MEASUREMENTS OF HEAT TRANSFER TO A MASSIVE CYLINDRICAL OBJECT ENGULFED IN A REGULATORY POOL FIRE

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ABSTRACT

A series of large-scale experiments were performed to measure heat transfer to a massive cylindrical calorimeter engulfed in a 30-minute circular-pool fire. The calorimeter inner surface temperature and the flame black body emissive power were measured at several locations as functions of time. An inverse conduction technique was used to determine the net heat flux to the calorimeter. Light winds of around 1 m/s tilted the fire so that the windward side of the calorimeter was only intermittently engulfed. As a result the flame temperatures on the windward side were substantially less than the leeward surface. The variation of calorimeter temperature and heat flux with time was closely correlated with the flame emissive power. The current data set is well suited for benchmarking computer codes that simulate heat transfer from large-scale fires to massive engulfed objects.

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. Regulations describing these tests are contained in Title 10, Part 71 of the Code of Federal Regulations, known as 10CFR71 (U.S. Nuclear Regulatory Commission, 1992) and IAEA ST-1 (IAEA, 1985). Cask designers as well as transportation risk analysts require computational tools that can accurately predict the response of packages to both regulatory and historic accident conditions.

The Cask Analysis Fire Environment (CAFE) computer code is currently under development at the Sandia National Laboratories (Suo-Anttila et al. 1999). It is designed to provide an accurate fire boundary condition and may be linked to finite element analysis programs. The linked system will be able to accurately predict the interior response of packages to a range of fire conditions. CAFE performs two-dimensional computational fluid dynamics simulation and employs a number of fire and radiation models. These models allow simulation of a thirty-minute fire in only a few hours on a standard workstation. These short turnaround times make CAFE an appropriate tool for designers and risk analysts. However, CAFE must be benchmarked and calibrated with heat transfer data from full-scale fire experiments before it can be used with confidence.

Numerous fire tests have been performed on transportation packages over the past 20 years. However, most of these tests evaluated regulatory compliance and were not designed to quantify heat transfer (Nuclear Packaging, Inc., 1989). A small number of large-scale fire tests were performed to measure heat transfer from fires to massive objects (Koski et al. 1994, Gregory, et al. 1989, Koski et al. 1996, Nakos and Keltner 1989). These tests concentrated on how thermal mass and surface temperature effect heat transfer, and how the cold object surface influences the fire environment. However these objects were not the same general size and shape as transport casks. Moreover, the tests did not measure heat transfer as functions of location over the entire object.
The goal of the current experiment is to measure heat transfer versus time and location to a massive cylindrical object engulfed in a round pool fire. The object is roughly the same size as a high level nuclear waste package transported by tractor trailer truck. The fire was designed to comply with the regulations used to license such packages. These data will be well suited for benchmarking CAFE and other fire simulation codes.

**NOMENCLATURE**

- $D$: diameter of calorimeter
- $E_b$: black body emissive power of flames
- $L$: length of calorimeter
- $S$: measured wind speed
- $T_{\text{flame}}$: local flame temperature
- $T_{\text{inner}}$: calorimeter inner surface temperature
- $T_{\text{outer}}$: calorimeter outer surface temperature
- $W$: calorimeter wall thickness
- $q^\prime$: calorimeter surface heat flux
- $t$: time after fully engulfed
- $x$: distance variable from south end of calorimeter
- $\alpha$: thermal diffusivity
- $\theta$: angular coordinate around calorimeter
- $\sigma$: Stefan-Boltzmann constant

**EXPERIMENTAL METHOD**

The objective of the current experiment was to measure the spatial and temporal variations of heat flux to a large object engulfed in a regulatory pool fire. The 10CFR71 regulations specify that the fuel pool must extend horizontally between 1 and 3 m beyond the package. Moreover, the wind conditions must be sufficiently calm so that the object will be fully engulfed for the duration of the fire.

Figure 1a shows a plan view of the experiment test facility along with its orientation relative to compass directions. The test object was a 3800 kg (8400 lb) cylindrical carbon steel calorimeter of length $L = 4.6$ m (15 ft), diameter $D = 1.2$ m (4 ft), and wall thickness $W = 2.54$ cm (1 in). Two disk shaped caps, 2.54 cm (1 in) thick, are fastened to each end. The south end cap was penetration welded to the cylindrical body while the north end cap was bolted to allow access.

