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# TEMPERATURE RESPONSE OF A RAIL-CASK-SIZE PIPE CALORIMETER IN LARGE-SCALE POOL FIRES

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## ABSTRACT

The Container Analysis Fire Environment (CAFE) computer code is being developed at Sandia National Laboratories (SNL) to predict the response of massive spent nuclear fuel transport casks to a range of severe fire environments. It is designed for use in transportation risk and design studies. CAFE employs physics-based reaction chemistry and radiation heat transfer models that are appropriate for fuel-rich and highly sooty pool fires. These models allow CAFE to produce accurate fire heat transfer results even when relatively coarse (and fast running) computational grids are employed. Parameters for these models must be determined from large-scale fire test data.

Three fire tests were performed at the SNL outdoor fire test facility to benchmark CAFE. In these tests, the interior surface of a 2.4 m diameter, 4.6 m long, and 2.5 cm thick pipe calorimeter was instrumented with 70 Type-K thermocouples. It was suspended above a 7.2 m diameter water pool with enough JP8 jet fuel on top to burn for up to 40 minutes. Heat flux gages, directional flow probes, thermocouples, and anemometers were used to characterize the environment in the vicinity of the calorimeter during and after the fire.

Transient wind conditions and calorimeter temperatures were recorded during and after the fires. The average wind speed was roughly 0.8 m/s during the first test, 1.1 m/s during the second, and 2.6 m/s during the third. CAFE simulations were performed using the measured wind conditions as boundary conditions and a range of model parameters. The resulting calculated calorimeter temperatures are compared to the experimental measurements.

## INTRODUCTION

This paper describes a series of fire tests conducted at the Sandia National Laboratories Burn Site in Albuquerque, NM, during the summer of 2007. Temperature response of a rail-cask-sized calorimeter is presented as well as comparisons with simulations.

Transport systems for nuclear waste and other hazardous materials must be designed to withstand transportation accidents involving fuel fires. The range of possible fire scenarios which must be considered is large, and therefore fire testing to validate every transport system design is not practical. Fire simulations by specialized fire physics codes are able to accurately predict heat flux and fire behavior using first principles. Typically, these codes operate with small time steps and require specialized computing platforms to run. Because of this they may not be suitable for parametric design and risk assessment studies which involve many simulations of a transport system in different configurations.

The Container Analysis Fire Environment (CAFE) [1] computer code links the Isis 3D fire code with a finite element code to predict the response of a large fire engulfed object. The linked complex finite element model of a transport package is solved concurrently with the Isis 3D calculation. The Isis 3D fire simulation defines the heat flux boundary condition, as the finite element code supplies the object surface temperatures back to Isis 3D. The Isis 3D code uses simplifying models to reduce run time by using longer time steps and larger computational grid sizes than more fundamental fire codes, thus it is more suitable for quick turn-around studies.

Because fire phenomena are complex and sensitive to outside influences such as wind, any fire model must be benchmarked and calibrated using real fire test data. This is especially true for a simplified code such as CAFE, where parameters for underlying physics-based models are based upon data [2]. In order to ensure the code can predict heat flux to an engulfed object with reasonable accuracy, fire tests in various conditions must be conducted. In this series of tests, the thermal response of a steel calorimeter approximately the size of a spent nuclear fuel rail cask is analyzed. Previous studies have compared CAFE simulations of fires with larger [3] and smaller [4] engulfed objects.

## EXPERIMENT DESCRIPTION

Figure 1 shows the test calorimeter suspended above the fire pool at the Sandia Burn Site and its orientation relative to compass directions. The calorimeter is 2.44 m in diameter, 4.57 m long, and suspended 1 m above the center of a 7.2 m diameter fuel pool. The wall thickness is 2.54 cm and it is capped on both ends. It is made from uncoated A36 carbon steel and supported by an insulated stand. Fifty-eight thermocouples were attached to the calorimeter inside surface, as well as 12 additional thermocouples embedded inside the calorimeter wall. This paper concentrates on the thermocouples at the 3 circular sections labeled in Fig. 1. The West and East sections each have 8 thermocouples and the Center Section has 16 equally spaced thermocouples for a total of 32. The other 26 interior surface thermocouples were inside the end caps (5 at each end cap), and at two additional circular sections between the labeled sections. In this paper, the data from these additional thermocouples were used only to calculate the calorimeter average temperature. Data from the embedded thermocouples are not presented in this paper. All interior thermocouples were backed by 3 one-inch thick strips of Kaowool insulation inside the calorimeter to reduce radiation transfer within the hollow calorimeter to the thermocouple locations.

