Measurements of Heat Transfer to a Massive Cylindrical Calorimeter Engulfed in a Circular Pool Fire

A large-scale experiment was performed to measure heat transfer to a massive cylindrical calorimeter engulfed in a 30 minute circular-pool fire. This test simulated the conditions of a truck-sized nuclear waste transport package in a severe fire. The calorimeter inner surface temperature and the flame environment emissive power were measured at several locations as functions of time. An inverse heat conduction technique was used to estimate the net heat flux to the calorimeter. Tall porous fences surrounded the test facility to reduce the effect of wind on the fire. Outside the fences, 2.9 m/s winds blew across the calorimeter axis at the beginning of the test but decreased with time. The wind tilted and moved the fire so that the initial flame environment emissive power was substantially less on the windward side than the leeward side. The calorimeter became more uniformly engulfed as the winds decreased. The maximum heat flux to the calorimeter was 150 MW/m$^2$ on the leeward side at the beginning of the fire, and generally decreased with time. The local variations of calorimeter temperature and heat flux were closely related to the local flame environment emissive power. [DOI: 10.1115/1.1527905]

Keywords: Experimental, Fire, Heat Transfer, Radiation

Introduction

Large radioactive materials transport packages must withstand severe fire conditions without releasing their contents. Regulations describing a 30 minute fully engulfing fire test that is used for licensing these packages are contained in Title 10, Part 71 of the Code of Federal Regulations, known as 10CFR71 [1], and International Atomic Energy Agency ST-1 [2]. Cask design studies, transportation risk and safety studies, and regulatory analyses all require computational tools to predict the response of packages to both regulatory and historically based accident conditions. Since these analyses require multiple fire simulations, the computational tools must be rapid as well as accurate.

The Container Analysis Fire Environment (CAFE) computer code is currently under development at Sandia National Laboratories as a tool for package design and risk studies [3]. It uses computational fluid dynamics simulations and a number of fire and radiation models to calculate heat transfer from large fires to massive engulfed objects. CAFE may be linked to finite element analysis (FEA) programs that calculate the internal response of a package to the fire. The velocity boundary conditions required in CAFE’s fluid dynamics simulator are chosen based on heat transfer data from full-scale fire experiments. CAFE’s accuracy is based on experimental data and so it cannot be considered a fully predictive fire model. However, it will be a valuable tool for rapidly interpolating between benchmarked conditions, making it useful for design and risk studies. Its usefulness will be increased after it has been benchmarked against a variety of fire conditions.

Numerous large-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 [4]. A small number of large-scale fire tests were performed to measure heat transfer from fires to massive objects [5–7]. These tests concentrated on how thermal mass and surface temperature affect 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 was to measure heat transfer versus time and location to a massive cylindrical calorimeter engulfed in a pool fire. The calorimeter 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 10CFR71 regulations used to license such packages. These data will be used to adjust the CAFE fire model [8] and to develop engineering models for radiant heat transfer in large fires [9].

Experimental Method

The 10CFR71 regulations specify that a transport package under test must be suspended one meter above a hydrocarbon fuel pool, and that the pool must extend horizontally between 1 and 3 m beyond the object [1]. Moreover, the wind conditions must be sufficiently calm so that the object will be engulfed in a fire environment characterized by a temperature of at least 800°C and emissivity of at least 0.9 for 30 minutes. Figure 1 shows plan views of the experiment test facility that was designed to comply with these conditions. It is located at the Sandia National Laboratories Burn Site and its orientation relative to compass directions is shown in the figure.

The experiment was designed with the intention of eliminating wind effects. Tests were performed during early morning periods when the winds are generally light. Figure 1(a) shows that 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. 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 (the area porosity of the fencing was less than 20 percent). The bottoms of the wind fences were 0.3 m above the ground and the fences were separated from each other by one-meter gaps. These gaps were used so that the barriers would not disrupt the natural inward flow of air toward the fire. Measurements for a slightly different wind fence arrangement show that the wind speed inside the barriers without fire is roughly half that outside the fences.
The wind direction and speed 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. The manufacturer’s stated accuracy of the anemometers was ±0.3 m/s, and wind data were collected at 15 second intervals.