The entire setup was located above a 9 m wide, 18 m long and 1 m deep concrete pool at the Sandia National Laboratories Burn Site. The pool was filled with water. A 7.16 m (23.5 ft) diameter sheet metal fuel dam, shown in Fig. 1b (and seen in Fig. 3), allowed the JP-8 fuel to float on the water and be contained in a circle. The calorimeter was supported horizontally 1 m above the center of the fuel pool. The minimum horizontal distance between the calorimeter end caps and the edge of the fuel pool was 1.22 m and the maximum distance from the sides to the pool edge was 2.97 m. These distances are in compliance with the regulations.

The structure supporting the calorimeter above the pool was constructed from 10 cm square cross section steel tubing and it was designed to support it at six locations. The support stand and the instrumentation wire bundle exiting the calorimeter were insulated and water-cooled during the tests. The wire bundle temperature was measured and never exceeded 40°C.

Efforts were made to minimize the effects of wind. Winds are able to tilt the fire and prevent it from fully engulfing the object. Tests were scheduled for 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 reduce the effect of wind. As shown in Fig. 1a, each barrier formed a V-shape with the apex pointing toward the fire. Each wind barrier was constructed from chain link fencing with aluminum strips woven into each slot. One-meter gaps between the wind fences were used so that the barriers did not disrupt the natural inward flow of air toward the fire.

The wind direction and speed data were monitored with propeller type anemometers attached to wind vanes. The measurements were taken outside of the wind fences due to the high temperatures inside the barriers. The anemometers were located 30 m (100 ft) to the northwest of the fire pool, with the intention of measuring the wind speed independent of the fire effects. Measurements were performed at heights of 3.0 m
(10 ft) and 6.1 m (20 ft) above the ground. Measurements are currently being performed to correlate wind speed measured outside the barriers to wind speed inside. A correlation for a slightly different wind fence arrangement has shown that the wind speed inside the fencing is roughly half that outside the fences.

The small circles in Fig. 1b show the locations where thermocouples were fastened to the interior surface of the calorimeter. Each thermocouple was a Chromel/Alumel type K wire pair, sheathed in inconel tubing, insulated using MgO, and was ungrounded. They were attached to the interior surface of the calorimeter using spot welded nichrome metal strips. The interior volume of the calorimeter was filled with 2.54 cm thick Thermal Ceramics Kaowool insulation next to the interior surface and standard fiberglass insulation everywhere else. The thermocouple lead wires were isolated from the walls by placing them inside the Kaowool insulation.

Most of the thermocouples were arranged in four rings. Using the x-coordinate system shown in Fig. 1b (x = 0 is at the inner surface of the south end cap), the rings are located at x = 0, 0.73, 1.96, and 3.78 m. The rings at the end cap, south, and north (x = 0, 0.73 and 3.78 m) had eight thermocouples equally spaced around the interior circumference, while the central ring at x = 1.96 m had 16 thermocouples. In addition to these rings, five other thermocouples were placed in a line along the top surface at x = 0.43, 1.04, 1.35, 1.65, and 2.26 m. Two were attached to the south end cap in a vertical line, each 19.5 cm from the center of the cap. Two more thermocouples were used to monitor the temperatures of the center of the calorimeter insulation, and thermocouple wire bundle. Detailed diagrams of thermocouple locations are provided in Kramer, et al, 2000.

Six of the thermocouples were randomly selected and calibrated at 30, 500, and 1100°C. All six were certified to have 99% confidence error limits of ±1.1°C or 0.4% of reading, whichever is greater.

Heat flux from the fire to the calorimeter was determined using the measured inner surface temperatures in conjunction with an inverse conduction code. This technique was used because it is difficult to measure exterior surface heat flux directly using heat flux gages. This is because gages strapped to the exterior surface respond differently to the fire convection and radiation than the surface itself.

If the interior surface is well insulated and if axial and azimuthal conduction within the calorimeter can be neglected, the interior surface temperature responds to the local outer surface heat flux. The thermal mass of the wall causes a short delay in the interior surface response and acts as a low pass filter. The thermal diffusion time for the 2.54 cm thick steel calorimeter was roughly W/α = 80 sec, where α is the steel thermal diffusivity and W is the wall thickness. As a result, a given temperature versus time response does not specify a unique heat flux versus time trace.

The Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) code was used to determine the heat flux to the outer surface from the inner surface temperature measurements. SODDIT is a Fortran-based computer program (Blackwell et al. 1987). Temperature versus time data, material properties (density, specific heat and thermal conductivity versus temperature) and the dimensions of the conduction domain are given to SODDIT as input. It uses this data along with sensitivity coefficients and the future time method to determine a unique heat flux versus time trace for one-dimensional heat conduction problems. It has been successfully used to solve inverse conduction problems in other fire heat transfer measurement experiments (Gregory et al. 1989, Koski et al. 1994).

