Proceedings of the 16th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2010
October 3-8, 2010, London, UK

Fire Tests and Analyses of a Rail Cask-Sized Calorimeter

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ABSTRACT

Three large open pool fire experiments involving a calorimeter the size of a spent fuel rail cask were conducted at Sandia National Laboratories' Lurance Canyon Burn Site. These experiments were performed to study the heat transfer between a very large fire and a large cask-like object. In all of the tests, the calorimeter was located above the center of a 7.93m diameter fuel pan, elevated 1m above the fuel pool. The relative pool size and positioning of the calorimeter conformed to the required positioning of a package undergoing certification fire testing. Approximately 2000 gallons of JP-8 aviation fuel were used in each test. The first two tests had relatively light winds and lasted 40 minutes, while the third had stronger winds and consumed the fuel in 25 minutes. Wind speed and direction, calorimeter temperature, fire envelop temperature, vertical gas plume speed, and radiant heat flux near the calorimeter were measured at several locations during each test. Fuel regression rate data was also acquired.

The experimental setup and observations pertaining to fire characteristics are described in this paper. Results from three-dimensional fire simulations performed with the Cask Analysis Fire Environment (CAFE) fire code are also presented. Comparisons of the thermal response of the calorimeter to the results obtained from the CAFE simulations are discussed. In general, CAFE underestimated the average internal surface temperature near the top of the calorimeter, while it over estimated the average internal surface temperature on all other sides of the calorimeter. Thus, results showed that CAFE slightly over estimated the overall average temperature of the surface of the calorimeter.

INTRODUCTION

Large, fully-engulfed objects, such as rail-cask-type spent fuel packages, have a great impact on the surrounding fire environment. To adequately predict incident heat flux to rail-cask-type spent fuel packages, computational fluid dynamics (CFD) models have been employed at Sandia National Laboratories (SNL). Because of the impact that this massive objects have on fires, CFD models must be benchmark against experimental data from tests that have similar size objects [1] to adequately assess the predictive capabilities of the CDF models.

Three very large open pool fire experiments were conducted at SNL to gather heat flux and temperature data from pool fires using a calorimeter the size of a spent fuel rail cask. These data were used to benchmark temperature response predicted by the Container Analysis Fire Environment (CAFE), the CFD code used at SNL to analyzed 10 CFR 71.73 regulatory fire cask scenarios. In all tests, the calorimeter was located above the center of a 7.93m (26ft) diameter fuel pan which had approximately 7.58m^3 (2000 gallons) of JP8 per test. The total burn time for each test was greater than 25 minutes. All tests were conducted in relatively low wind conditions (<5m/s) to assure the calorimeter was fully or partially engulfed.

This paper presents the pool fire experimental setup and data that was collected. Due to the large amount of data collected, only the data for Test 1 is presented here. A more complete description of the test data is included in Greiner et al [2]. This data includes wind data, fuel pool regression rate, and calorimeter temperatures. The calorimeter internally measured surface temperatures are then compared to results obtained from the CAFE/P-Thermal benchmark run.

BACKGROUND

CAFE was design to calculate the thermal insult to a spent fuel transportation package using computationally fast and proven numerical methods. To achieve computational efficiency, CAFE relies on some physics-based empirical models to predict the fire environment enveloping the spent fuel transportation package.

CAFE uses the finite volume approach with orthogonal Cartesian discretization to solve: (1) the three momentum equations, (2) the mass continuity equation, (3) the energy equation, (4) the equation of state, (5) a number of scalar transport equations for tracking the flow of species, and (6) participating media equations to solve diffusive radiation inside the flame zone and view factor radiation outside the flame zone [3]. CAFE uses a variable density Pressure-Implicit Split-Operator (PISO) algorithm to obtain a velocity field which satisfies both the momentum and continuity equations. CAFE has a number of turbulence models, but for this study a large eddy simulation formulation was used.