Even though wind barriers were employed and the wind speeds were low, the Results section of this paper shows that the external winds had a significant effect on the measured heat transfer to the calorimeter. Additional wind measurement locations would have better characterized the external environment than the two used in this experiment. However, the current wind measurements do characterize the general trends of the external environment and are therefore useful for benchmarking and adjusting fire simulation codes.

Figure 1(b) shows that the calorimeter was located above a 9 m wide, 18 m long, and 1 m deep, water-filled concrete pool. A 7.16 m (23.5 ft) diameter sheet metal fuel dam (seen in Fig. 3) contained JP-8 fuel floating on the water in a circle. The calorimeter was a 3800 kg (8400 lb) carbon steel pipe of length \( L = 4.6 \text{ m} \) (15 ft), diameter \( D = 1.2 \text{ m} \) (4 ft), and wall thickness \( W = 2.54 \text{ cm} \) (1 in). Two caps, 2.54 cm (1 in) thick, were 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 to the interior.

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 10CFR71 regulations. The structure supporting the calorimeter above the pool was constructed from 10 cm square cross section steel tubing. It was designed to contact the calorimeter at six locations. The support stand was insulated and water-cooled during the tests.

The small circles in Fig. 1(b) 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 with MgO, and was ungrounded. They were attached to the interior surface of the calorimeter with spot welded nichrome metal strips. A 2.54 cm-thick layer of Thermal Ceramics Kaowool insulation was placed next to the interior surface and standard fiberglass filled the remaining volume. To avoid shunting errors the thermocouple lead wires were insulated from the metal calorimeter walls by placing them inside the Kaowool insulation. The instrumentation wire bundle exiting the calorimeter was exposed to the fire environment. To further avoid shunting errors, the bundle was insulated and water-cooled during the tests. Its temperature was measured and never exceeded 40°C.

Most of the thermocouples were arranged in four rings. Using the \( x \)-coordinate system shown in Fig. 1(b) \((x = 0 \text{ is at the inner surface of the south end cap})\), the rings were 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. The central ring at \( x = 1.96 \text{ m} \) had 16 thermocouples. In addition to these rings, five thermocouples were placed in a line along the top at \( x = 0.43, 1.04, 1.35, 1.65, \) and 2.26 m. Two more were attached to the south end cap in a vertical line, each 19.5 cm from the center of the cap. A thermocouple was used to monitor the temperature of the center of the calorimeter insulation. Detailed diagrams of thermocouple locations are provided in Kramer et al. 2000 [10].

Six of the thermocouples were randomly selected and calibrated at 30, 500, and 1100°C. All six were certified to have error limits that are the greater of ±1.1°C or 0.4 percent of their reading. Only a small portion of this uncertainty was found to be random in nature [11]. Each thermocouple was connected to a signal conditioner (electronic ice-point/amplifier) whose output was read by a 12-bit computer data acquisition system. The temperature input resolution for this system was ±0.4°C. Temperatures were recorded at 5 second intervals. Each data point represents the average of 300 samples taken over one second. This averaging reduced random errors that can be caused by radio frequency interference.

Small rectangles in Fig. 1(b) marked "DFT" show locations where eight Directional Flame Thermometer (DFT) fixtures were placed outside of the calorimeter [12,13]. These devices are designed to measure the radiant heat flux they receive from their environment. The DFT’s were located above, to the west, below and to the east of the calorimeter (angular positions \( \theta = 0, 90, 180, \) and 270 deg, respectively) at axial position \( x = 2.82 \text{ m} \). At each of these locations, two fixtures were placed 15.25 cm (6 in) and 30.5 cm (12 in) from the outside surface of the calorimeter.

Each DFT fixture is a cylinder-shaped object that has thin stainless steel foils on the end caps. In this experiment, the foils face the north and south directions (parallel to the calorimeter axis). The foils have thermocouples attached to the interior surface, and the interior volume of the fixture is filled with insulation. The foils rapidly approach thermal equilibrium with the radiant heat flux they receive from their surroundings. The measured temperature \( T_{\text{DFT}} \) is used to determine the emissive power the DFT receives from its environment, \( E_{\text{DFT}} = \sigma T_{\text{DFT}}^4 \) (corrections are made for phase lag in an unsteady environment [13]).