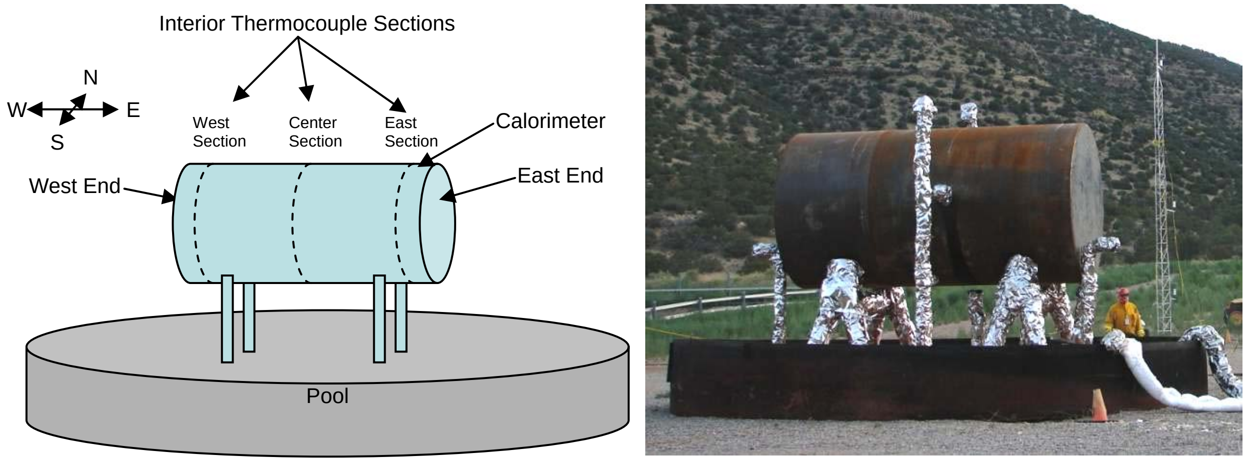

**Figure 1. Test Calorimeter and facility**

A thermocouple rake just below the fuel surface consists of 8 thermocouples spaced at 2.54 cm which are used to estimate the fuel burn rate. For each test a depth of 15.2 cm JP8 fuel was floated on top of water in the pool. This is equivalent to 7571 liters (2000 gallons) of fuel.

The tests were conducted at the Sandia Burn Site located in Lurance Canyon, which is known to have dominant east winds at night and west winds during the day. In early morning the wind changes direction and at this time the wind speed is typically low. For this reason the 3 fire tests were performed at about 7:10 am on different days. Four anemometer towers were placed 24 m from the calorimeter center in each direction corresponding to the compass directions N, S, E, and W. Each tower had 3 ultrasonic anemometers at heights of 2, 5, and 10 m above ground level for a total of 12 anemometers. The North anemometer tower is visible in the background of the photo in Fig. 1. No wind-reducing fences of any kind were used.

Other instrumentation including Heat Flux Gauges, Directional Flow Probes, and a thermocouple rake near the calorimeter surface were also recorded but those data will not be presented at this time. Support structures for these instruments were insulated for protection from the harsh fire environment. All instruments were recorded at 1 second time intervals.

## COMPUTATIONAL MODEL

The CAFE computer code is under development to be a tool for risk assessment and engineering analysis. Its purpose is to provide reasonably accurate estimates of the total heat transfer to objects engulfed in large fires under a variety of conditions, predict the general characteristics of the object temperature distribution, and run relatively fast (compared to other CFD fire codes) on a standard workstation. CAFE models liquid fuel evaporation, transport of fuel vapor, oxygen and other relevant species, reaction and heat release, and soot and intermediate species formation/destruction [2]. It models diffuse radiation within the flames, and view factor radiation from the flame edge to nearby objects and surroundings.

One-dimensional transient conduction capability allows stand-alone CAFE to model simple solid objects in the fire and predict their response. If a complex object is to be modeled, the CAFE code allows the underlying Isis 3D fire code to be linked with a finite element code which more accurately and effectively models and solves the complex internal heat conduction problem.

