Design of an Experiment to Measure Heat Transfer to a Massive Object Engulfed in a Full Scale Regulatory Fire

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ABSTRACT
This paper describes the design of a full-scale experiment to measure the heat transfer from a large pool fire to an engulfed 1.2 m diameter, 2.54 cm wall thickness hollow cylindrical calorimeter. This work is focused at determining whether temperature measurements made on the interior calorimeter surface can be used with a one-dimensional inverse conduction solver to accurately determine the heat flux from the fire. The Cask Analysis Fire Environment (CAFE) computational fluid dynamics code is coupled with a commercial finite element program to predict the heat flux to the calorimeter and the calorimeter interior temperatures. Time dependent temperature results for the inner surface are used as input to the Sandia One-Dimensional Direct and Indirect Thermal (SODDIT) solver. This computer program predicts time-dependent surface heat flux profiles that are capable of causing a given temperature variation within one-dimensional solid conduction problems. However, conduction within the calorimeter is multidimensional since the heat flux varies around its circumference. This work shows that circumferential heat flux variation is sufficiently mild to allow accurate use of the inverse solver. A simple correction technique is developed that allows the use of the inverse solver even near the Curie point of the calorimeter material.

INTRODUCTION
Large packages that transport significant quantities of Type B radioactive materials must be qualified to withstand 30 minutes in a fully engulfing pool fire without significant release of contents. These regulations are described in, for example, Title 10, Part 71 of the Code of Federal Regulations, known as 10CFR71 (U.S. Nuclear Regulatory Commission, 1992). Analysis of such fires is complicated by several factors. First, the range of length scales encountered in the physical phenomena is large. For example, turbulence and combustion consist of physical phenomena with scales that range from sub-millimeters to several meters. Secondly, air and thus oxygen are introduced into large pool fires through a complex turbulent mixing process that controls both the location and the intensity of the combustion. Because the fuel-air mixing is limited, combustion temperatures are much lower than the stoichiometric limit. The central region of a pool fire is starved of oxygen, and a vapor dome exists immediately above the pool where evaporated fuel does not have sufficient oxygen to burn. Finally, the presence of soot particles strongly influences the flames. Soot is formed through the inefficient combustion
process that is typical of large pool fires. These particles radiate thermal energy with the characteristic orange-yellow glow observed in fires. Recent studies indicate that the absorption length for thermal radiation in sooty flames is short, on the order of a few centimeters (Gritzo et al., 1998). Evidence of all these effects has been experimentally observed (Koski et al., 1996).

### THE CAFE COMPUTER MODEL

Computer simulations of large pool fires using general-purpose computational fluid dynamics codes require massive amounts of run time on specialized computing platforms. These general-purpose codes are not well suited for cask design studies or transportation risk analyses since these studies require multiple runs under varying conditions. 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. CAFE models the physical phenomena that dominate heat transfer from large pool fires to massive engulfed objects. These models greatly reduce the computer turnaround time.

The CAFE code can be coupled with finite element analysis (FEA) computer codes that model the interior components of specific package cask designs. The calculation procedure is as follows. The cask temperature is set to some initial distribution, \( T_1 \). CAFE calculates the net heat flux from the fire to the engulfed cask. This flux is a function of location and time and it is responsive to the cask surface temperature. The FEA code uses the heat flux to calculate new cask temperatures. 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. CAFE also incorporates four approximations that are specifically designed to maximize its accuracy for this particular problem while minimizing computer time. First, it performs coupled two-dimensional simulations of the fire rather than a full three-dimensional simulation. It actually performs quasi-three-dimensional simulations by using a variable mesh depth in the direction normal to the plane of the simulations. This variable depth allows the code to produce accelerated velocities near the center of the fire that are caused by radially in-flowing air. However, the code cannot model tornado-like vortices). Secondly, it uses a small computational domain with carefully chosen thermal and velocity boundary conditions. Thirdly, 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. 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 and not directly simulated. A more detailed description of CAFE may be found in (Suo-Anttila et al., 1999).

### PROBLEM DEFINITION

All of the approximations used in CAFE are based on current knowledge of large fires. However, benchmarking experiments are planned for the summer of 2000 at Sandia National Laboratories to access the accuracy and/or adjust the overall code. The goal of this paper is to describe the design of a large-scale fire experiment that will be used to benchmark the CAFE computer code.