Because SODDIT is a one-dimensional code, there was a concern that spatial non-uniformity of the surface heat flux would not be modeled accurately. During the design phase of this experiment, an unbenchmarked version of CAFE was linked to a finite element model of the current calorimeter (Kramer et al. 2000). Simulations were performed to predict both the exterior surface heat flux and interior surface temperature versus time and location. The specific heat used in the finite element model of the calorimeter contained a spike covering the narrow temperature range (726–768°C) of the Curie solid-solid phase change. This spike modeled the latent heat of the phase change.

The heat flux predicted by CAFE varied rapidly with time due to the unsteady motion of the fire. The interior surface temperatures were much less unsteady due to the thermal mass of the wall. The interior temperatures and calorimeter properties were then used as input to the SODDIT code. The SODDIT-predicted heat flux was compared to the actual heat flux applied to the calorimeter model by CAFE.

The SODDIT-calculated heat flux contained sharp oscillations in the narrow temperature range of the Curie phase change but did not exhibit any other high frequency oscillations. If the sharp oscillation at the Curie temperature is simply bridged using a straight line, then the SODDIT predicted heat flux is within 7% of a window-average of the applied heat flux. We conclude the spatial variation of the heat flux in the current experiment is likely to be sufficiently uniform to allow the use of a one-dimensional inverse conduction solver. Moreover, while the SODDIT heat flux does not exhibit rapid oscillation, it accurately represents the window average of the heat flux versus time.

The estimated uncertainty (95% confidence) of the heat flux measurements is less than ±10% of the calculated values (Kramer 2001). This estimate is based on random errors in temperature measurements (estimated to be ±0.018°C with 95% confidence) and uncertainties in the measured material properties. The uncertainties in the measured density, thickness, specific heat and thermal conductivity are 0.7%, 3.1%, 5%, and 11.2%, respectively.

Small rectangles in Fig. 1b show locations where five of eight Directional Flame Thermometer (DFT) fixtures were placed outside of the calorimeter. They were located above, below and on the east and west sides of the calorimeter at x = 2.82 m. At
each of these locations two fixtures were placed 15.25 cm (6 in) and 30.5 cm (12 in) from the surface of the calorimeter. Each DFT fixture is a cylinder-shaped object that has thin stainless steel foils on the two ends (Koski et al. 2000). The foils have thermocouples attached to the interior surface, and the interior volume of the fixture is filled with insulation. The axes of each of the DFT cylinders were parallel to the axis of the calorimeter. The foils rapidly come into thermal equilibrium with the effective flame radiation temperature north and south of the fixtures. As a result, the devices give a measure of the local “flame” temperatures, $T_{\text{flame}}$. The flame black body emissive power, $E_b$, is calculated by an algorithm developed at Sandia National Laboratories (Blanchat, Humphries, and Gill, 2000) that corrects for the time lag present in the DFT data. The flame black body emissive power is approximately equal to $\sigma T_{\text{flame}}^4$. The eight double-sided DFT fixtures gave a total of sixteen flame temperature measurements.

The data acquisition system used rack-mounted thermocouple and voltage input modules, which allowed a portable computer to display and write the data to a file as it was collected. The thermocouple modules use an electronic ice-point to yield absolute temperatures. All temperature data channels were recorded at intervals of 5 seconds. For each data point, the data acquisition system collected 300 samples over a one second time period and averaged the 300 values to yield the instantaneous temperature. This was done to reduce the random errors that can be caused by periodic and random RF interference. The wind data were collected at 15 second intervals by another data acquisition system.

Two tests were performed on August 24 and 25, 2000. The calorimeter exhibited a blotchy rusted surface before the first test. The extreme heat and oxidation that occurred during that test left the surface a nearly even gray color, and this was the initial condition for the second test. The dominant mode of heat transfer in a pool fire is radiation (Nakos et al. 1989), and the surface emissivity affects this transport. The emissivity of the uniform surface is more easily characterized than that of the original conditions. The surface emittance of the calorimeter steel was measured after the tests. Measurements were taken from a soot-covered area, and from an area without soot. Two different reflectometers, covering the infrared and near infrared spectrums were used in the measurements. The soot yielded a surface emittance of 0.9-0.94. The bare steel had a measured emittance of 0.8-0.85. The results of the second test are considered more useful for benchmarking purposes and are described in this paper.