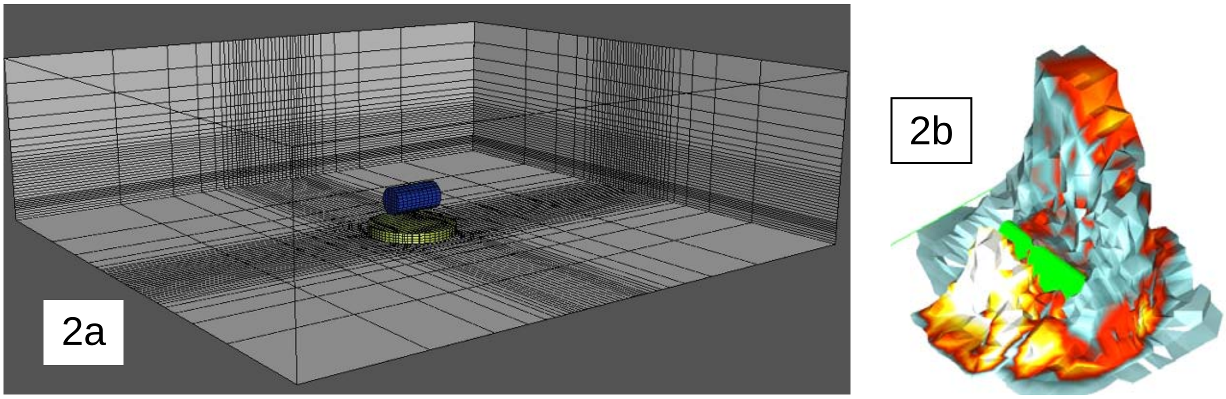

**Figure 2. Computational domain and simulated fire**

Figure 2a shows the computational domain which was used to simulate the present fire experiments. The domain extends 25 m beyond the calorimeter in the horizontal directions and 15 m vertically. The computational volumes are finest near the calorimeter and become coarser far away from the calorimeter. The measured wind velocities are employed as boundary conditions at the vertical surfaces. A pressure boundary condition is specified on the top of the domain, and a no-slip (zero velocity) condition is employed at the bottom. A pressure boundary condition is also employed on the lowest 1.5 m of the vertical surfaces to model boundary layer effects. The calorimeter is a simple solid that was modeled using the CAFE transient conduction model. Figure 2b shows a simulated fire picture produced by one of the CAFE simulations.

## EXPERIMENTAL DATA AND SIMULATION RESULTS

### Test Wind Conditions

Three fire tests were performed on July 12, August 1, and September 13, 2007 with varying amounts of wind. Figure 3a shows the wind data from Test 1, with all 12 anemometer signals averaged. Test 1 had the least wind of all the tests and averaged 0.8 m/s. For the first 5 minutes the wind came from the East. After 5 minutes the wind began to shift from the North and then from the West for the remainder while slowly increasing in speed to a peak of 1.3 m/s. The fire burned for 41 minutes. Figure 3b shows a photo of the fire taken in the first few minutes, while Figure 3c was taken later when the wind was blowing from the west. The windward end of the calorimeter is not fully engulfed and visible in both photos, even though the wind was less than 1 m/s.

Figure 4 shows the wind data from Test 2. The direction of the wind was similar to Test 1. However the wind speed was slightly higher, averaging 1.1 m/s. The change in wind direction happened 12 minutes into the test. The fire plume behavior was similar to Test 1 and therefore photos of this test are not shown. The fire in test 2 burned for 38 minutes.

Figure 5a shows the wind data from Test 3. The wind blew from the southwest initially and gradually shifted to the west while growing in magnitude to an average of 2.6 m/s and maximum of 4 m/s. Figure 5b shows the plume behavior near the end of test 3. The windward half of the calorimeter, especially the top surface, was not engulfed. The high wind speed caused the fuel to be consumed faster and the fire duration was only 26 minutes.

