THE USE OF CAFE-3D FOR THE SIMULATION OF TUNNEL FIRES

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ABSTRACT

Fires after accidents inside tunnels, such as the July 2001 Howard Street Tunnel fire in Baltimore, Maryland, USA, have raised stakeholder questions concerning the survivability of a spent nuclear fuel (SNF) transport cask when exposed to similar thermal environments. The analysis of tunnel fires is a computational challenge because of the need for very large computational domains in order to fully simulate such a problem. In this paper, the analyses of two different tunnel fire scenarios are described and the performance of typical SNF casks when exposed to these tunnel fire environments is discussed. The CAFE-3D fire code is used to model a series of fires inside tunnels, and the thermal performance of a SNF transportation cask within such fire environments is estimated with the use of the MSC PATRAN-P/Thermal finite element analysis code. The methodology used to simulate this type of fire scenario as well as a description of the manner in which the CAFE code couples the computational fluid dynamics and the finite element analysis techniques are also presented.

1. OVERVIEW

The July 2001 Howard Street Tunnel fire in Baltimore, Maryland, USA, raised stakeholder questions in the U.S. concerning the survivability of a spent nuclear fuel (SNF) transport cask in a similar thermal environment. The U.S. NRC and the State of Nevada, USA, have both conducted analytic studies to address these questions. However, there is still debate over the two studies and the applicability to SNF shipments. A technical program at Sandia National Laboratories sponsored by the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, is underway to study the effect of tunnel fires on spent fuel transportation packages. This study will analyze several tunnel fire scenarios and casks in order to better understand this thermal environment, and will determine the severity of tunnel fires relative to the regulatory thermal requirements. This program will also focus on providing sufficient analysis and testing to increase the knowledge of the thermal environment of tunnel fires and improve the analysis techniques currently used in order to better predict the thermal performance of SNF transportation casks in tunnel fires.

Because of the comprehensive nature of this evaluation on the effects of tunnel fires on packages used for the transportation of spent nuclear fuel, a thorough literature survey was performed. A wealth of information was obtained, and a sorting process was established to make the data available to the researchers. Information gained from this literature search forms a firm background, not only for this current Sandia National Laboratories/Department of Energy investigation, but also to provide a comprehensive set of data for other researchers in the field. This sorting process divided the listings found into seven basic categories: 1) Tunnel Fire Theory, 2) Modeling, 3) Testing, 4) Actual Tunnel Fires, 5) Risk Assessment, 6) Tunnel Data, and 7) Routing. Some of these categories are rather large. For example, Tunnel Fire Theory contains subheadings of Heat Release, Simulations, Temperature Stratification, Standards, Smoke Formation, and Ventilation Theory. Both highway and rail tunnels are considered in this study, and the literature search has data on both types of tunnels.

The results from the studies in this program are expected to provide guidance as to the resistance of cask designs to tunnel fires. The studies are also expected to reveal the severity of fires as a function of tunnel design and position within the tunnel. Finally, this work will provide useful data and information for conducting routing analyses and for the communication of the relative safety of SNF shipments to the public.

Two tunnel lengths are examined in this paper as part of the preliminary simulations performed. The first is a tunnel of similar dimensions to the Howard Street Tunnel [1], in which a fire occurred following a derailment in 2001. In this paper, this tunnel is referred to simply as “rail tunnel.” The second is a tunnel of similar dimensions to the Memorial Highway Tunnel [1, 2], in which extensive fire testing was conducted in the late 1980’s. In this paper, this tunnel is referred to as “highway tunnel.” The results from these preliminary fire simulations are presented in this paper in addition to a discussion on the response of SNF transportation packages to these simulated tunnel fires.

2. CAFE CODE AND ITS APPLICATIONS

CAFE, which stands for Container Analysis Fire Environment, is a three-dimensional computational fluid dynamics (CFD) and radiation heat transfer computer code that realistically simulates fires and has been successfully coupled to commercially available finite-element analysis (FEA) computer codes. This coupling facilitates the design and the study of the performance of packages that are used for the transportation of radioactive material (RAM) when exposed to fires. The CAFE fire model is based on a three-dimensional finite volume formulation of basic fire chemistry and fluid dynamics. The code is designed to run on desktop PC, UNIX, or Linux workstations with emphasis on fast-running simulations. While CAFE was originally designed to analyze packages that are used for the transportation of RAM in fully-engulfing pool fires, it has now evolved into a more general fire code that can be used to analyze most fire scenarios of interest. The FEA-CFD coupling is a very powerful tool that can be used for the analysis and assessment of the performance of almost any object that is exposed to a fire environment, whether the object is fully-engulfed, partially-engulfed and/or not engulfed by the fire being modeled. Extensive testing of the coupling of CAFE with MSC PATRAN/Thermal (P/Thermal) has been performed thus far. Therefore, the CAFE-P/Thermal coupling was used for the analyses presented in this paper.