CAFE only generates the fire conditions outside the external surfaces of the calorimeter. To adequately model the effects of the calorimeter on the fire, CAFE was coupled to P-Thermal to obtain the thermal response of the calorimeter and the subsequent heat flux feedback to the fire. P-Thermal uses CAFE-predicted external cask temperatures, convection coefficients and fluid temperatures to calculate the spatial temperature distribution inside the calorimeter. A specialized mapping scheme is used to transfer this data to the external surfaces of the P-Thermal, finite element model [3]. The subsequent outer-surface spatial temperature distribution is then used by the CAFE code to adjust the fire response to the calorimeter. The advantage of using this method is that CAFE is able to adjust the fire environment as a result of the three-dimensional thermal response of the large calorimeter.

Since the development of the CAFE code, there has been a continuing effort to benchmark and fine-tune this fire model by making use of relevant empirical data obtained from experiments that used various size calorimeters and different calorimeter-pool configurations [4-8]. In this study, CAFE was benchmarked against experimental data obtained from a fire test series conducted at SNL Lurance Canyon Burn Site during the summer of 2007. The unique feature of this benchmark effort is that the calorimeter was close to the actual size of a rail cask, and the experiment setup was closely matched to the regulatory hypothetical fire accident scenario outlined in 10CFR71.73 for the certification of nuclear spent fuel transportation casks. In addition, unlike similar calorimeter size benchmark efforts [7, 8] results presented here assesses predictions of CAFE/P-Thermal coupled code using a three-dimensional, calorimeter thermal response model.