The test article for this experiment will be a mild steel hollow-cylindrical calorimeter with an outer diameter of 1.22 m (4 ft), wall thickness of 2.54 cm (1 inch) and axial length of 4.57 m (15 ft). This calorimeter will be suspended 1 m over a JP-8 fuel pool and subjected to the conditions of a 30 minute, 10CFR71 regulatory fire. The calorimeter outer surface temperature \( T_o \) and heat flux \( q_o \) will be determined during the experiment as functions of azimuthal (\( \theta \)) and axial (\( z \)) location as well as time \( t \). These data will be compared to CAFE simulation results.

One method for determining the outer surface temperature and heat flux of a cylindrical object is to measure the inner surface temperature and then use an inverse heat transfer calculation to “back out” the outer surface values. Interior thermocouples are used because of the difficulty in obtaining accurate outside surface temperature measurements in large fires. Thermocouple beads strapped to the outer surface of the calorimeter respond to an unknown combination of thermal radiation from the fire and conduction from contact with the calorimeter surface. The resulting measurement does not accurately represent the outer surface temperature. Thermocouples located inside the calorimeter and backed with thermal insulation are shielded from the fire thermal radiation, and respond quickly and accurately to the temperature of the inner surface. This leads to a more accurate estimate of the heat transfer at the outer surface.

Inverse heat transfer calculations attempt to solve an inherently ill posed problem. Specifically, there are an infinite number of exterior heat flux profiles than can cause a given interior temperature trace. In fire tests, the actual exterior surface heat flux experiences a rapid rise from zero to a high value soon after combustion begins. It eventually decreases with time as the calorimeter surface temperature increases and the temperature difference between the test object and the fire decreases. The Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) code (Blackwell et al., 1987) is a Fortran-based computer program that uses sensitivity coefficients and the future time method to determine a unique heat flux versus time trace. It has been successfully used to solve inverse heat
transfer problems in a number of fire measurement experiments (Gregory et al., 1989, Koski et al., 1998).

Simulations were recently performed to predict heat transfer from a 10CFR71 fire to engulfed, hollow cylindrical calorimeters, as well as the resulting calorimeter temperature response (Koski et al., 2000). These simulations were performed using the current version of CAFE coupled with the commercial finite element code MSC PATRAN/P-Thermal. Four different objects were studied to determine the effect of calorimeter diameter and wall thickness on the heat flux distribution. The heat flux to the larger diameter objects was found to be lower than that to the smaller cylinders. Moreover, while thicker walled objects responded more slowly to the fire conditions, their heat flux versus surface temperature boundary conditions were nearly identical to those of thinner walled objects.

One of the objects studied by Koski et al. had the same diameter and thickness as the calorimeter that will be used in the planned experiment. In the current paper, we use those simulation results to generate “artificial” data that is expected to be similar to the data that will be acquired in the planned experiment. We use the simulated data to test the ability of the SODDIT code to accurately determine outer surface temperature and heat flux based on inner surface temperature measurements.

The SODDIT code is designed to solve one-dimensional heat transfer problems. However, we will see that the heat flux to the test article is predicted to be non-uniform. As a result the inverse heat transfer problem is multi-dimensional. A recent paper evaluated the ability of SODDIT to solve inverse heat transfer problems on hollow cylinders with non-uniform heat flux distributions (Lopez et al., 2000). That work found that SODDIT performed well during times soon after heat flux was applied to the object, and in regions where the spatial variation of heat flux was not severe. However, under some circumstances, the SODDIT-predicted heat flux was significantly different from the applied value. In the current work we determine if the heat flux predicted by the CAFE/PATRAN simulations is mild enough to allow the use of a one-dimensional inverse method to accurately predict the outer surface conditions.

Finally, inverse heat transfer solvers perform best when analyzing conduction within bodies with regular material properties. The experimental test article will be constructed from 1020 carbon steel. The product of density and effective specific heat and the thermal conductivity versus temperature of this alloy are shown in Fig. 1. Mild steel exhibits a solid-solid phase change (phase rearrangement) at 768°C known as the Curie point. This phase change causes a spike in the effective specific heat. The area under this spike is equal to the latent heat. However, the temperature width is dependent on the rate of heat input. In this paper, we describe how this spike causes SODDIT to predict incorrect outer surface temperature and heat flux over a certain temperature range. Moreover, we describe a correction that can be applied to handle this problem.

![Figure 1 1020 Carbon steel properties](image)

The next section describes external surface temperature and heat flux versus time as predicted from the current version of CAFE. After that we describe the use of SODDIT to predict the outer surface values based on inner surface temperatures. Finally, conclusions are drawn.

