COMPUTER SIMULATIONS OF A GENERIC TRUCK CASK IN A REGULATORY FIRE USING THE CASK ANALYSIS FIRE ENVIRONMENT (CAFE) CODE

Hyunchul Ju
Miles Greiner (greiner@unr.edu)
Mechanical Engineering Department/312
University of Nevada, Reno, NV 89509

Ahti Suo-Anttila (ajsuoan@swcp.com)
Innovative Technology Solutions Corporation
Albuquerque NM, 87110-4162

ABSTRACT

The Cask Analysis Fire Environment (CAFE) computer code is designed to accurately predict convection and radiation heat transfer to a thermally massive object engulfed in a large pool fire. It is well suited for design and risk analyses of spent nuclear fuel transport systems. CAFE employs computational fluid dynamics and several fire and radiation models. These models maximize CAFE's accuracy while minimizing its computer turnaround time. However, these models must be benchmarked using experimental results. In this paper, a set of wind velocity conditions are determined that allow CAFE to accurately reproduce recent heat transfer measurements for a thick walled calorimeter in a regulatory pool fire. CAFE is then used to predict the response of an intact (thin walled) generic legal weight truck cask. The maximum temperatures reached by internal components are within safe limits. A simple 800°C, gray-radiation fire model gives maximum component temperatures that are somewhat below those predicted by CAFE. However, the difference would be larger for damaged (thick walled) packages.

INTRODUCTION

Large packages that transport significant (Type B) quantities of radioactive materials must be qualified to withstand 30 minutes in a fully engulfing pool fire without significant release of contents. Regulations describing these tests are contained in International Atomic Energy Agency ST-1 [1] and Title 10, Part 71 of the Code of Federal Regulations [2]. Package designers use a variety of analytical tools to determine if candidate devises would likely meet regulatory requirements. Transportation risk analysts also use computational tools to determine the consequence of both regulatory and extra-regulatory fire conditions. Both design and risk assessment studies require multiple simulations to be performed under a variety of conditions. The computational tools must therefore be rapid as well as accurate.

Simple thermal radiation/convection models are commonly used to predict the heat transfer from a fire to an engulfed package. For example, the ST-1 regulations require that if calculations are performed, they must assume the fire is characterized by a temperature of at least $T_{Fire} = 800°C$, a thermal radiation emissivity of at least $\varepsilon_{Fire} = 0.9$, and an appropriate thermal convection coefficient h_{Conv}. Moreover, the surface absorptivity must be at least $\alpha_{Surface} = 0.8$. Calculations that were recently used to demonstrate compliance of a legal weight truck package employed values of $\varepsilon_{Fire} = 1.0$, $\alpha_{Surface} = 0.9$, $T_{Fire} = 801°C$, and $h_{Conv} = 20\ W/m^2K$ [3]. In this paper, this particular model is referred to as the standard gray fire model. Simple gray fire models require minimal computational time. However, they do not account for the effects that wind or the package have on the fire. These factors may be of particular interest to transportation risk analysts.

A number of sophisticated fire physics and commercial computational fluid dynamics codes are available for simulating fires. These codes include Kameleon from SINTEF, Vulcan from Sandia, CFX from AEA Harwell, and Fluent. These codes have primarily been used to model processes internal to fires, but have not been widely used to predict heat transfer between a fire and a massive engulfed body. Moreover, they require large amounts of run time on specialized computing platforms and hence are not suited for transport cask design or risk calculations.

The Cask Analysis Fire Environment (CAFE) computer code is currently under development at Sandia National Laboratories to meet the need of design and risk studies [4]. CAFE employs a number of models for the physical phenomena that dominate heat transfer from large pool fires to massive engulfed objects. These models greatly reduce the computer turnaround time compared to fire physics codes. The CAFE code can be coupled with finite element analysis (FEA) computer codes that model thermal radiation and conduction within specific cask designs. The coupled CAFE/FEA system simulates a half-hour fire in a few hours on standard workstations.