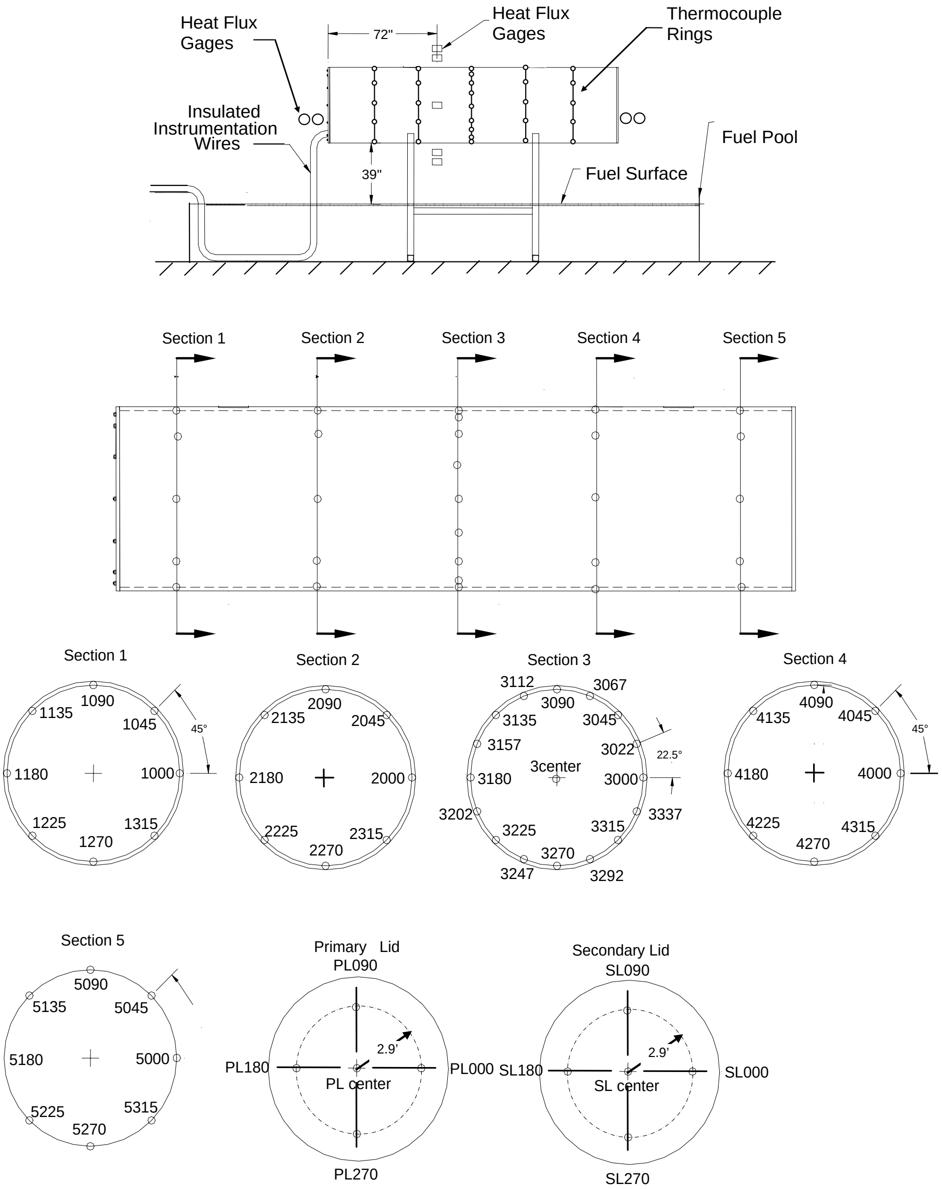
EXPERIMENTAL SETUP

The calorimeter was a carbon steel cylindrical pipe approximately 2.43m (96in) in diameter,4.6m (180in) in length, and a nominal 2.54cm (1in) thickness wall, and had bolted lids on each end [see Figure 1(a)]. The calorimeter was placed on two stands at the center of a 7.93m (26ft) diameter fuel pool. The stands maintained the calorimeter 1m (39.4in) above the fuel surface. Approximately 7.58m^3 (2000 gallons) of JP8 were used per test. Total burn time varied with each tests, but was at least 25 minutes long. All the tests were conducted in relatively low wind conditions (<5m/s) to assure the calorimeter was fully or partially engulfed [see Figure 1(b)].

(a) (b)

Figure 1. Large calorimeter fire test: (a) test setup and (b) fire fully engulfing the calorimeter.

Thermocouples (TCs) were installed on the interior walls of the calorimeter to measure interior surface temperatures. All TCs on the round walls were installed in a ring configuration as shown in **Figure 2**. Heat flux gages were placed just outside the round walls of the calorimeter in a ring configuration and outside the lids to obtain incident heat flux measurements close to the outer walls of the calorimeter. Fuel burn rates were measured using a linear array of TCs traversing the depth of the fuel layer at known distance intervals. Directional flow probes were installed just outside of the calorimeter walls to measure the flow speed of the hot gases near the calorimeter walls. Finally, ultrasonic sensors were placed on four towers to measure wind speed and wind direction: (1) two sensor towers aligned with the calorimeter lids and (2) the other two sensor towers perpendicular to the cylindrical section of the calorimeter, on opposite sides. Each tower was approximately 24.4m (80ft) from the center of the pool and had three ultrasonic sensors 2, 8, and 10m (6.5, 26.2, and 32.8ft) from the ground.