**CAFE RESULTS**

This section describes the results of a coupled CAFE and PATRAN/P-Thermal calculation (Koski et al., 2000). That calculation is used to predict the outer surface heat flux and the inner and outer surface temperatures versus time and location of a long hollow cylinder engulfed in a 10CFR71 fire. The CAFE portion of the calculation used a single two-dimensional rectangular computational domain. It simulated the behavior of a fire and the resulting heat flux versus time and location from the fire to the engulfed object. The PATRAN portion of the calculation employed an annular-shaped two-dimensional finite element model with forty nodes in the azimuthal direction and four nodes in the radial direction. It predicted the temperature response of the 1.22 m outer-diameter, 2.54 cm thick cylindrical calorimeter to the heat flux predicted by CAFE. The inner calorimeter surface was perfectly insulated.

Figure 2 is a gray-tone temperature plot of the two-dimensional cylindrical object at the end of a thirty-minute fire. These temperatures are calculated by the P-Thermal FEA program in response to the CAFE predicted heat flux. In this figure, lighter hues represent higher temperatures. We see that the object temperature is not uniform, but is hottest at the top and coolest at the bottom. A relatively cool vapor dome between the object and the fuel pool, which is below the object, contributes to this temperature stratification. Moreover, the temperature field is nearly symmetric left-to-right. Four locations are also identified at the top, bottom and both sides of the object.

The time-dependent temperatures on the outer surface of the top, side and bottom locations are shown in Fig. 3. The side location represents the average of the left- and right-hand nodes in Fig. 2. Note that the bottom of the calorimeter is predicted to be the coolest location throughout the fire period. The side temperature slightly exceeds the top value for the first
eight minutes of the fire. After that time, the top of the calorimeter becomes the hottest location on the object. We note a decrease in the slope of all three curves during the time that they are near the temperature $768^\circ C$ (time $t = 11.5$ minutes for the top node and $t = 15$ for the bottom). The high effective specific heat of the material at its Curie point causes this. At the end of the thirty minute fire, the temperature at the top of the cask is $1041^\circ C$ while the temperature at the bottom is $129^\circ C$ cooler.

Figure 4 shows the net heat-flux from the fire to the calorimeter versus time and location. These flux values are predicted by CAFE. These curves are smoothed with eight-point moving averages. The heat flux before the fire begins is zero. We see that the net heat flux at all three locations jumps to a high value at the beginning of the fire. The flux then decreases with time as the temperature of the calorimeter increases. Moreover, the heat-flux is not uniform over the calorimeter surface. For the first 17 minutes of the fire, the bottom heat-flux is the lowest of any location due to its proximity to the relatively large vapor dome. Initially the side heat-flux is the greatest of the three locations. However, after four minutes, the heat-flux at the top becomes the highest. At 

t = 17 minutes, the net heat-flux at the top and side drop below the flux at the bottom. We see that the heat flux to the outer surface is highly dependent on time and location.

**SODDIT RESULTS**

Figure 5a shows temperatures at the top of the calorimeter versus time. The inner surface temperature $T_i$ is shown using a thin line while the outer surface temperature $T_o$ is represented by a thick line. Both of these temperatures are predicted by the PATRAN/P-Thermal FEA program. The triangles show the outer surface temperature predicted by SODDIT, $T_{os}$. The SODDIT predictions are based solely on the inner surface temperature trace using a four-future-time calculation.

![Figure 3](image3.png)

**Figure 3** Surface temperature versus time and location

![Figure 4](image4.png)

**Figure 4** Smoothed Heat Flux versus Time and location

![Figure 5a](image5a.png)

**Figure 5a** Temperature versus time of inner and outer surfaces at the top location
Both temperatures begin at $T_1 = 38°C$ and rise after the fire begins. However, outer temperature exceeds that of the inner boundary during the fire period. We see that the SODDIT prediction is in good agreement with outer surface temperature for the full 30-minute duration of the fire except for times $t = 12$ to 14 minutes. The errors at this time are caused by the Curie point specific heat spike at $T = 768°C$.

The ‘x’ data trace in Fig. 5a shows a linear bridge between the temperatures before and after the irregular jump. This line is also in good agreement with the outer surface temperatures. Figure 5b shows the percent error in the temperature rise $E_T = 100\% \times (T_{os}(t) - T_o(t))/T_{mean}$ versus time and location. In this expression $T_{os}(t)$ is the linear bridge temperature during the temperature spikes at each location (time $t = 12$ to 14 minutes for the top location), and it is the SODDIT predicted temperature outside that time period. Furthermore, $T_{mean}$ is the time average value of $T_o(t)$ at each location. We see that the percent error in the temperature rise is always less than 3%.