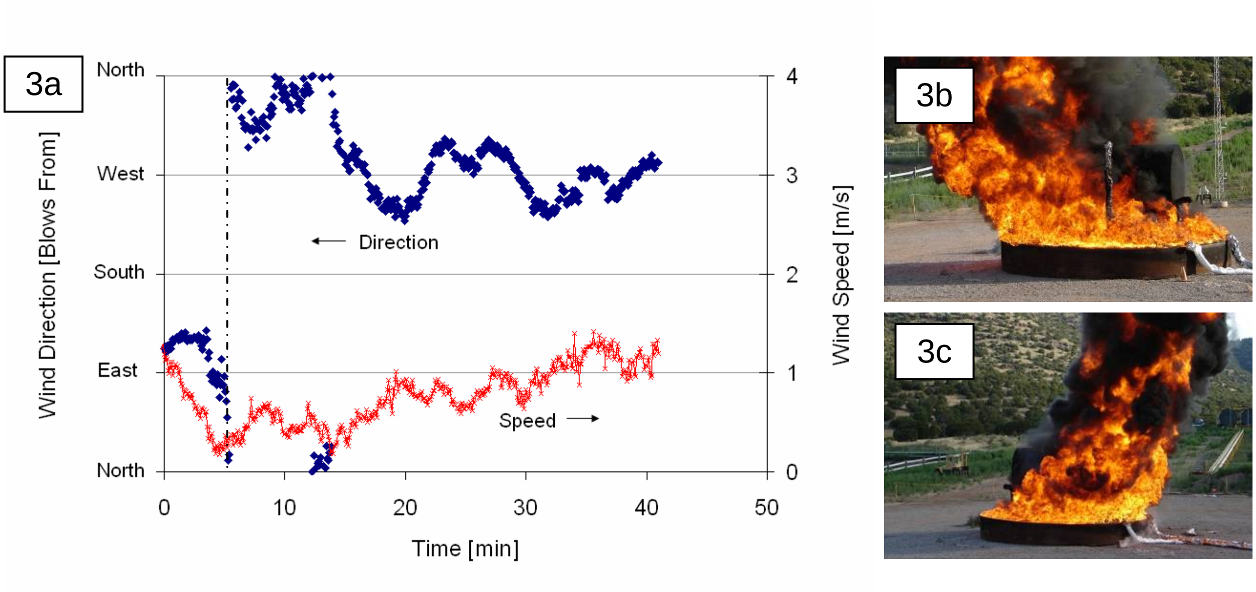

Figure 3. Test 1 wind data and photos

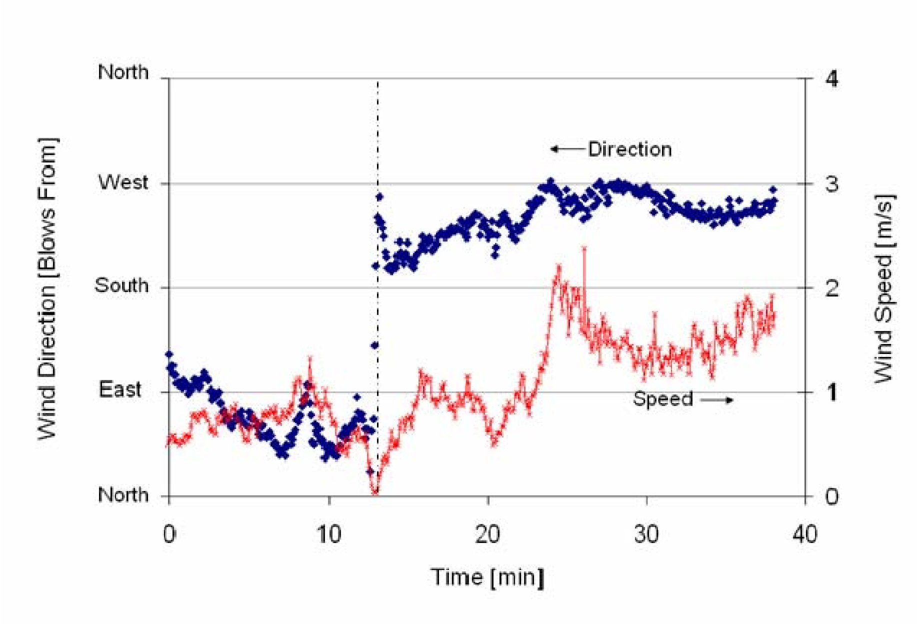

Figure 4. Test 2 wind data

### Fuel Consumption Rate

Once the experiment wind conditions were measured, the series of three fire tests could be simulated using the measured wind speed and direction as boundary conditions for the CAFE model. The experimental fuel consumption was measured as a function of time by the pool thermocouple rake. Another way to measure the fuel consumption rate is to divide the total amount of fuel present by the fire burn time. This yields an average value during the test. The experiment fuel consumption rates using both methods are presented in Figure 6a. The two methods are in reasonable agreement for Tests 1 and 2 and both report about 0.05 to 0.06 kg/(s-m$^2$). The rake measurements show that fuel consumption is fairly constant during the fires with low wind speeds. During Test 3, the thermocouple rake was not in the proper position and therefore the data was not used in this paper. The overall fuel consumption for Test 3 was just over 0.08 kg/(s-m$^2$). This suggests the fuel consumption rate is a strong function of wind speed, which is in agreement with previous fire experiments [5]. Since the wind speed gradually rose during Test 3, and the overall fuel consumption rate was about 45% higher than the low wind tests, the fuel consumption rate may have increased with time.