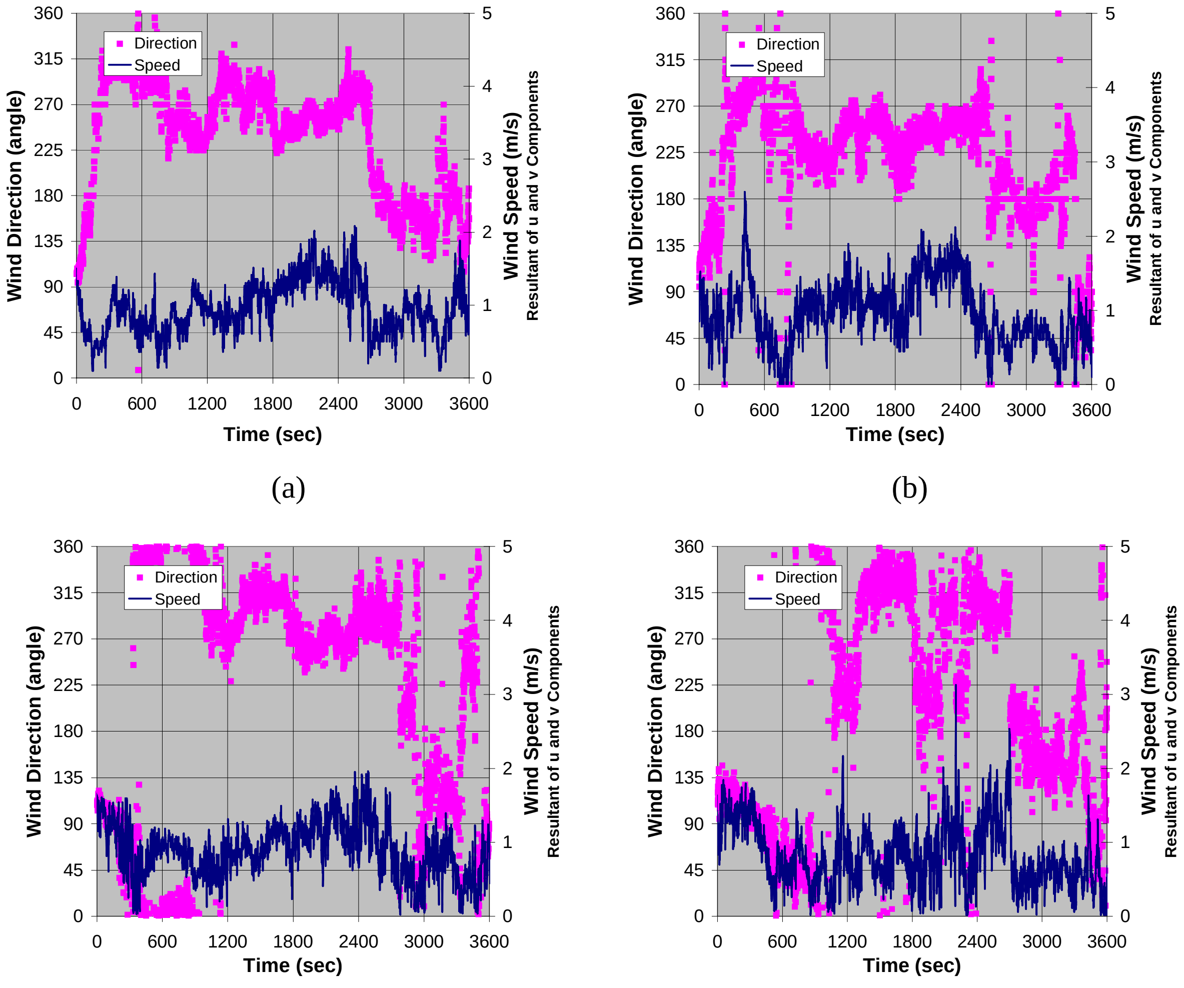
Note: “PL” stands for primary lid and “SL” stands for secondary lid

Figure 2. Schematic of experimental setup with instrumentation locations.

EXPERIMENTAL DATA

All three tests were conducted in the early hours of the day to take advantage of calm wind conditions. Data was sampled for all channels at 1000 Hz with a running average recorded at one sample per second. Since the data that was collected in these experiments was extensive, only the data for Test 1 is presented here. Data from Test 1 were chosen because the wind conditions lead to the object being nearly fully engulfed, which best matched the regulatory conditions specified in 10CFR71.73.

In Test 1, the fire lasted approximately 2400 seconds (40 minutes) and the fuel recession rate was calculated to be approximately 3.8mm/min (0.15in/min). **Figure 3** shows wind conditions 8m (26.2ft) from the ground from all four towers. For this test, wind speeds were less than 3m/s (6.7miles/hr) for the entire duration of the test.



(a)

(b)