Figure 6a shows the heat flux versus time to the top of the calorimeter. The solid line shows the heat flux to the outer surface predicted by CAFE. The triangles show SODDIT predictions based on the inner surface temperature using a four-future-time calculation. The predicted heat flux is in good agreement with the applied value for the full fire duration except during the time period $t = 11$ to 18 minutes. During this time the predicted heat flux oscillates wildly above and below the actual values. Both the period of time when significant errors are observed and the magnitude of these errors are much larger for the heat flux than they are for the predicted outer temperature shown in Fig. 5a. However, a straight-line bridge is in good agreement with the applied outer surface heat flux.

Figure 6b shows the percent error in the heat flux, defined as $E_q = 100\% \times (q_{os}(t) - q_o(t))/q_{mean}$ versus time at the top, bottom and side locations. In this expression $q_{mean}$ is the time average value of $q_o(t)$ at each location. Moreover, $q_{os}(t)$ is the linear bridge value for times during the period when the SODDIT-predicted heat flux is irregular ($t = 11$ to 18 minutes for the top location) and it is the SODDIT-predicted value outside the time period. The value $E_q$ is both positive and negative during the fire period and its maximum value is less than 12% for the majority of the time, with a larger error at the initial time.

Figure 7 is a radial plot of outer surface temperature versus azimuthal location and time. Solid lines are used for the PATRAN/P-Thermal predicted outer temperatures. Dotted lines are SODDIT predicted values based on inner surface temperature using four-future-time calculations. These predicted values employed the linear bridge correction described in connection with Fig. 5a. At time $t = 0$ (not shown) the cask temperature is uniform at $T_1 = 38°C$. The outer surface temperature increases with time. The temperature profile exhibits a square-shape for times $t \leq 10$ minutes, with the maximum temperatures at the upper and lower left-hand and
right-hand portions of the object. Moreover, we see that the temperatures along the upper half of the calorimeter are generally higher than values near the bottom. Finally, we see that the SODDIT predicted temperatures with the linear bridge corrections are in good agreement with the outer surface temperature at all locations throughout the 30 minute fire.

Figure 8 shows the variation of outer surface heat flux with azimuthal location and time. The solid lines are from CAFE calculations. The dotted lines are SODDIT predicted values with linear bridge corrections. In this plot we see that the heat flux magnitude is generally highest early in the fire period and it decreases with time as the calorimeter surface temperature increases. We see that the flux profile also has a square-shape at early time $t \leq 10$ minutes and it becomes rounder at later times. The heat flux to the bottom of the object is lower than that to the upper portion. Moreover, the linear-bridge corrected SODDIT heat flux is in good agreement with the applied values. Finally, examining figures 7 and 8 we see that twenty azimuthal measurements will resolve the predicted heat flux and temperature variations.

**CONCLUSION**

The Cask Analysis Fire Environment (CAFE) computer code simulates the thermal behavior of large pool fires and their interaction with massive engulfed objects. It is currently under development to provide accurate thermal boundary conditions for predicting the temperature response of nuclear waste transport casks engulfed in regulatory fires. This code employs a number of special models that are designed to maximize its accuracy while minimizing the required computer run time. These models are based on current knowledge of fire behavior. However, benchmarking experiments will be performed in the summer of year 2000 in order to assess the accuracy and/or adjust the overall code. The heat flux and temperature at the outer surface of an engulfed hollow cylindrical calorimeter will be measured and compared to results from CAFE. This calorimeter will be fabricated from mild steel.

This paper describes the use of a technique to determine the time and location dependent outer surface heat flux and temperature from temperature measurements made from locations on the inner surface of the calorimeter. This technique employs the Sandia One-Dimensional Direct and Indirect Thermal (SODDIT) code. This code is designed to solve one-dimensional inverse heat transfer problems in solid bodies with regular (smooth) thermal properties. However, simulations using the current version of CAFE show that the heat transfer from the fire to the calorimeter is multi-dimensional. Moreover, mild steel experiences a spike in its
effective specific heat at 768°C due to a solid-solid phase change known as the Curie point.

A correction technique was developed that allows SODDIT to give accurate results even near the Curie point. Furthermore, the results of this study show that the circumferential heat flux variation is sufficiently mild to allow the use of a one-dimensional inverse heat transfer technique to be used over the entire cask and throughout the fire duration. The error in the predicted surface temperature rise is always less than 3%, while the error in the heat flux was nearly always less than 12%. Moreover, measurements at twenty azimuthal locations will resolve spatial variation in the heat flux. Finally, this paper assesses errors introduced through the use of SODDIT. Other errors (thermocouple calibration errors, material property errors, etc.) have not yet been addressed, but will be considered further in the design process.

ACKNOWLEDGMENTS

The US Department of Energy funded this work under DOE/EPSCoR Notice 98-02.

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