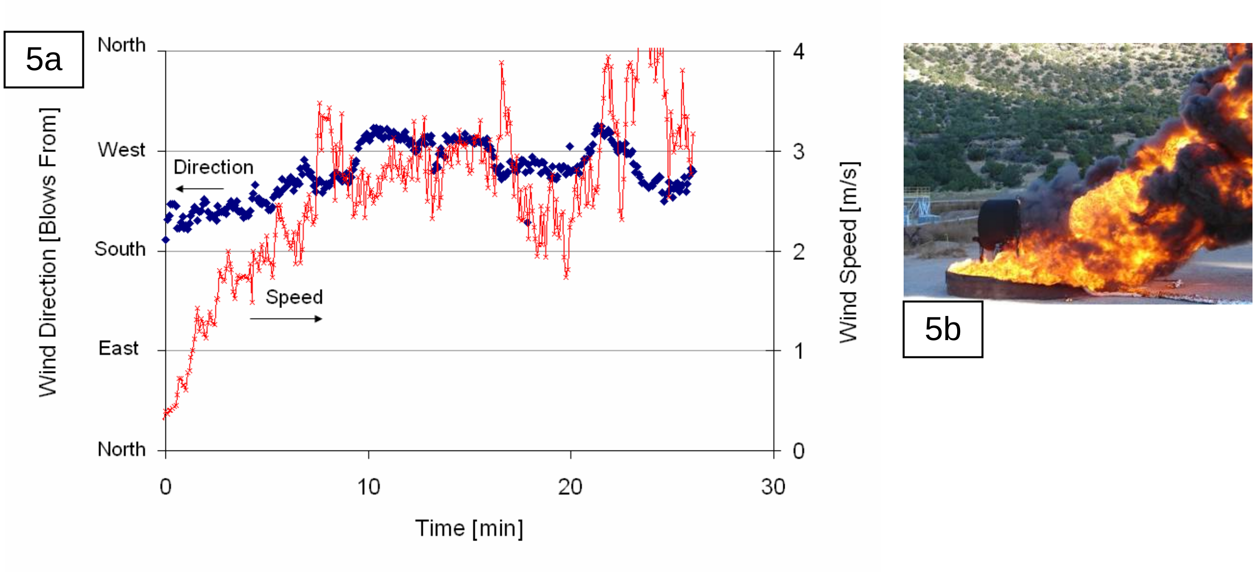

**Figure 5. Test 3 wind data and photo**

The CAFE model calculates fuel evaporation rate based on the specified fuel thermal properties, the incident radiation onto the fuel surface from the fire, and a user defined fuel surface absorptivity (for details see [6]). Figure 6b shows the simulation fuel consumption rate versus time. The simulated fuel consumption for each simulation was very similar, so only one set of simulated data is shown here. The simulation did not predict an increase in fuel consumption with increasing wind speed. The simulated fuel consumption starts low and rapidly increases for the first 5 minutes, then gradually increases for the rest of the test. This is different than the experimental measurements, which were fairly constant at low wind speeds. This could cause a simulated fire to be initially cooler than an experiment. A steady state consumption rate is never reached. The average simulated consumption rate is 0.07 kg/(s-m$^2$), which lies between the values measured during the experiments.