3. DESCRIPTION OF THE CAFE TUNNEL FIRE MODELS

To confirm the usefulness of the CAFE code in predicting thermal environments for casks in or near fires that could occur in tunnels, two basic computer models were developed. One model simulated a fire near a spent fuel truck cask in a two-lane highway tunnel of moderate length, while the other modeled a fire near a rail cask in a long single-track rail tunnel. Cask models were based on the generic steel-lead-steel cask construction provided in the recent NUREG/CR-6672 study of transportation safety [3]

The simulated highway tunnel is 850 m long, 7.9 m high, and 8.8 m wide. A tunnel grade of 3.2 percent was assumed. The truck cask is assumed to have an overall cask length of 5.2 m, and a diameter of 0.7 m, with balsa wood impact limiters of 0.6 m length at each end and 1.3 m outside diameter. Total length of the cask with impact limiters is 5.8 m. From outside to inside, the thicknesses of the steel-lead-steel layers are 2.54, 13.97, and 1.27 cm, respectively. See Figure 1 for grid and model details for the portion of the tunnel near the cask. The cask is assumed to be at the mid-point of the length of the tunnel. Also modeled are the truck tractor and automobiles stopped in the tunnel. A hydrocarbon fuel fire is located adjacent to the cask in the opposite traffic lane and is 4 m by 4 m in dimensions with a fixed evaporation rate of 0.04 kg/(m^2-s). Hydrostatic boundary conditions are applied at the portals of the tunnel with small panels of fixed air ventilation to assist in stabilizing the numeric solution. No attempt was made to model airflow from the fans of the tunnel ventilation system. For the purpose of this paper, the walls of the tunnel are assumed to be adiabatic in both the highway and rail tunnel simulations. In addition, the casks receive heat by radiation and convection from the adjacent large fire described above. The fire duration in both simulations was one hour. Post-fire cooling of the heated objects was not simulated.

The CAFE model of the highway tunnel and scenario has 32,200 finite volume cells. The P/Thermal model has 45,464 finite elements. For the purpose of this paper, no heat generation was assumed inside the cask. Instead, adiabatic boundary conditions were assumed on the interior walls of the cask. Therefore, cask heating is purely induced by the fire.