In the current paper we only report results from the south-facing DFT sensing foils that are located 15.25 cm from the calorimeter surface. Figure 1(b) shows that the south-facing foils are exposed to the environment outside the central thermocouple ring at \( x = 1.96 \text{ m} \). The DFT emissive power \( E_{\text{DFT}} \) is only a good indication of flame emissive power \( E_{\text{Flame}} \) when the DFT is fully engulfed in optically thick flames. If it is not engulfed, then it is exposed to the external environment or the calorimeter surface and \( E_{\text{DFT}} \) can be significantly less than \( E_{\text{Flame}} \).

Two tests were performed on August 24th and 25th, 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 with regions of soot, and this was the initial condition for the second test. Two different reflectometers, covering the infrared and near infrared spectrums were used to measure the emissivities of the gray and soot covered regions. The soot yielded a surface emittance of 0.9–0.94, while the gray regions had a measured emittance of 0.8–0.85. A dominant mode of heat transfer in pool fires is radiation, and the surface emissivity affects this transport. The results of the second test are therefore described in this paper because its initial surface properties are better known than those of the first test.

Results

Before the test was initiated 5110 liters (1350 gal) of JP-8 fuel was placed on top of the water in the fuel dam. This corresponds to a 12.7 cm (5 in) deep layer. 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 set to \( t = 0 \) when the fire first engulfed the calorimeter. The fire lasted until \( t = 34 \) minutes. The burning rate of the fuel was not measured as a function of time, however nearly all of it was consumed during the 34 minute fire.

Figure 2 shows the wind speed measured outside the fences. Traces are included for data measured 3.0 and 6.1 m above the ground, and for a two-minute window average of both sets of measured data. The wind came from the east for the first 24 minutes of the test. 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 value 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 pictures show that the flames neck inward with increasing height above the ground. Figure 3(a) was taken during a time of low wind. We see that the end cap of the calorimeter is not engulfed even though the fuel pool extends 1.2 m beyond it. An observer standing directly east of the calorimeter took Fig. 3(b). It was taken during a period when the wind was blowing 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 was engulfed in flames for a greater fraction of time than its east side.

Figure 4 shows two-minute-window-averaged DFT emissive power versus time for regions near the west, bottom, east, and top of the calorimeter (\( \theta = 0, 90, 180, 270 \) deg). 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/m² with peaks as high as 230 kW/m². Oscillations with periods between 5 and 7 minutes and amplitudes between 15 and 30 kW/m² persisted throughout the test. The period of these oscillations is similar to that of the window-averaged wind speed shown in Fig. 2.

The west-side emissive power appears to decrease slightly during the last 6 minutes of the test, after the wind died down and then shifted direction. The higher emissive power during the first 24 minutes suggests the presence of a recirculation zone. Efficient air/fuel mixing in this zone may have increased the effective fire...
temperature relative to the levels that existed during the last 6 minutes of the fire when there was no crosswind.

The emissive power near the bottom of the calorimeter rose from 120 to 180 kW/m² during the period \( t = 1 \) to 25 minutes. It then dropped during the last five minutes of the test, after the wind shifted. The lower emissive power at the end of the test suggests that a fuel-vapor rich zone formed between the fuel pool and the calorimeter. Combustion in such a vapor dome is limited by the lack of sufficient oxygen. This vapor dome may not have existed at earlier times due to the stronger cross winds. The temporal oscillations at the bottom were 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 powers measured near the top and east regions of the calorimeter were very similar to each other throughout the fire. They were between 40 to 50 kW/m² 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 tilted the flames so that the east and top portions of the calorimeter were only intermittently engulfed. The emissive power levels exhibit a 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/m², 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. 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 emissive power appear to indicate periods when a location is engulfed in thick flames. Seen as a whole, Fig. 4 shows that the calorimeter was much more uniformly engulfed at the end of the fire test (when the winds were light) than it was at the beginning. Comparing Fig. 4 with the wind data in Fig. 2 shows that the emissive power on the east (windward) side of the calorimeter increased as the wind speed decreased. However, the west (leeward) side emissive power was not significantly affected by wind speed.