Results from the coupled CAFE/FEA simulation system are sensitive a number of user-defined parameters. In order for CAFE to be used with confidence, these parameters must be chosen based on measurements in fires whose conditions are similar to those of a severe transportation accident. Large-scale fire experiments were recently performed to assess the accuracy and adjust the overall code [5]. In these experiments, a thick wall calorimeter whose outer dimensions are roughly the same as a legal weight truck (LWT) cask was subjected to a 30-minute ST-1 regulatory fire. The net heat transfer to the calorimeter was measured as a function of location and time.

The current work has two primary goals: (a) Benchmark and adjust CAFE using the recent calorimeter heat transfer measurements, and (b) Use the benchmarked CAFE code to predict the performance of a generic LWT package. This effectively evaluates the package under the same fire conditions that were present during the benchmark experiments (same wind and fuel pool). The thesis by Ju [6] contains a detailed description of this work.

CASK ANALYSIS FIRE ENVIRONMENT (CAFE)

In this work, CAFE is linked to the PATRAN P-Thermal finite element analysis (FEA) computer code (MacNeal-Schwendler Corp., Costa Mesa, California, USA). The calculation procedure is as follows. The cask temperature is set to an initial distribution within the FEA code. CAFE simulates the fire motion and calculates the net heat flux from the fire to the engulfed object. This flux is a function of location and time and it is responsive to the object surface temperature. The FEA code uses the CAFE predicted heat flux to calculate the new object temperature. The new surface temperatures are fed back to CAFE, which then calculates new heat flux distributions. CAFE and the FEA code run alternately for the duration of the simulation.

CAFE uses computational fluid dynamics (CFD) with a one-equation turbulence model to predict fuel and oxygen transport and mixing as well as convection heat transfer to the engulfed object. It uses Arrhenius kinetics to predict reaction rates and Rosseland conduction to model diffuse radiation heat transfer. These models require the user to specify reaction rate constants and a radiation mean free path length.

CAFE incorporates four methods that are specifically designed to maximize its accuracy for this particular problem while minimizing computer time. First, it performs two-dimensional simulations of the fire rather than a full three-dimensional simulation. The second method involves the use of a small computational domain. This requires the user to carefully choose thermal and velocity conditions at the boundary of the CAFE domain. The third method is that CAFE does not run continuously for the duration of the fire. It runs for short periods of time until the fire conditions are in quasi-equilibrium with the cask (roughly 0.5 sec). It then stops running until the FEA program determines that the cask surface temperature has changed by some user-defined value (for example 5°C). As a result, the CAFE CFD simulator only runs for a fraction of the fire duration. Finally, radiation heat loss from the fire to the surroundings is modeled using an artificially reduced heat of reaction (specified by the user) and not directly simulated. Enhancements to CAFE are underway to allow it to perform three-dimensional computational fluid dynamics. The article by Suo-Anttila et al [4] contains a detailed description of CAFE.

RECENT EXPERIMENTAL MEASUREMENTS

This section briefly summarizes the experimental measurements that are used to benchmark CAFE [5,7]. The objective of the experiment was to measure the spatial and temporal variations of heat transfer to a massive cylindrical calorimeter engulfed in a 30-minute, ST-1 regulatory pool fire. The dimensions of the calorimeter are roughly the same as a LWT cask.

The cylindrical calorimeter had length 4.6 m (15 ft), diameter 1.2 m (4 ft), wall thickness 2.54 cm (1 in), mass 3800 kg (8400 lb). It was suspended 1 m over a 7.16 m (23.5 ft) diameter JP-8 aviation fuel pool. Tests were performed during early morning periods when the wind conditions are generally light. Sixteen 6 m (20 ft) high fences were placed in a 24.4 m (80 ft) diameter circle around the facility to further reduce the effect of wind. The individual fences were separated by 1 m gaps to avoid reducing the natural draft of air toward the fire. The wind direction and speed were measured outside of the wind fences. At the beginning of the test the outside-fence wind blew across the calorimeter axis with a maximum speed of 2.9 m/s (6.5 mph). The cross-axis wind component generally decreased for the next 24 minutes and then stopped. The windward side of the calorimeter was not engulfed in flames at the beginning of the test when the wind was strongest. The calorimeter was much more uniformly engulfed after the winds decreased.