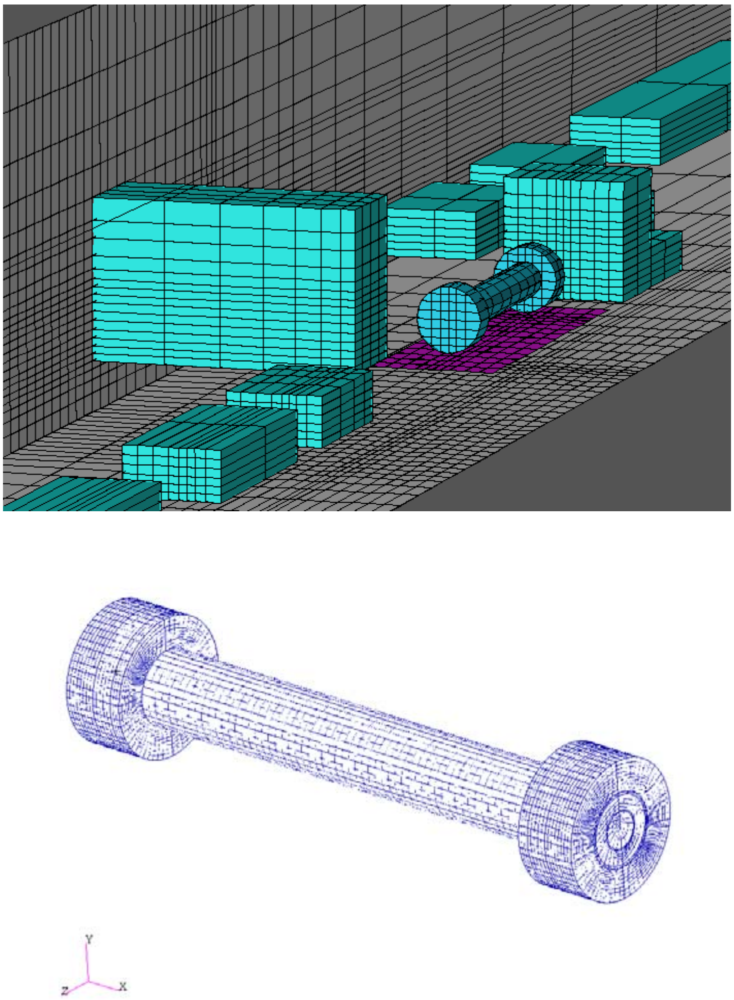


Figure 1. CFD and FEA computer models used for the highway tunnel analysis. On the top, the CAFE CFD highway tunnel fire model. On the bottom, the P/Thermal FEA model of the generic steel-lead-steel truck cask. All objects are floating above the tunnel floor. The large rectangular object to the left of the truck cask simulates a large trailer sideways.

The rail tunnel is 2650 m in length, with a height of 6.4 m and a width of 9.9 m. A grade of 0.8 percent was assumed. The generic steel-lead-steel rail cask is 5 m long and has a diameter of 2 m. From outside to inside, the thicknesses of the steel-lead-steel layers are 4.75, 10.16, and 2.54 cm, respectively. Balsa wood impact limiters of 2 m length at each end have 3 m outside diameter. The overall length of the cask with impact limiters is 6 m. A hydrocarbon fuel fire 14 m in length and 2 m wide with an evaporation rate of 0.04 kg/(m^2-s) is assumed to occur near one tunnel wall adjacent to the cask. Details of the model and grid near the cask are shown in Figure 2. Similar to the highway tunnel accident scenario, the rail cask was also assumed to be at the mid-point of the tunnel length. Again, hydrostatic boundary conditions at the tunnel portals were assumed with small panels of fixed airflow to stabilize the solution. The tunnel was assumed to have no other ventilation than the end portals. Other objects modeled included long strings of boxcars stretching to 120 m in both directions along the tracks.

The CAFE model of the rail tunnel has 25,088 finite volume cells. The P/Thermal model of the rail cask has 82,737 finite elements. As was the case for the truck cask, no heat generation was assumed inside the rail cask. Instead, adiabatic boundary conditions were assumed on the interior walls of the cask. Therefore, any heating of the cask is purely induced by convection and incident thermal radiation from the fire.