**RESULTS**

Before the test was initiated 5110 liters (1350 gal) of fuel was placed on top of the water in the fuel dam. This corresponds to a 12.7 cm (5 in) deep layer of fuel. The fuel was ignited at the edge of the pool using a torch and the flames spread slowly across the pool. Roughly 2 minutes was required before the calorimeter was fully engulfed. The time scale was arbitrarily set to $t = 0$ when the fire first engulfed the calorimeter. The fire lasted until $t = 34$ minutes. The burning rate of the pool fire was not measured as a function of time, however nearly all of the fuel was burned during the 34 minute fire.

Figure 2 shows the wind speed, $S$, measured outside the fences. Traces are included for data measured 3.0 and 6.1 m (10 and 20 ft) above the ground, and for a two-minute window average of both sets of measured data. As mentioned previously, the wind speed inside the fence may be half the level outside the fence. For the first 24 minutes, the wind came from the east. If the direction inside the fence is the same as that outside, then this corresponds to the wind blowing across the calorimeter axis. There was a lull between $t = 24$ and 27 minutes. After $t = 27$ minutes the wind came from the south (parallel to the calorimeter axis).

The wind speeds at the higher and lower elevations are close to each other. They both exhibit oscillations with periods between one and seven minutes and amplitudes of roughly 0.5 m/s. The wind speed had its highest values at the beginning of the test, 2.9 m/s (6.5 mph), and generally decreased with time. The average wind speed throughout the test was 1.02 m/s.

Figure 3 shows two photographs taken during the fire. Both photos show that the flames neck inward with increasing height above the ground. Figure 3a was taken during a time of low wind. We see that the end cap of the calorimeter is not engulfed even though the pool extends 1.2 m beyond it. An observer standing directly east of the calorimeter took Fig. 3b. It was taken during a period when the wind was blowing westward, away from the observer and across the calorimeter axis. At this time a large portion of the eastern side of the calorimeter is not engulfed. Figure 2 shows that the wind blew across the calorimeter for much of the test. This suggests that the west side of the calorimeter may have been engulfed in flames for a greater fraction of time than its east side.

Figure 4 shows flame blackbody emissive power versus
time for regions near the west, bottom, east and top of the calorimeter. These emissive powers were calculated using an algorithm developed by Blanchat, Humphries, and Gill that calculates incident black body emissive power based on directional flame thermometer temperature data. The data in Fig. 4 are based on south facing directional flame thermometers that are nearer to the calorimeter. The other DFT’s at the same locations gave similar results.

The emissive power was essentially zero at all locations before the fire was lit. The west side emissive power increased very rapidly after the fire was ignited. After \( t = 4 \) minutes it reached a steady state level that averaged roughly 200 kW/m\(^2\) with peaks as high as 230 kW/m\(^2\). Oscillations with periods between 5 and 7 minutes and amplitudes between 15 and 30 kW/m\(^2\) persisted throughout the test. The period of these oscillations is similar to that of the window-averaged wind speed shown in Fig. 2. The emissive power appears to decrease slightly during the last 6 minutes of the test, after the wind died down and then shifted direction. This suggests that the crosswinds that existed during the first 24 minutes formed a recirculation zone on the west (leeward) side of the calorimeter. This zone contained vortices that mix oxygen and fuel vapor very effectively. The mixing in this zone may have increased the effective fire temperature relative to the levels that existed when there was no crosswind.

The emissive power near the bottom of the calorimeter rose from 120 to 180 kW/m\(^2\) during the period \( t = 1 \) to 25 minutes. It then dropped at the end of the test, after the wind shifted. This suggests that a fuel-vapor rich zone exists below the calorimeter at the end of the test. Combustion in such a vapor dome is limited by the lack of sufficient oxygen. The temporal oscillations at the bottom were much smaller than they were on the west side. This may be because the bottom was more sheltered from unsteady wind effects than the upper portions of the calorimeter.