The heat flux from the fire to the central ring of the calorimeter was measured at sixteen equally spaced locations around the diameter. The solid line in Fig. 1 shows the total heat per unit area delivered from the fire to the central ring versus time. The heat flux rate (the slope of this curve) is roughly 100 kW/m^2 at the beginning of the test. This rate is much greater at the beginning of the test, when the calorimeter is relatively cool, than it is later when the calorimeter surface approaches thermal equilibrium with its surroundings.

BENCHMARK SIMULATIONS

This section describes the method used to benchmark CAFE against the measured heat transfer data. A two-dimensional FEA model of the experimental calorimeter cross section was constructed. The

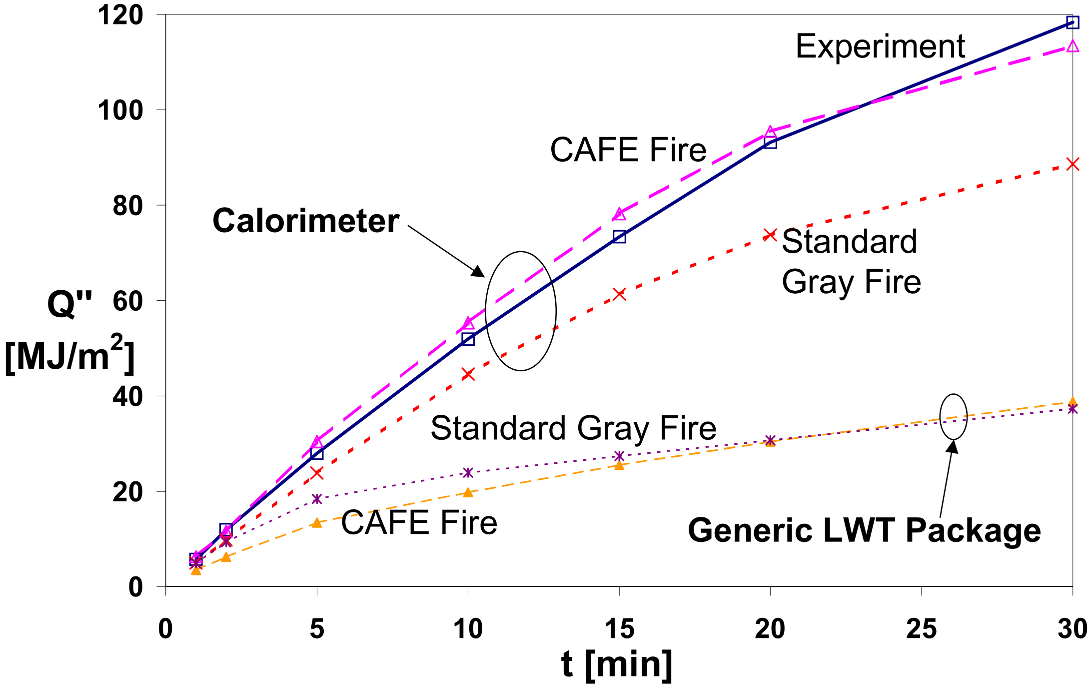

Figure 1, Total Heat Delivered Per Unit Area Versus Time

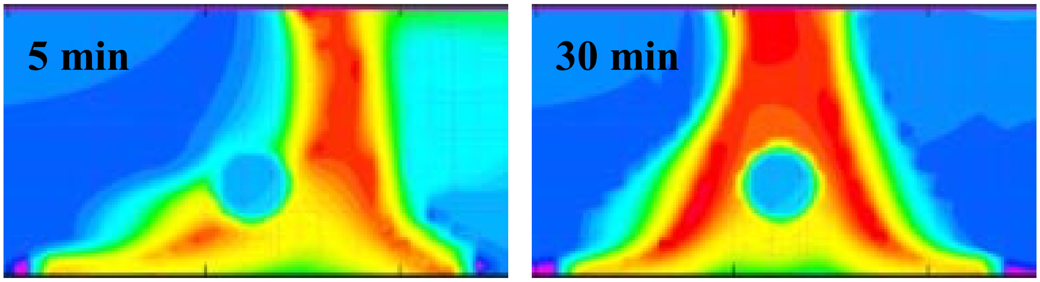

Figure 2. CAFE Simulation Fire Temperature Contour Plots

exterior surface was then subjected to heat flux determined from CAFE. The CAFE-predicted heat flux is dependent on the user-defined velocity applied to the left and right hand boundaries of the computational domain, V_L and V_R, respectively. An iterative technique is used to determine the time-dependent values V_L and V_R that bring the CAFE-predicted heat flux versus time close to the measured data given in Fig. 1. The measured wind velocity was used to guide these iterations.

The boundary velocities have two components. One component is caused by the radial inflow of air due to buoyancy, V_{Inflow}. This component exists even in the absence of wind. The second component is caused by the wind, V_{Wind}. In the current work, the wind blows into the computational domain from the left. Using this convention, the left and right boundary velocities are $V_L = V_{\mathrm{Inflow}} + V_{\mathrm{Wind}}$ and $V_R = -V_{\mathrm{Inflow}} + V_{\mathrm{Wind}}$, respectively. The wind is in the same direction as the buoyancy-induced inflow of air for the left side of the domain, but opposes it on the right side. The buoyancy induced velocity was set to a constant value of $V_{\mathrm{Inflow}} = 0.6$ m/s. The wind induced component decreased linearly with time from $V_{\mathrm{Wind}} = 