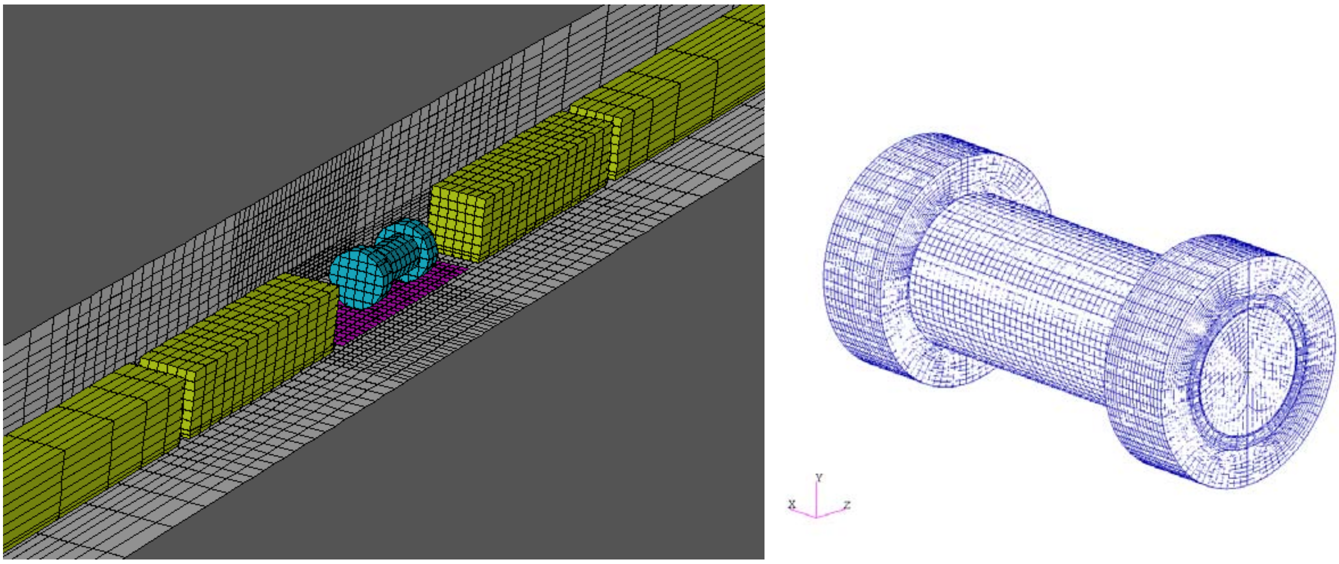


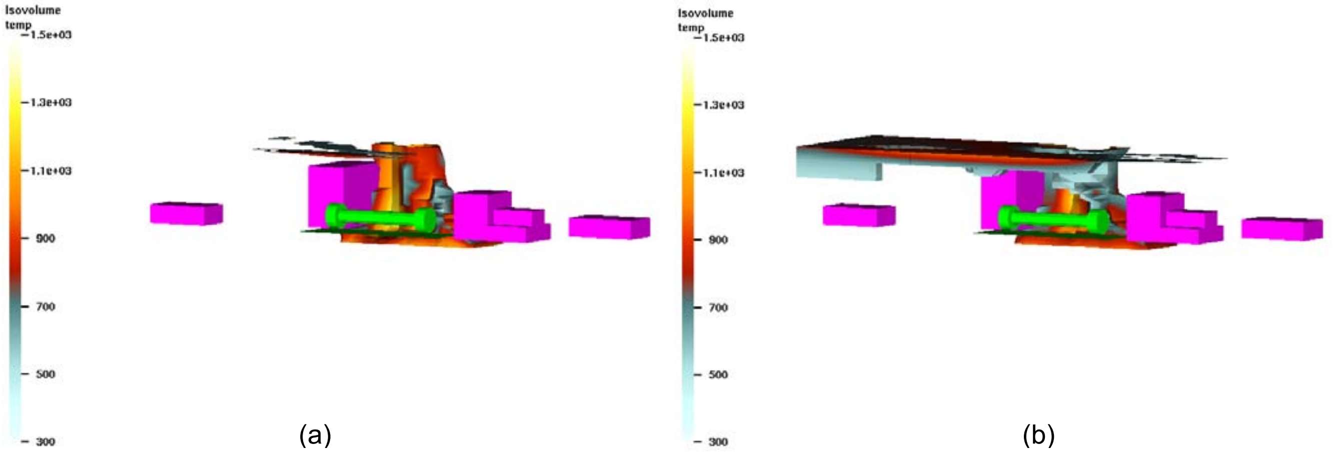
Figure 2. CFD and FEA computer models used for the rail tunnel analysis. On the left, the CAFE CFD rail tunnel fire model. On the right, the P/Thermal FEA model of the generic steel-lead-steel rail cask.

4. PRELIMINARY RESULTS

Results from the preliminary tunnel fire analyses discussed above are presented in Figure 3 through Figure 7. The highway tunnel fire simulation involving the truck cask is presented in Figure 3. In this figure, the fire is illustrated by plotting all cells that contain a soot volume fraction of 0.5 ppm or greater and then coloring this soot with the local gas temperatures. Figure 3(a) is at the early stage of the simulation while Figure 3(b) shows the accumulation of soot inside the tunnel at a later time.