Figure 5 shows inner surface temperature versus time at the west, bottom, east and top locations of the calorimeter central section \((x = 1.96 \text{ m})\). Before the fire was lit the calorimeter temperature was essentially uniform at \(20 \pm 2 \text{°C}\). The fire was ignited at \( t = -2 \) minutes, and the interior temperature started rising at \( t = -40 \) seconds. 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 reported in Fig. 4. The temperature of the west side began to decrease at \( t = 24 \) minutes. This corresponds to the time when the wind stopped blowing across the calorimeter. In general, the slope of each temperature-versus-time curve is proportional to the local heat flux. However, the slope of all four curves briefly level off (drop to zero) as they approach 750°C. This is caused by the latent heat of the Curie solid-to-solid phase change, which mild steel experiences at this temperature.

Figure 6 shows polar plots of the inner surface temperature as a function of angular location \((\theta = 0)\) is at the top of the calorimeter) at times \( t = 1, 5, 10, 20, \) and 30 minutes. Plots are presented for the end cap, south, central and north cross-sections, at \( x = 0, 0.73, 1.96, \) and 3.78 m, respectively. While the temperatures were highest at the central section, the profile shapes were similar at each axial station. Moreover, the temperature at all locations increased with time. The following discussion is focused on the central section. The temperature distribution is asymmetric, especially for the first 10 minutes. The west side and bottom (between \( \theta = 45 \) deg and \( \theta = 225 \) deg) were always hotter than the east side and top. This is consistent with the relative values of the local emissive power reported in Fig. 4. For the first 20 minutes the temperature rise rate was fairly uniform within this leeward (western) region, indicating that the heat transfer rate was fairly uniform. The temperature rise rate in the last 10 minutes of the test, after the wind shifted, was much lower than it was between \( t = 10 \) and 20 minutes.

The temperature rise rate on the eastern (windward) side was much slower during the first 10 minutes of the test than it was on the western (leeward) side. However, the rise in the east side temperature was much more rapid after \( t = 10 \) minutes, when its environment emissive power began to increase rapidly. Finally, the temperature data shows that the leeward side (from \( \theta = 45 \) deg to \( \theta = 225 \) deg) received 94 percent more energy during the first 10 minutes of the fire than the windward side, and 51 percent more energy during the first 20 minutes. However, at \( t = 30 \) minutes, after the wind shifted, the energy absorbed by the west side was only 22 percent more than the east side.

Figure 7 shows the variation of inner surface temperature with dimensionless axial location \(x/L\) at \(t = 20 \text{ minutes}\). Profiles are shown for lines along the top, west, bottom and east sides of the calorimeter, \( \theta = 0, 90, 180, \) and 270 deg, respectively. 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). At the south end cap the edge of the fire pool extended only 1.2 m from the calorimeter. As seen in Fig. 3(a) 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 profiles at the west side and bottom are fairly uniform over the central 60 percent 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 top and east than it was on the bottom and west.

The Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) computer code [14] was used in conjunction with the interior temperature measurements to calculate the heat flux to the calorimeter exterior surface as a function of time and location. The inputs to SODDIT are the measured inner surface temperature \(T_w(t_i)\) at equally spaced times \(t_i = i \Delta t\), the measured calorimeter diameter \(D\) and wall thickness \(W\), and its measured material properties (temperature-dependent specific heat \(c_p(T)\) and thermal conductivity \(k(T)\), and a temperature-independent value of the density \(\rho\)). In the expression for the evaluation times \(t_i = i \Delta t\), \(\Delta t\) is the measurement time interval, \(i = 1,2,3, \ldots\) , and the integer \(m\) designates the fraction of data points that are skipped \((m = 1\) uses all the data, \(m = 4\) uses ever fourth data point). For the current work, \(\Delta t = 5 \text{ sec}\) and \(m = 4\).

SODDIT uses a one-dimensional conduction model along with sensitivity coefficients and the future-time method to determine the outer surface heat flux \(q_{OUT}(t_i)\) and temperature \(T_{OUT}(t_i)\) at times \(t_i\). In the current work the number of future times in the SODDIT calculation was set to 4. SODDIT was used to calculate the exterior surface heat flux and temperatures for locations that are in proximity to all the thermocouples shown in Fig. 1(b) ex-
cept those near the south end cap (at $x=0$). SODDIT was not used near the end cap because the conduction in this region is clearly not one-dimensional.