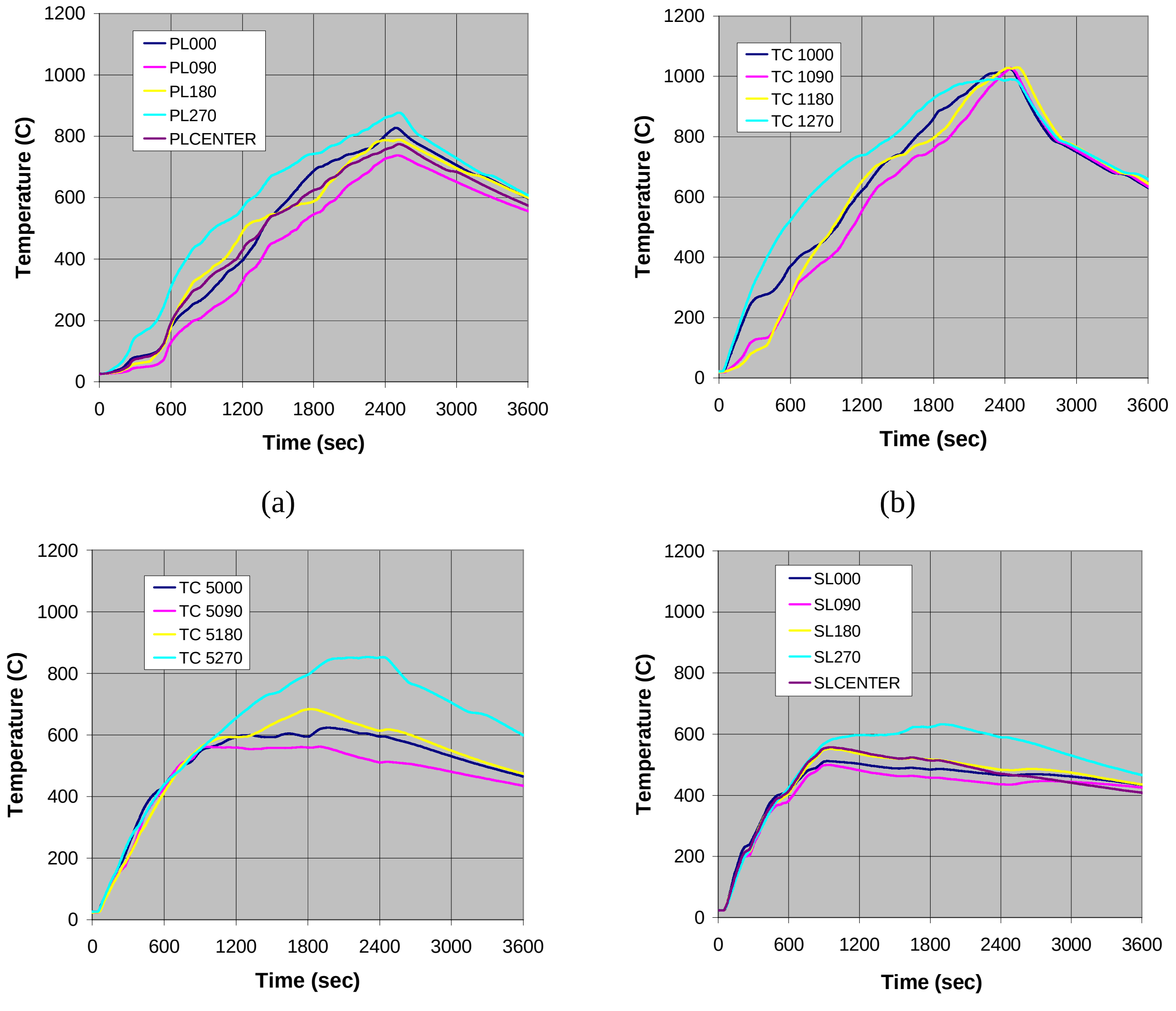
(c)

(d)

Figure 3. Test 1 Wind Speed and Wind Direction on: (a) West, (b) South, and (c) North and (d) East Towers.

Due to the topography of the canyon, the wind direction was predominantly out of the east or west. Moreover, historical data shows that wind direction is out of the east prior to sunrise and out of the west just after sunrise as depicted by the shift in wind direction 5 to 10 minutes into the test.

Figure 4 shows temperatures measured on the interior of the calorimeter. The numbers in the legends correspond to the location of the TCs shown in **Figure 2**. PL is the primarily lid and SL the secondary lid. TC temperatures on the secondary lid and near section 5 increased slightly faster than the other locations at the beginning of the test due to the initial wind direction. As the wind shifted to out of the west, TC temperatures near the primary lid continued to increase and reached a maximum at the end of the test. In general the TCs reached highest temperatures on the upwind side.