0.45$ to 0 m/s during the time period $t = 0$ to 23 min, and held at $V_{\mathrm{Wind}} = 0$ thereafter. Figure 2 shows temperature contour snapshots at $t =$ 5 and 30 min. Early in the fire when the wind from the left is strongest the hottest region is blown to the right of the calorimeter. As the wind speed decreases, the calorimeter becomes more completely engulfed in flame. This is consistent with the visual record.

The heavy dashed line in Fig. 1 shows the total heat delivered per unit area versus time as calculated by CAFE and using the wind conditions described above. The predicted heat transfer is close to the measured rate throughout the fire and is 4% below the experimental value at the end. The wind conditions described above are not the only ones that bring the CAFE results close to the experimental data. However, the close agreement suggests that CAFE accurately determines the dependence of net heat transfer on surface temperature for these conditions.

Another CAFE simulation was performed using constant wind conditions of $V_{Wind} = 0.18$ m/s and $V_{Inflow} = 0.42$ m/s. In these calculations, the level of package engulfment did not change with time and the shape of the total heat flux versus time curve was significantly different from the measured curve shown in Fig. 1. We conclude that, even for the light winds present in the experiment, it is necessary to take the unsteady wind conditions into account in order to accurately simulate heat transfer from the fire to the calorimeter. Finally, the heavy dotted line in Fig. 1 shows the heat transfer that is predicted using the standard gray fire model. This model predicts 28% less heat transfer to the calorimeter than is experimentally measured.

GENERIC LEGAL WEIGHT TRUCK (LWT) CASK

In this section, the benchmarked version of CAFE is used to determine the response of a generic LWT cask to a regulatory fire. This determines the package response to the same fire conditions that existed during the calibration experiment (same pool size and wind conditions). The maximum temperature reached by each internal component is determined and compared to limit values. Simulations using the standard gray fire model are then compared to the CAFE calculations.