The calorimeter steel thermal diffusivity $\alpha = k/pc_p$ was measured as a function of temperature using the laser pulse diffusivity technique. Differential scanning calorimetry was used to measure the specific heat $c_p$ as a function of temperature. The room temperature density $\rho$ was determined from the dimensions and mass of a small cylindrical sample. The 95 percent confidence-level uncertainties of the thermal conductivity, specific heat, density and wall thickness were estimated to be $\pm 11.2$ percent, $\pm 5$ percent, $\pm 0.75$ percent, and $\pm 3.5$ percent of their respective measured values. The measured effective specific heat exhibited a spike in the temperature range 726–768°C. This spike was caused by the latent heat of the Curie solid-solid phase change. The uncertainty in the effective specific heat is much greater in this temperature range than it is at higher and lower temperatures.

Figure 8 illustrates the use of the SODDIT computer code to

![Figure 6](image)

Fig. 6 Measured inner surface temperature $T_{in}$ versus angular position and time for $x=0$, 0.73, 1.96, and 3.78 m

![Figure 7](image)

Fig. 7 Measured inner surface temperature versus axial location at $t=20$ min for $\theta=0$ deg, 90 deg, 180 deg, and 270 deg

![Figure 8](image)

Fig. 8 SODDIT-calculated exterior surface heat flux and temperature, and the measured inner surface temperature versus time for $\theta=90$ deg at $x=1.96$ m. The Curie-bridge is also shown.
quantify the time dependent heat flux to the west side ($\theta=90$ deg) of the central ring ($x=1.96$ m). The solid line marked $T_{IN}$ shows the measured interior surface temperature (also shown in Fig. 5). The line with open circles marked $T_{OUT}$ is the SODDIT-calculated exterior surface temperature outside the location where $T_{IN}$ was measured ($\theta=90$ deg, $x=1.96$ m). Two horizontal dashed lines show the temperature range of the Curie phase change (726–768°C) for the calorimeter steel. The line with square symbols is the SODDIT-calculated net heat flux to the exterior surface of the calorimeter, $q_{OUT}^\theta$. Positive values of $q_{OUT}^\theta$ indicate heat transfer from the fire to the calorimeter.

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 ($q_{OUT}^\theta>0$). The direction of the heat transfer causes the exterior temperature $T_{OUT}$ to be greater than the interior value, $T_{IN}$. 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. These oscillations are caused by the inaccuracy of the effective specific heat in the Curie temperature range. In this work, we ignore the SODDIT predicted heat flux during the time period when the calorimeter is within the Curie temperature range. We use a linear bridge between the SODDIT predictions at the beginning and end of this period. In this paper the Curie-bridge technique is applied to the heat flux data whenever the inner or outer surface temperatures are within the Curie range.

Simulations with the linked CAFE/Finite Element Analysis system were used to evaluate the ability of SODDIT with the Curie bridge to calculate an 80 second window-average of the applied heat flux [11,15]. The estimated 95 percent confidence level uncertainty of the SODDIT-calculated heat flux is less than ±15
kW/m² when the calorimeter temperature is not inside the Curie range (726°C to 768°C). The uncertainty is considerably higher when the calorimeter temperature is inside that range. The error bars in Fig. 8 show the 95 percent confidence level uncertainty at $t = 3$, 7, 15, and 25 min.