(a) (b)

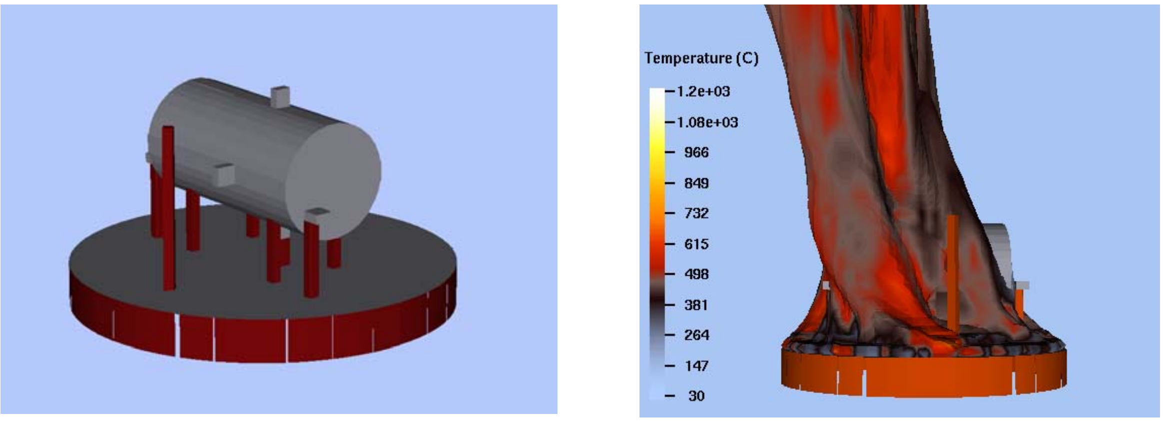
(c) (d)

Figure 4. Test 1 Internal Calorimeter Temperatures: (a) Primary Lid, (b) Section 1, (c) Section 5, and (d) Secondary Lid

CAFE BENCHMARK RESULTS

The CAFE model created in Reference [3] was used for this analysis [see Figure 5(a)]. An extensive model parameter and grid sensitivity study was performed on the CAFE model in Reference [7] to obtain optimum results. These results showed some sensitivity to the large instrument fixtures; therefore, these were included. In this study, some additional sensitivity studies were performed to account for the CAFE/P-Thermal coupling and changes in models implemented in CAFE since References [7, 8].

Figure 5(b) shows fire outer surface temperatures from the CAFE benchmark run at an arbitrary time step. The internal surface temperatures of the calorimeter were obtained using P-Thermal. These surface temperatures were then compared to the internally measured surface temperature obtained with the surface-attached TCs. In general, surface temperature measurement uncertainties for ungrounded sheathed TCs are in the order of 2.5% of the temperature read [9]. Additional noise errors are expected from other sources such as magnetic field induced within the fire. Bias errors exist due to the presence of the thermocouple on the surface and the lag time in TC response. These errors have been estimated to account for 4-8% reduction in surface temperature measurement when compared to the surface temperature in the absence of the TC [9].