Figure 3 shows a finite element model of the cask cross section. This package transports seven fuel assemblies. The cross sections of these assemblies are 7.72 cm wide by 8.18 cm tall. Each assembly is modeled as a smeared solid with a uniform heat generation rate and temperature dependent effective thermal conductivity. The assemblies are placed in a stainless steel fuel basket with 8.7376 cm square openings. Air gaps of 0.508 cm separate the assemblies from the basket on the sides and top, and a 0.0508 cm gap is on the bottom. The basket is placed inside a 1.76 cm thick stainless steel inner shell with an inner radius of 17.15 cm. The basket is shifted downward under the influence of gravity and the minimum distance between the basket and inner shell is 0.178 cm. The inner shell is surrounded by a 14.5 cm thick lead gamma shield, a 0.14 cm air gap, a 3 cm thick stainless steel outer shell, and a 12.7 cm thick neutron shield tank with a 0.6 cm thick stainless steel outer wall. The neutron shield tank contains a 56% ethylene glycol/water solution during normal conditions of transport. During and after the fire, the solution is assumed to be lost and the tank is filled with air. The outer diameter of the generic package is 0.96 m, while the diameter of the experimental calorimeter is 1.2 m.

Before the fire, the package operates at steady state under normal conditions of transport (38°C ambient air, 193.82 W/m^2 insolation). In Fig. 4, the bars with horizontal lines shows the maximum temperature within the neutron shield shell, the thick outer shell, the lead gamma shield, the inner shell, the fuel basket and the fuel cladding. The components near the center of the package have higher maximum temperatures than those near the edge due to the payload heat generation.