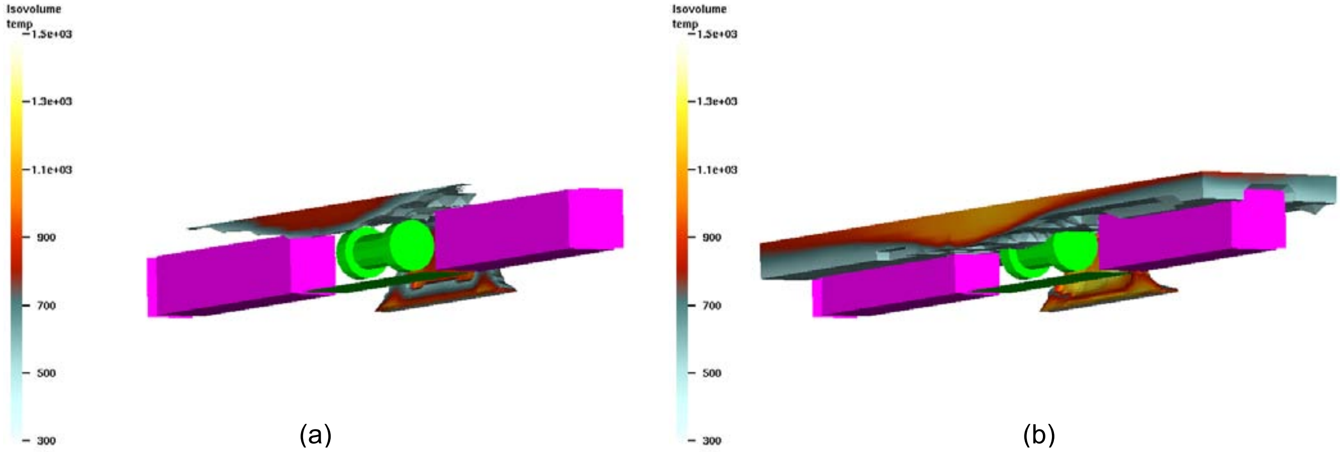
The CAFE results from the rail tunnel fire simulation are presented in Figures 4 and 5. In Figure 4, the cells containing a value of 0.5 ppm for soot volume fraction are displayed and mapped by temperature. Similar to the highway tunnel fire plots, Figure 4(a) is at the early stage of the simulation while Figure 4(b) is at a later time. Temperature layers or isothermal surfaces of 600 and 900 K are presented in Figure 5 for early and late stages in the simulation. In this calculation, isothermal surfaces hotter than 900K were only present in the areas very close to the fire. However, the size of the 900 K and hotter zones depends upon the details of the ventilation within the tunnel and the boundary conditions at the tunnel ends. Figure 5 is important because it clearly illustrates that a fire inside a tunnel will mostly affect the cask only if it is collocated or adjacent to the fire. Heating by convection due to the flow of hot gases in regions away from the fire will require very long exposure times in order to heat the cask significantly.

The heat transfer response of the truck and rail casks to their respective tunnel fire environment is presented in Figures 6 and 7. Note that both casks were mainly heated by radiation heat transfer from the adjacent fire and that the non-uniform, one-sided heated zone clearly illustrates such occurrence. Also, note that the flat face of the impact limiter on the right side of the cask picture in Figure 6 did not experience substantial heating. This is because the large rectangular object representing a large trailer located to the left of the cask (as it is presented in the CFD model shown in Figure 1) obstructed the line of sight to the fire for that flat end of the impact limiter.



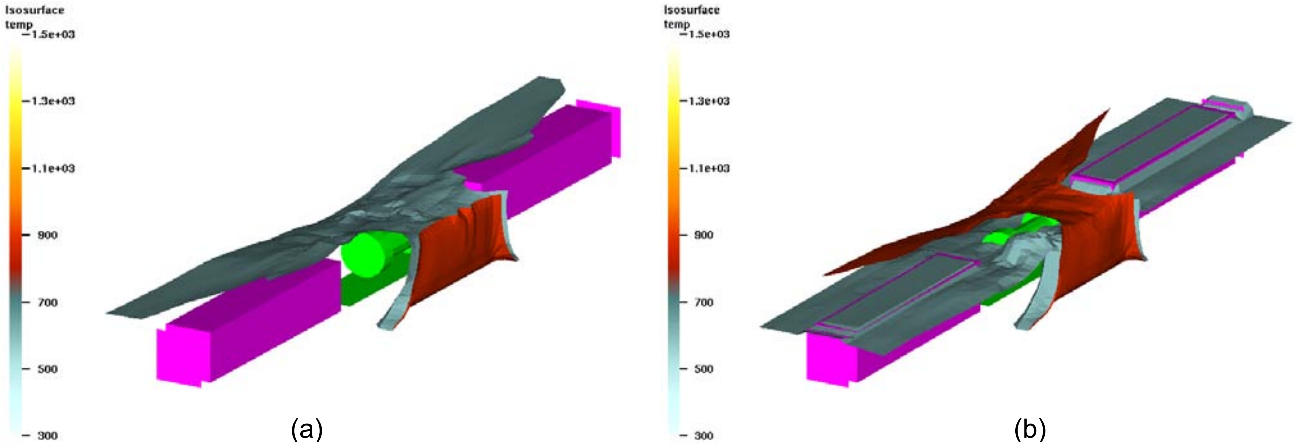
(a) (b)