The emissive power levels near the top and east side of the calorimeter were very similar to each other throughout the fire. They were between 40 to 50 kW/m\(^2\) for the first 10 minutes of the fire, significantly lower than the other locations. During this period, the outside-fence wind speed was greater than 1.2 m/s. This may have tipped the flames so that the east and top portions of the calorimeter were only intermittently engulfed. The emissive power levels exhibit a large spike during the period \( t = 11 \) to 14 minutes, corresponding to a time when Fig. 2 shows a dip in the wind speed. From \( t = 10 \) to 24 minutes the emissive power grew from 50 to 140 kW/m\(^2\), as the wind speed decreases from 1.2 to 0 m/s. The emissive power at these locations grew very rapidly after \( t = 24 \) minutes when the wind stopped blowing across the calorimeter. The low crosswind condition may have allowed the top and east side to be more continuously engulfed in flames. At these locations the emissive power has a strong negative correlation with wind speed. Finally, the top and east side emissive powers exhibited oscillations that were similar to those at the west side of the calorimeter.
High values of the emissive power appear to indicate periods of time that certain locations of the calorimeter were engulfed in flames. Seen as a whole, Fig. 4 shows that the calorimeter was much more uniformly engulfed at the end of the fire test than it was at the beginning. Moreover, wind speed and direction appear to have strongly affected the flame emissive power.

Figure 5 shows inner surface temperature versus time at the west, bottom, east and top locations of the calorimeter central section (x = 1.96 m). Before the fire was lit the calorimeter temperature was essentially uniform at 20 ± 2°C. The fire was ignited at t = -2 minutes. The interior temperature started rising at t = 40 seconds. This 80 sec delay is in close agreement with the calculated thermal diffusion time for the 2.54 cm thick steel calorimeter wall.

After t = 0, when the calorimeter was first engulfed, the west and bottom were significantly hotter than the east and top locations, especially for the first 24 minutes. This is consistent with the flame emissive powers seen in Fig. 4. At t = 24 minutes the temperature of the west side begins to decrease. This corresponds to beginning of the period when the wind first stopped blowing across the calorimeter and the west side flame emissive power decreased.

The slope of the temperature-versus-time curves is an indication of the heat flux rate to the calorimeter at each location. The slopes of the west side and bottom traces are initially high and steadily decrease with time, indicating that the heat flux at these locations was also decreasing. This is expected since the surface temperatures at these locations increased with time and approached thermal equilibrium with their surroundings. However the slopes of the east side and top traces remain fairly constant. Figure 4 shows that at these locations the flame emissive power (and effective flame temperature) increased with time for the entire test duration. Moreover, wind speed and direction appear to have strongly affected the flame emissive power.

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The following discussion will be focused on the central section. It is immediately apparent that the temperature distribution is asymmetric, especially for the first 10 minutes. The west side and bottom (between θ = 45° and θ = 225°) were always hotter than the east side and top. For the first 20 minutes of the fire the temperature rise rate was fairly uniform within the region θ = 45° to θ = 225° (the leeward side). This indicates that the heat transfer rate in this region was also fairly uniform. The temperature rise rate in the last 10 minutes of the test, during the time when the wind shifted, was much lower than it was between t = 10 and 20 minutes.

During the first 10 minutes of the test, the temperature rise rate on the eastern (windward) side was much slower than it was on the western (leeward) side. However, the rise in the east side temperature was much more rapid after t = 20 minutes. We see from Fig. 4 that the flame emissive powers exhibit a spike during the time t = 11 to 14 minutes and then continue to rise thereafter. Finally, we see from Fig. 4 that the leeward side (from θ = 45° to θ = 225°) received 94% more energy during the first 10 minutes of the fire, and 51% more energy during the first 20 minutes of the fire than the windward side. However, at t = 30 minutes,
after the wind shifted, the energy absorbed by the leeward side is only 22% more than the windward side.

Figure 7 shows the variation of inner surface temperature with dimensionless axial location x/L at t = 20 minutes. Profiles are shown for lines along the top, bottom, east and west sides of the calorimeter. The temperatures were highest at the center and drop off as the end caps are approached. The north end cap at x/L = 1 was not instrumented, so the temperature at that location is not known. At the south end cap the edge of the fire pool was only 1.2 m away from the calorimeter. As seen in Fig. 3a the flames sloped inward from the pool edge and did not engulf the end caps, allowing them to remain cooler than the rest of the calorimeter. The temperature profile at the west side and bottom are fairly uniform over the central 60% of the calorimeter, while the profiles at the east side and top drop off more rapidly. This suggests that the flame region was narrower on the bottom and west sides than the top and east sides.