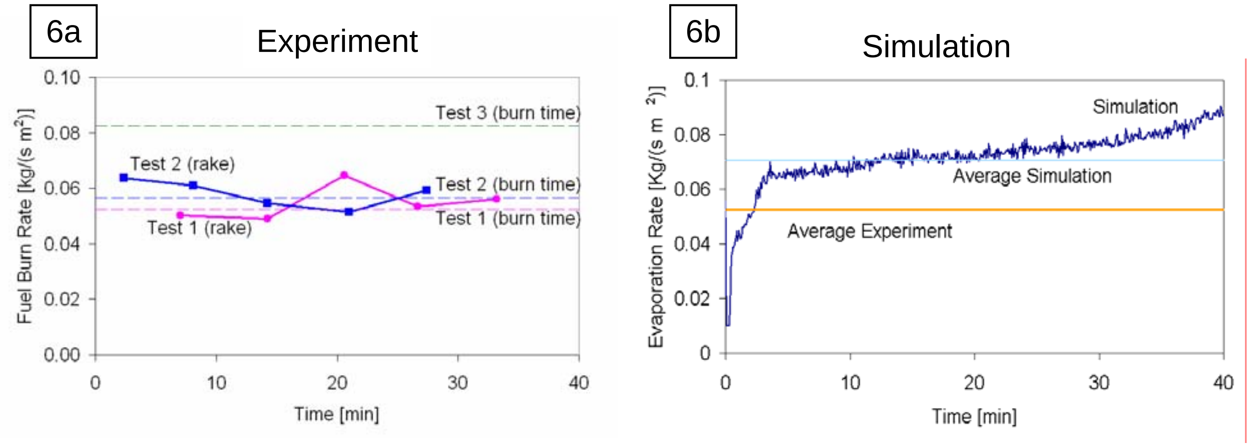

**Figure 6. Experiment and Simulation Fuel Consumption Rates versus Time**

### Temperature Comparisons

Figure 7 shows the calorimeter average temperature rise versus time for Test 1, both experiment and simulation. The average temperature rise is calculated using an area-weighted average of the 58 thermocouples affixed to the inner surface of the calorimeter and subtracting the initial temperature. This is an indication of the total energy input from the fire, which is an important quantity for risk assessment studies [7, 8]. The same method was used for the simulated average temperature rise calculation, since CAFE outputs node temperatures at the same locations as the experiment thermocouples.

The average temperature rise curves of the experiment and simulation are similar in shape. However, they deviate from the start and at t=15 minutes the simulation prediction is 16% lower than measured. This could be due to the slow start in simulated fuel consumption causing a cooler simulated fire. At t=40 minutes the simulation is only 4% lower than measured.