Figure 3. Contour of 0.5 ppm soot volume fraction mapped by temperature (a) early and (b) late in the highway tunnel simulation. The tunnel slopes upwards from left to right.



(a) (b)

Figure 4. Contour of 0.5 ppm soot volume fraction mapped by temperature (a) early and (b) late in the rail tunnel simulation. The tunnel slopes upwards from left to right.



(a) (b)

Figure 5. Isothermal surface plots at 600 (gray) and 900 Kelvin (red) (a) early and (b) late in the rail tunnel simulation. The tunnel slopes upwards from right to left.

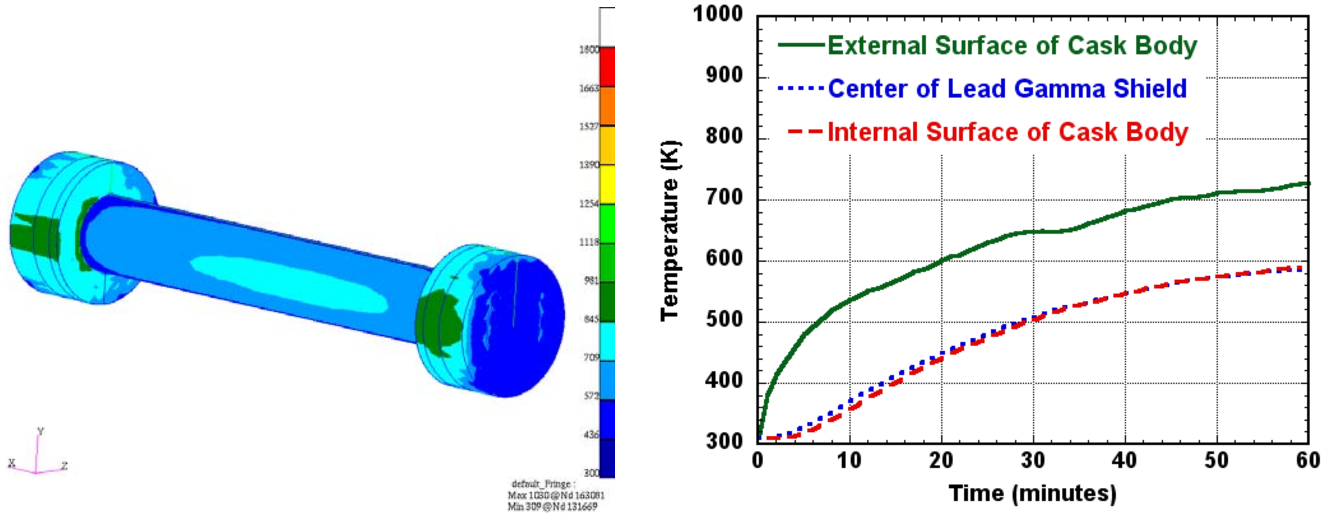


Figure 6. Thermal response of the truck cask. On the cask depiction, the temperature distribution (in Kelvin) is shown on the heated side of the generic truck cask at one hour. The graph shows the temperature history at three locations through the wall on the side of the truck cask facing the fire.