Figure 9 shows net SODDIT-calculated heat flux $q_\text{OUT}$ versus time at $\theta = 0$, 90, 180, and 270 deg for 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. They decrease with time as the calorimeter surface temperatures increase. The heat flux on the east side and top of the calorimeter exhibit oscillations. However, their levels are roughly constant with time. Although the surface temperatures at these locations were rising with time, the flame emissive power shown in Fig. 4 was also rising. This is the reason that the net heat flux at these locations remained nearly constant. Figure 4 also shows that the fire environments at the top and east locations were very similar. This caused the net heat fluxes at the two locations (shown in Fig. 9) to be very similar. All four traces in Fig. 9 exhibit low frequency unsteadiness with oscillatory periods between 4 and 7 minutes. The oscillatory amplitudes on the west, 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 $t = 1, 5, 10, 20, \text{ and } 30$ minutes. Plots are presented for the south, central and north cross-sections at $x = 0.73, 1.96, \text{ and } 5.78$ m respectively. SODDIT was not used to find the heat flux at the end caps since conduction in that region is clearly not one-dimensional. The heat flux profiles are similar at all three cross sections. On the west side of the calorimeter ($\theta = 22.5$ deg to 202.5 deg) 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 $\theta = 45$ deg to 135 deg at the end of the fire when the wind direction shifted. 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 increased in the region $\theta = 270$ deg to 0 deg after that region became more continuously engulfed in flames.

**Conclusion**

A large-scale experiment measured heat transfer to a massive pipe calorimeter suspended in a circular JP-8 pool fire for 30 minutes. These conditions approximated a truck-sized nuclear waste transport package in a regulatory test. Tall, porous fencing surrounded the outdoor test facility. The fencing was designed to reduce the effect of wind while allowing a natural indraft of air. The speed and direction of the wind were measured as functions of time at two elevations outside the barriers. The calorimeter inner surface temperature and the flame environment emissive power were also measured at several locations as functions of time. The net window-average heat transfer rate to the calorimeter was determined using an inverse heat conduction technique.

Winds with an outside-fence speed of 2.9 m/s blew across the calorimeter axis at the beginning of the test but decreased with time. The average speed during the test was 1.02 m/s. Even with the wind barriers, the winds tilted and moved the fire so that the initial flame environment emissive power on the windward side was substantially less than the leeward side. The calorimeter became more uniformly engulfed as the winds decreased. The maximum calculated heat flux to the calorimeter was roughly 150 MW/m² on the leeward side at the beginning of the fire, and generally decreased with time. The local and temporal variations of calorimeter temperature and heat flux were closely related to the local environment emissive power, which, in turn, was affected by the wind.

The current data are well suited for benchmarking and adjusting the Container Analysis Fire Environment (CAFE) computer code, which is intended for use in design and risk analyses of massive nuclear waste transport packages. The benchmarked version of CAFE can be linked to a finite element analysis model of a transport package and then used to determine package response for the wind conditions that existed during the current test. CAFE can be used for other wind conditions after additional benchmarking experiments have been performed.

**Acknowledgments**

The US Department of Energy funded this work under DOE/EPSCoR Grant DE-FG02-98ER45715. The authors would like to thank W. R. Jacoby, Rodney Oliver, Terrence Aselage, and A. R. Mahoney for their valuable help and expertise.

**Nomenclature**

\[
\begin{aligned}
c_p & = \text{calorimeter effective thermal conductivity} \\
D & = \text{calorimeter diameter} \\
E_{\text{DFT}} & = \text{emissive power measured by a directional flame thermometer (DFT)} \\
E_{\text{Flame}} & = \text{emissive power of the flames} \\
i & = \text{integer index, } 1,2,3, \ldots \\
k & = \text{calorimeter thermal conductivity} \\
L & = \text{calorimeter length} \\
m & = \text{inverse of the fraction of measured data points used in SODDIT analysis} \\
q_\text{OUT} & = \text{calorimeter outer surface heat flux} \\
T & = \text{time after the calorimeter is fully engulfed} \\
\Delta t & = \text{measurement time interval} \\
T_{\text{Flame}} & = \text{local flame temperature} \\
T_{\text{IN}} & = \text{calorimeter inner surface temperature} \\
T_{\text{OUT}} & = \text{calorimeter outer surface temperature} \\
S & = \text{Outside-fence wind speed} \\
W & = \text{calorimeter wall thickness} \\
x & = \text{axial coordinate (} x = 0 \text{ is at the south end of the calorimeter)} \\
\alpha & = \text{calorimeter thermal diffusivity, } k/c_p \rho \\
\rho & = \text{calorimeter density} \\
\theta & = \text{angular coordinate around calorimeter (} \theta = 0 \text{ is at the top of the calorimeter)} \\
\sigma & = \text{Stefan-Boltzmann constant} \\
\end{aligned}
\]

**References**


