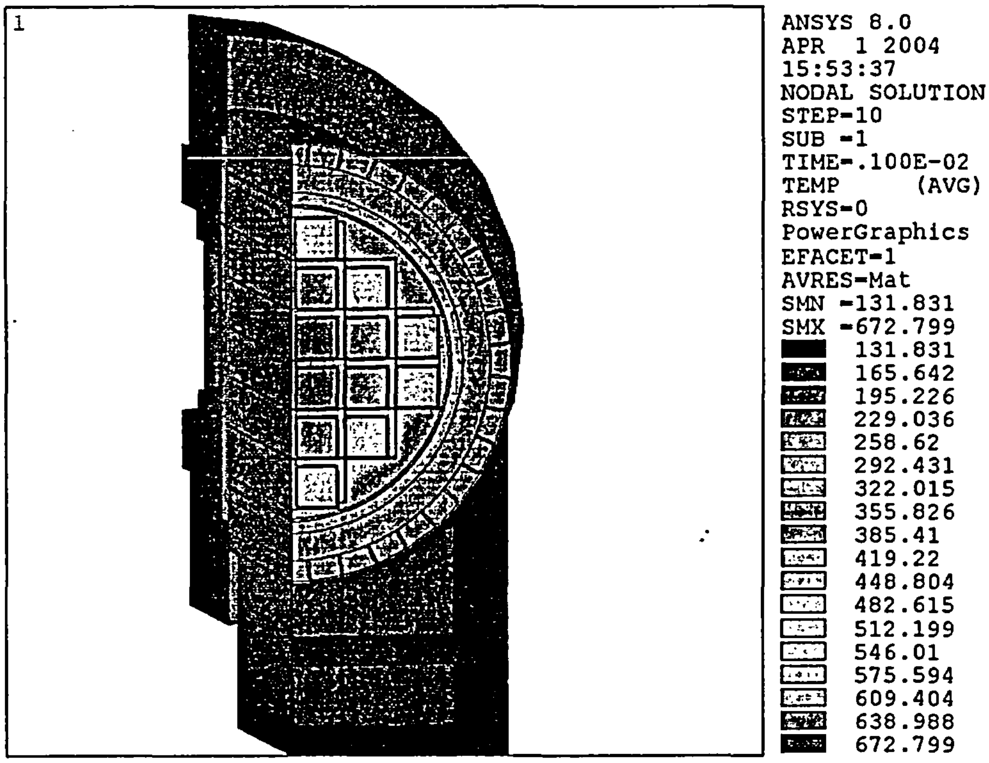

Figure 6. HI-STAR 100 Cask Normal Condition Temperature Distribution

Figures

Tripropylene Tank Car (Figure 1.jpg)

Howard Street Tunnel Fire Model (Figure 2. jpg)

HOLTEC HI-STAR 100 Spent Fuel Cask (Figure 3.jpg)

Spent Fuel Transportation Cask on Railcar (Figure 4.jpg)

ANSYS HI-STAR 100 Cask Analysis Model Element Plot (Figure 5a.png)

ANSYS HI-STAR 100 Cask Analysis Model Element Plot (Figure 5b.png)

HI-STAR 100 Cask Normal Condition Temperature Distribution (Figure 6.png)

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