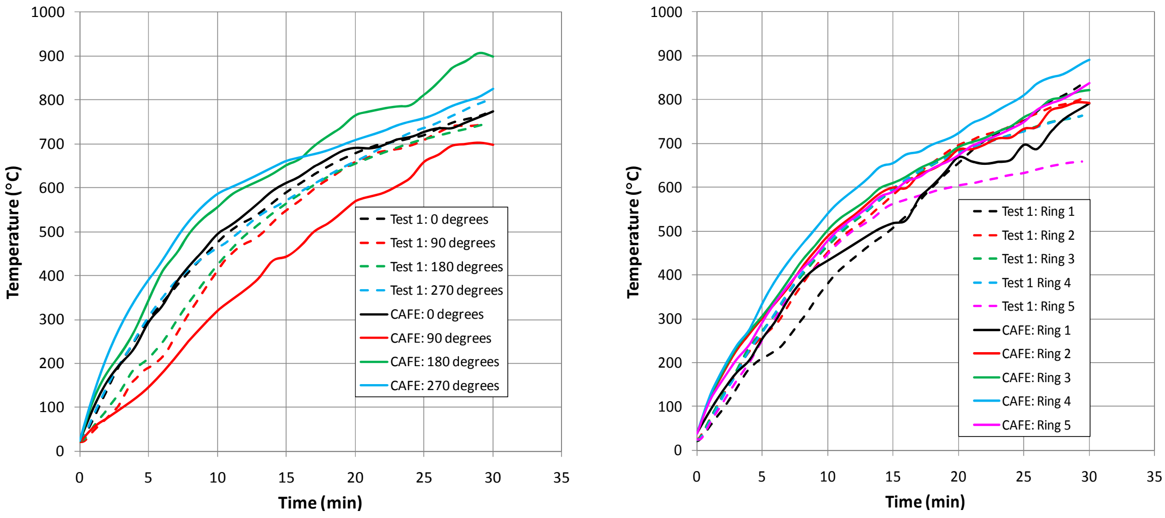


(a) (b)

Figure 5: (a) CAFE model of calorimeter test and (b) CAFE benchmark results at an arbitrary time step.

Figure 6(a) shows calorimeter outer surface temperatures along the four circumferential sides. The outer surface temperatures were averaged over all TC locations along the line pointing out of the page in the bottom diagram of **Figure 2** at 000 (right side), 090 (top side), 180 (left side) and 270 (bottom side) degrees. From this perspective CAFE over predicts the temperatures underneath and on the left side of the calorimeter (see lower diagram in Figure 2), and under predicts the temperatures on the top of the calorimeter. **Figure 6**(b) shows the average surface temperatures over each thermocouple ring starting from the left side of the calorimeter in upper diagram of **Figure 2**. From this perspective CAFE predicts the average surface temperatures over the rings reasonably well.

Closer inspection of the temperatures histories obtained from CAFE at each of the nodes corresponding to TC locations revealed excellent agreement with test data over most of the cask, except at locations where the wind effects were strongest, the last two rings on the right side of **Figure 2** at 90 (top side), 180 (left side) and 270 (underneath) degrees. Temperatures at 180 and 270 degrees were higher than expected, while temperatures at 90 degrees were under predicted. Differences rapidly diminished going from the rings on the right side of the calorimeter to the rings on the left side as shown in **Figure 6**(b). Part of the reason for these discrepancies is the way in which the wind boundary conditions were applied in the CFD model. In the tests, wind speeds were obtained only at four locations around the pool, and at three heights. These height dependent data were applied uniformly over the corresponding cross sections of the computational domain, which does not necessarily reflect the actual conditions in the test. This leads to wind speeds being higher than expected in some locations around the calorimeter such as the right side of the calorimeter near Ring 5 (Section 5 in **Figure 2**).



(a) (b)

Figure 6. CAFE benchmark results using fully engulfed large calorimeter: (a) temperatures average along the 0, 90, 180, and 270 degree, and (b) temperatures averaged over each ring starting from section 1 (e.g., Ring 1 is Section 1 in Figure 2).

CONCLUSION

Three open pool fire experiments were conducted at Sandia's Lurance Canyon Burn Site to gather heat flux and temperature data from pool fires using a calorimeter the size of a spent fuel rail cask. Only the regression rate, wind boundary conditions, and internally-measured, calorimeter surface temperature for Test 1 were presented in this paper. Internally-measured, calorimeter surface temperatures were used to benchmark CAFE model results.

A CAFE model was created to simulate the open pool fire experiments. Only simulation results for Test 1 were compared here and show that CAFE bounds the experimental calorimeter temperatures. In general, CAFE underestimated the average internal surface temperature near the top of the calorimeter, while it over estimated the average internal surface temperature on all other sides of the calorimeter. Thus, these results showed that CAFE slightly over estimated the overall average temperature of the surface of the calorimeter. Therefore, it is expected that in an analysis of a cask exposed to the fully engulfing hypothetical fire environment described in 10CFR71.73, surface temperatures predicted by CAFE are likely to be close to or slightly higher than those measured.

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* Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.