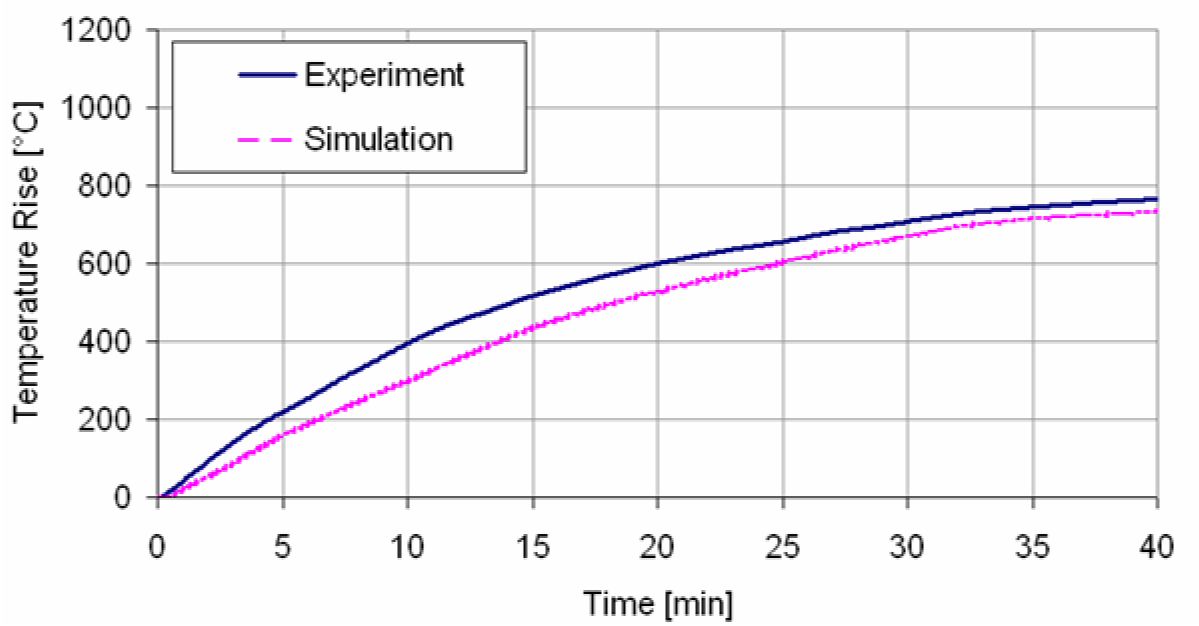

**Figure 7. Calorimeter Average Temperature Rise versus Time for Test 1**

Figure 8a shows the experiment average temperature rise versus time for all 3 experiments and Fig 8b shows them for the simulations. While the magnitude of the simulated temperature rise is low for all cases, the general characteristic shapes are quite similar to the experimental curves. This suggests the CAFE sensitivity to wind boundary conditions is similar to real fires. It is interesting to note that the average temperature rise at 26 minutes is 33% more for test 1 and 2 than test 3, even though test 3 consumed fuel about 45% faster. The photographic evidence of test 3 shows the flames did not engulf the windward end of the calorimeter for much of the time and hence the heat flux to that end was greatly reduced.

### Spatial Variations

Figure 9 shows temperature rise profiles along the axial length of the calorimeter at the top, bottom, north, and south locations for the Test 3 experiment and simulation. Profiles are presented at time snapshots of 12 and 24 minutes. Since the wind came from the west during the entire duration of test 3, the west end of the calorimeter is always coolest. The top edge is significantly cooler than the bottom edge. Simulations also predicted coolest temperatures on the west end and top, however these are cooler than experimental measurements.

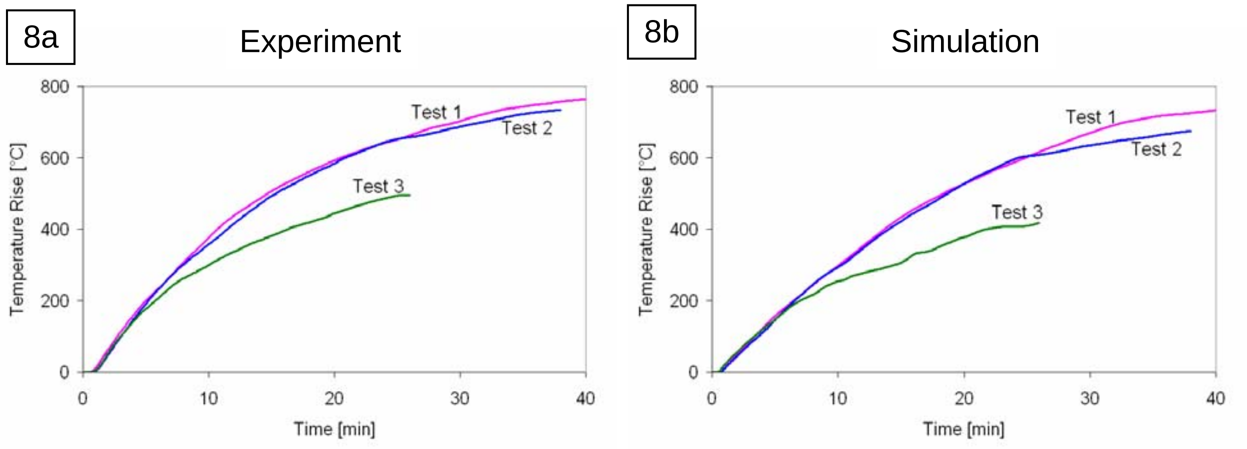

**Figure 8. Experiment and Simulation Calorimeter Average Temperature Rise versus Time for all tests**

## CONCLUSIONS

A series of three fire tests were performed at the Sandia National Laboratories Burn Site in which a 2.4 m diameter, 4.6 m long calorimeter approximating a spent nuclear fuel rail cask was suspended above a 7.2 m diameter JP8 pool fire. Wind speeds during the fire tests averaged 0.8, 1.1, and 2.6 m/s for tests 1, 2, and 3, respectively, and blew predominantly along the axis of the calorimeter.

The CAFE fire code is under development to provide a tool to predict the thermal response of an engulfed object under various circumstances and with quick turn-around times. CAFE was used to simulate the tests with the measured wind applied as model boundary conditions. Both measured and simulated temperature results were presented and compared here.

The fuel consumption rate of the low wind experiments was found to be relatively constant during the experiments, however the average fuel consumption rate increased by 45% when average wind speed increased from 0.8 m/s in test 1 to 2.6 m/s in test 3. The simulated fuel consumption rate was similar for all simulations and started very low and continually increased with time, never reaching a steady state. Despite the difference in fuel evaporation rates, the simulations accurately predicted average temperature rise versus time curve shifts in response to different wind speeds. The simulation snapshot temperature profile characteristics along the axis of the calorimeter shared similar trends with experiments but with generally cooler temperatures.