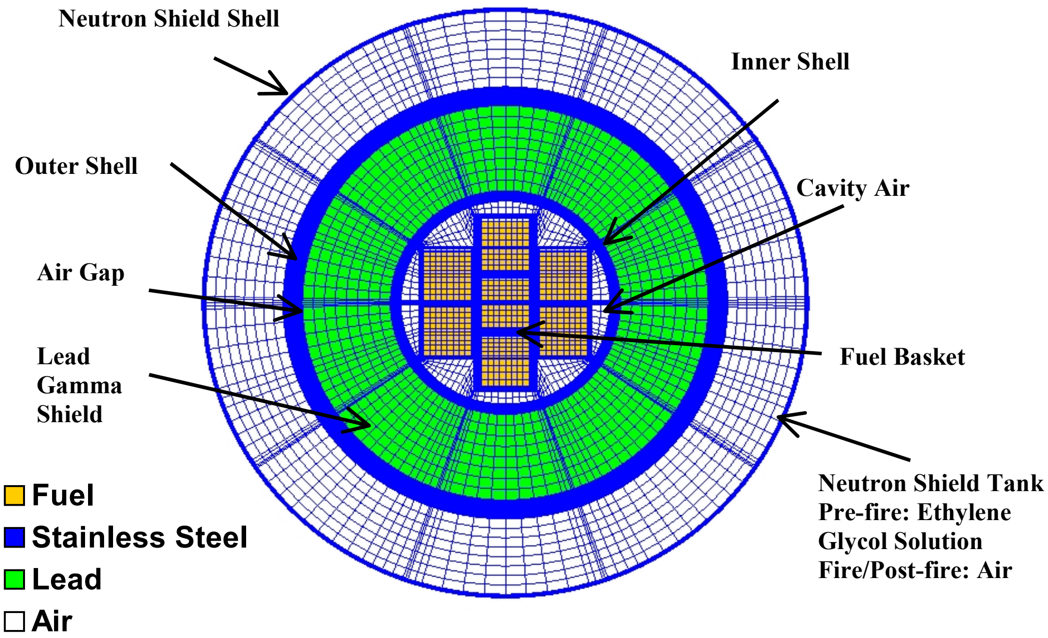

Figure 3, FEA Model of a Generic LWT Package

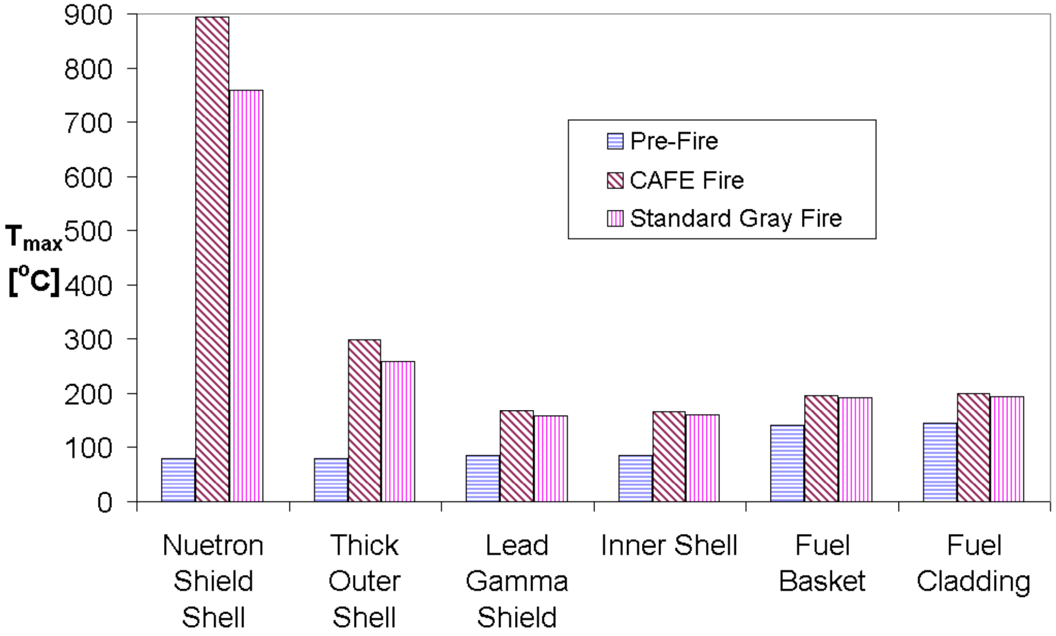

Figure 4, Maximum Component Temperatures

The temperature field from the pre-fire calculation is the initial condition for the 30-minute fire simulation. In Fig. 1, the thinner dashed line shows the total heat per unit area versus time predicted by the benchmarked versions of CAFE. At the end of the 30-minute fire, CAFE predicts that the generic LWT package absorbs only one third as much energy as the calorimeter, even though both objects have roughly the same diameter. The thermal resistance of the air-filled neutron shield causes the heat transfer to the LWT package to be significantly smaller than that to the calorimeter.

The generic LWT package has a relatively thin outer skin (0.6 cm). Its temperature rises to the effective fire temperature very rapidly, reducing the heat transfer rate. The outer surface of the calorimeter is four times thicker than that of the generic LWT package. Its surface temperature remains well below the effective fire temperature for the duration of the fire, leading to very high heat transfer rates.

The fire is followed by cool down period that is similar to normal conditions of transport. The neutron shield shell and outer shell temperatures decrease throughout the post-fire period. The inner components, however, reach their maximums during the post-fire period. In Fig. 4, the bars with diagonal cross hatching show the maximum temperature reached by each package component. The heat flux from the fire causes the neutron shield shell temperature to rise to 894°C, an increase of 815°C compared to the pre-fire condition. However, the fuel cladding temperature increases by only 54°C. The maximum lead gamma shield and fuel cladding temperatures are 167°C and 199°C, which are below the respective limit values of 316°C and 260°C [3].

The maximum component temperatures were re-calculated using the standard gray fire model. The thinner dotted line in Fig. 1 shows the resulting total heat per unit area versus time. The gray model prediction is very close to that from CAFE throughout the fire duration and is only 4% lower at the end of the fire. In contrast, for the thick walled calorimeter the standard gray fire model prediction was 28% below the CAFE prediction. The thermal resistance of the air-filled neutron shield tank is the limiting factor that controls heat transfer for both simulations.

In Fig. 4, the bars with vertical lines show the maximum component temperatures based on the standard gray fire model. This model predicts lower maximum temperatures than CAFE. It under predicts the neutron shield temperature by 135°C compared to CAFE. However, it under predicts the lead gamma shield and fuel cladding temperatures by only 8.0°C and 4.5°C, respectively. These relatively small differences are consistent with the close agreement in total heat delivery from the two models. Both fire models predict that the maximum temperatures for these components are within the allowed range. However, the margin of safety is smaller for the CAFE calculations.