Figure 8 illustrates the use of the SODDIT computer code to quantify the time dependent heat flux to the calorimeter. The solid line marked $T_{\text{inner}}$ shows the measured interior surface temperature on the west side of the central ring (also shown in Fig. 5). The line with square symbols is the SODDIT-predicted net heat flux to the exterior surface of the calorimeter, q". Positive values of q" indicate heat transfer from the fire to the calorimeter. The line marked $T_{\text{outer}}$ is the SODDIT-predicted surface temperature on the surface outside the location where $T_{\text{inner}}$ was measured. Two horizontal lines show the temperature range of the Curie phase change (726-768°C) for the calorimeter steel.

During the time that the inner surface temperature is rising (t = 0 to 24 minutes), the net heat flux is from the fire to the calorimeter. The direction of the heat transfer causes the exterior temperature to be greater than the interior value. We see that the outer surface temperature first passes into the Curie range at t = 9 minutes and the inner surface temperature does not pass out of that range until t = 13 minutes. The SODDIT predicted heat flux exhibits a sharp oscillation between time $t = 11$ and 13 minutes due to the spike in the effective specific heat (Curie effect). A straight line is used to bridge the heat flux data at $t = 9$ and 13 minutes to eliminate this oscillation. This technique is applied to all heat flux data used in this paper.

Figure 9 shows net heat flux q" versus time at four locations around the central section (x = 1.96 m). The heat flux values at the west side and bottom of the calorimeter are high at the beginning of the fire, when the calorimeter is relatively cold, and they decrease with time as the calorimeter surface temperatures increase. However, the heat flux on the east side and top of the calorimeter are relatively constant with time. Although the flame emissive power was rising throughout the fire duration at these locations, the surface temperatures were also rising. The net heat flux at these locations remained nearly constant as a result. As shown in Fig. 4, the fire environments at the top and east locations were very similar. This caused the net heat fluxes at the two locations to be very similar also. All four traces exhibit low frequency unsteadiness with oscillatory periods between 4 and 7 minutes. The oscillatory amplitude on the bottom, east and top are all around 12 kW/m², while the amplitude on the bottom is somewhat lower. These oscillatory periods and amplitudes are consistent with the flame emissive powers described in Fig. 4.
Figure 10 shows polar plots of net heat flux to the calorimeter as a function of angular position at times $t = 1, 5, 10, 20$ and $30$ minutes. Plots are presented for the south, central and north cross-sections at $x = 0.73$, $1.96$ and $3.78$ m respectively. SODDIT was not used to find the heat flux at the end cap ring since conduction in that region is clearly not one-dimensional. The heat flux profiles are similar at all three cross sections. Looking at the central section ($x=1.96$ m), on the west side of the calorimeter ($\theta = 22.5^\circ$ to $202.5^\circ$) the heat flux decreases at each successive time shown in the Figure. The heat flux is negative (from the calorimeter to the environment) in the region $\theta = 45^\circ$ to $135^\circ$ at the end of the fire when the wind direction has shifted and the flame emissive power decreases. For the first ten minutes of the fire, the heat flux on the east side of the calorimeter is substantially less than it is on the west side. Moreover, the east side heat flux is essentially constant during that period of time. It then increases in the region $\theta = 270^\circ$ to $0^\circ$ after that region becomes more continuously engulfed in flames. The heat flux distribution at the end of the fire is much more uniform than it was at the beginning of the test.

CONCLUSION

A series of large-scale experiments were performed to measure heat transfer to a massive cylindrical calorimeter engulfed in a circular pool fire for $30$ minutes. The tests were performed outdoors during a period of low wind and a circle of tall wind barriers was used to minimize the effect of wind on the fire. The speed and direction of the wind outside the barriers were measured as functions of time. The calorimeter inner surface temperature and the flame black body emissive power were also measured at several locations as functions of time. An inverse conduction technique was used to determine the rate of heat flux to the calorimeter based on the measured inner surface temperatures.

The maximum wind speed outside the barriers was $2.9$ m/s and the average value during the test was $1.02$ m/s. Even though the speed inside the barriers is likely to have been half these values, these light winds had a substantial effect on the flame temperatures near the calorimeter. The winds tilted the fire so that the windward side of the calorimeter was only intermittently engulfed. This substantially reduced the flame black body emissive power compared to the levels on the leeward side. The variation of calorimeter temperature and heat flux with time was closely correlated with the flame emissive power.

These results show that the heat transfer to a massive object engulfed in a fire is highly dependent on the wind conditions. While the wind speed inside the wind fences was not measured during the current test, measurements are currently underway to correlate the wind speed inside the wind barriers with measurements outside. Once this correlation is complete, the current data set will be well suited for benchmarking computer codes such as CAFE that simulate heat transfer from large-scale fires to massive engulfed objects.

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