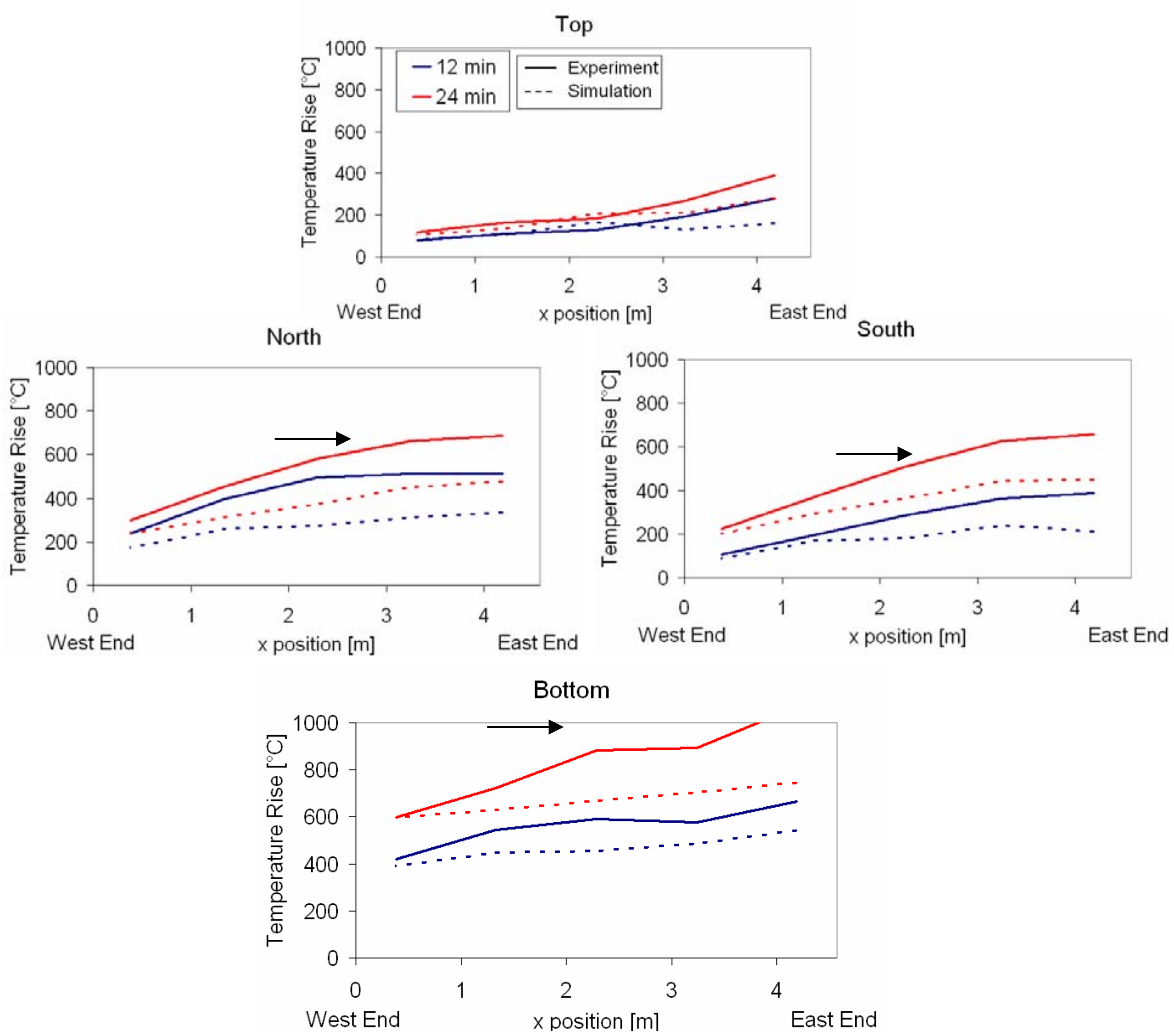

**Figure 9. Test 3 Axial Temperature Rise Profiles at the Top, Bottom, North, and South edges of the Calorimeter at t = 12 and 24 minutes**

## ACKNOWLEDGMENTS

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