SUMMARY AND CONCLUSIONS

In the current work, the Cask Analysis Fire Environment (CAFE) computer code was benchmarked against a recent fire test. That test measured heat transfer to a thick-walled calorimeter engulfed in a 30-minute regulatory pool fire. Light winds at the beginning of the test tilted the fire so that the calorimeter was not continuously engulfed. The calorimeter received 28% more heat from the fire than would be predicted by a standard 800°C gray-radiation fire model. The time-dependent wind conditions in CAFE were adjusted to bring its heat transfer calculation close to the measured data.

The benchmarked version of CAFE was then used to predict the response of an intact, generic legal weight truck (LWT) package to a regulatory fire. The exterior neutron shield tank of the package is filled with air during the fire and insulates the interior components. The maximum temperatures reached by these components were below their limit values. A simple, 800°C gray radiation fire model predicts only 4% less heat transfer to the package than CAFE, while the gray model is 28% lower for the thick walled calorimeter. The reason the LWT package is less sensitive to different fire environments than the calorimeter is that its air-filled neutron shield tank limits the heat transfer received by the interior components. For an intact transportation package, standard gray fire models predict interior temperatures that are relatively close to those predicted by CAFE. However, for thick-walled objects, such as a calorimeters or a damaged package without its exterior tank, the CAFE predicted heat transfer levels and interior component temperature may be significantly higher than those predicted by gray models.

Finally, the accuracy of CAFE is derived from experimental benchmarking. CAFE therefore cannot be considered a predictive code. Its main usefulness will be in interpolating between benchmarked conditions. CAFE's usefulness will be increased as it is benchmarked against more experimental data. Future benchmarking experiments should consider a range of wind conditions, fire sizes, calorimeter diameters and thicknesses, and locations of the calorimeter with respect to the fire.

ACKNOLEDGEMENT

The US Department of Energy EPSCoR University/Lab partnership program (Grant DE-FG02-98ER45715) and the Nevada Agency of Nuclear Projects (Agreement #00/01.0006) funded this work.

REFERENCES

[1] International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material - 1996 Edition*, Safety Standard Series No. ST-1/Requirements, IAEA, Vienna, 1996.

[2] U.S. Nuclear Regulatory Commission, *Packaging and Transportation of Radioactive Materials*, Title 10 Code of Federal Regulations, Part 71 (10 CFR 71), USNRC, Washington, DC, September 28, 1995.

[3] NAC International, "Safety Analysis Report for the NAC Legal Weight Truck Cask," Nuclear Regulatory Commission Accession Number ML003677743, January 30, 2000.

[4] Suo-Anttila, A. J., J. A. Koski, and L. A. Gritzo, 2000, "CAFE: A Computer Tool for Accurate Simulation of the Regulatory Pool Fire Environment for Type B Packages," in *Proc. 1999 ASME Pressure Vessels and Piping Conference*, Boston, MA, August 1-5, 1999.

[5]Kramer, M.A., Greiner, M., Koski, J.A., Lopez, C., and Suo-Anttila, A., "Measurements of Heat Transfer to a Massive Cylindrical Object Engulfed in a Regulatory Pool Fire," paper number NHTC01-11466, *Proc.* 35th National Heat Transfer Conference, Anaheim, California, June 10-12, 2001

[6] Ju, H. "Computer Simulation of a Spent Nuclear Fuel Transport Package Engulfed in a Pool Fire Using the Cask Analysis Fire Environment," MS Thesis, Mechanical Engineering Department, University of Nevada, Reno, August 2001.

[7] Kramer, M.A. "Measurements of Heat Transfer to a Massive Cylindrical Object Engulfed in a Regulatory Pool Fire", MS Thesis, Mechanical Engineering Department, University of Nevada, Reno, December 2001.