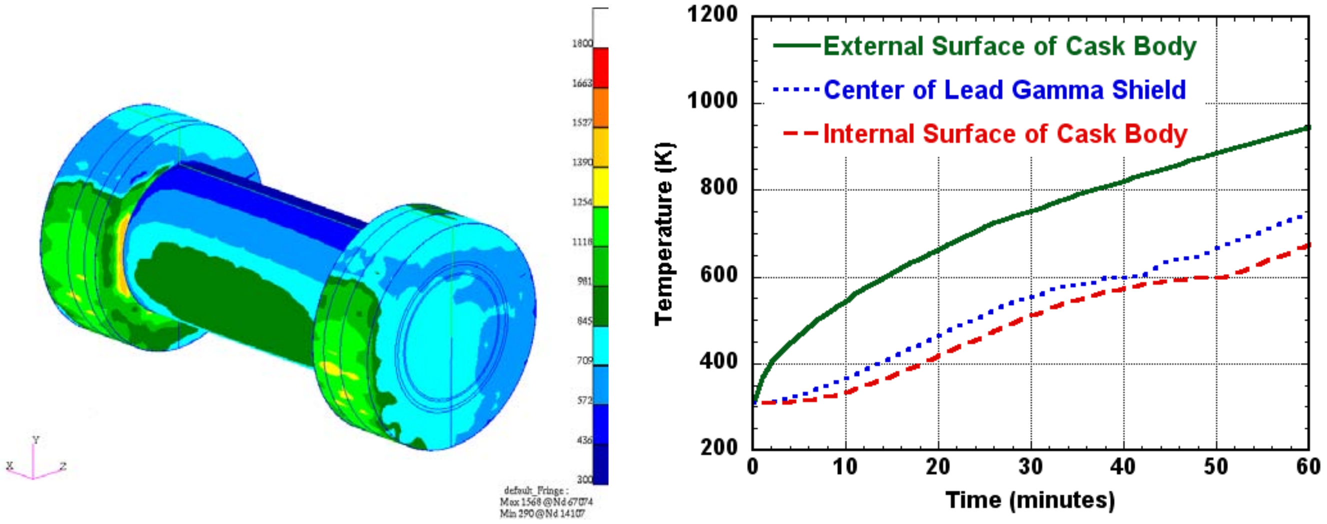


Figure 7. Thermal response of the rail cask. On the cask depiction, the temperature distribution (in Kelvin) is shown on the heated side of the generic rail cask at one hour. The graph shows the temperature history at three locations through the wall on the side of the rail cask facing the fire.

When the thermal response of the rail cask is compared to the truck cask, the rail cask is found to heat more rapidly than the truck cask. Even though the rail cask is more thermally massive than the truck cask, faster heating is due to its position, which was closer to the fire than the truck cask. Unlike the truck cask, portions of the rail cask lead gamma shield went through the solid-to-liquid phase change within the simulated hour. This is indicated in Figure 7 by the horizontal section of the lead gamma shield temperature curve around 40 minutes into the simulation and at the melting temperature of lead (600 K). The phase change of the lead gamma shield layer retarded the heating of the inner wall of the cask as is clearly illustrated in the same figure.

5. SUMMARY

The analysis of tunnel fires is a computational challenge because of the need for very large computational domains in order to fully simulate such a problem. The CAFE-3D fire code is being used to model a series of fires inside tunnels, and the thermal performance of a SNF transportation cask when exposed to these types of fire environments was estimated with the use of the MSC PATRAN/Thermal finite element analysis code.

The preliminary analyses presented in this paper demonstrate the potential use of the CAFE code to model tunnel fire scenarios. The major advantage of using the CAFE-P/Thermal analysis tool as compared to other CFD codes that can simulate fire is that the heat transfer response of an object of interest such as an SNF transportation cask inside a tunnel fire can be captured in detail. It is also important to mention that the different CFD codes that can model fire do it differently. Some of these codes may not have a combustion model and model fire simply as a pre-defined heat source. The CAFE code contains a fairly complete combustion model that allows realistic modeling of fires.

The transient response of the casks presented in this paper provides an indication of the overall thermal response of an SNF transportation cask when exposed to a thermal environment typical of rail and highway tunnel fires. However, these simulations are preliminary and are intended for illustration purposes, which was the reason why the internal heating of the cask was not considered. Detailed modeling of cask characteristics and many more tunnel fire scenarios are in the scope of the tunnel fire program being conducted at Sandia National Laboratories. Results from this comprehensive study will be presented in future conference papers. The benchmarking of the CAFE code against tunnel fire data is also part of this program and the results from those efforts will also be presented in future papers.

Finally, the CAFE code was able to handle the preliminary simulations presented in this paper very well and the computational times using a 3.2 GHz Intel® Xeon™ Linux desktop for the one hour simulations were on the order of 12 hours. Therefore, more robust models with larger mesh densities will be built in the future as part of the modeling efforts of the tunnel fire program at Sandia National Laboratories.

6. REFERENCES

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