Initial Measurements with an Actively Cooled Calorimeter in a Large Pool Fire*

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ABSTRACT

The initial measurements with a 1 m x 1 m water cooled vertical flat plate calorimeter located 0.8 m above and inside a 6 m x 6 m JP-4 pool fire are described. Heat fluxes in ten vertical 0.1 m high x 1 m wide zones were measured by means of water calorimetry in quasi-steady-state. The calorimeter face also included an array of intrinsic thermocouples to measure surface temperatures, and an array of Schmidt-Boelter radiometers for a second, more responsive, method of heat flux measurement. Other experimental measurement devices within the pool fire included velocity probes, directional flame thermometers (DFTs), and thermocouples.

Water calorimetry indicated heat fluxes of about 65 to 70 kW/m^2 with a gradual decrease with increasing height above the pool. Intrinsic thermocouple measurements recorded typical calorimeter surface temperatures of about 500°C, with spatial variations of ±150 °C. Gas velocities across the calorimeter face averaged 3.4 m/s with a predominant upward component, but with an off-vertical skew. Temperatures of 800 to 1100°C were measured with the DFTs.

The observed decrease in heat flux with increasing vertical height is consistent with analytical fire models derived for constant temperature surfaces. Results from several diagnostics also indicated trends and provided additional insight into events that occurred during the fire. Some events are correlated, and possible explanations are discussed.

Key Words: Pool fire, heat flux, measurements, calorimeter

INTRODUCTION

Most heat flux measurements made to date in large pool fires relied on transient temperature measurements of massive objects with data analysis through inverse heat conduction methods [1,2,3]. To complement this approach by fixing several fire variables, experiments with an actively cooled calorimeter in a large pool fire have been completed, and the initial results are reported here. By water cooling the fire-exposed face of the calorimeter, surface temperature variations with time and location are minimized, and quasi-steady-state heat fluxes can be determined from the temperature rise and flow rate of the cooling water. Segmentation of the face into zones also allows

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determination of the vertical heat flux profile. Other diagnostics used with the actively cooled surface include intrinsic thermocouples for surface temperature estimation, a directional flame thermometer (DFT) array in front of the calorimeter, and a velocity probe array in the fire. The goal of the program is to develop experimental data that can be used to calibrate analytical fire models [4] so that design tools for rapid and accurate analysis of objects exposed to large fires can be developed. Application of the models to shipping containers for hazardous materials will allow more accurate simulation of both regulatory and accident fire conditions.

Past experiments [1,2,3] used transient inverse heat conduction methods to estimate surface temperatures and heat fluxes. The inverse technique consists of monitoring temperature rises at internal calorimeter locations, and then solving the heat conduction problem "backwards" to estimate surface heat fluxes and temperatures that are consistent with the internal temperatures. Such fire tests have shown [5] that "massively thermal" objects are subject to lower incident heat fluxes than smaller objects. The gray gas analytical model developed by Nicolette and Larson [4] can be used to understand these characteristics. Unlike the previous experiments that provide only a brief time at each surface temperature as the calorimeter heats up, the current approach will allow a thorough, near steady-state investigation of the effect of surface temperature and other variables. The technique also lends itself to the easy inclusion of other diagnostic methods such as radiometers, intrinsic thermocouples, heat flux gauges, and fiber optic probes. By doing later tests in the Smoke Emissions Reduction Facility (SMERF) [6], a wind shielded facility, a major source of test-to-test experimental variation will be removed. Comparisons with tests in open pools will be used to assess wind effects.

EXPERIMENT DESCRIPTION

Calorimeter

The calorimeter shown in Figures 1 and 2 includes a 1 m x 1 m actively cooled surface. The cooled surface consists of 20 0.1 x 0.5 m copper plates with brazed 3/8 inch nominal diameter copper coolant tubes. Plates and tubes are arranged into 10 vertical zones. The copper plates are mounted with long stainless steel studs to a steel box frame that is enclosed with sheet metal and insulation. The long studs thermally isolate the copper plates from the steel frame. Stainless steel tiles (0.1 m x 0.1 m x 1.8 mm) form the fire facing surface. To provide high, uniform surface emittance, the tiles are coated with Pyromark Black. Calorimeter surface temperatures are controlled on an experiment-to-experiment basis by changing the thickness of the insulators located between the stainless steel tiles and the cooled copper plate. The stainless steel surface tiles are bolted with Belleville type spring washers to preserve good thermal contact even when heating causes differences in thermal expansion between the tiles and the ceramic substrate.

For the experiments reported here, 6.4 mm thick Macor ceramic insulators were used. Analyses show [7] that the calorimeter with these tiles should reach steady state in two to three minutes. Water flow is distributed into upper and lower banks of five tubes as shown in Figure 1. The flow velocity in each tube is typically set for 2 m/s, resulting in water temperature rises of about 20 to 30°C. Water temperatures are measured with type K thermocouples. One inlet thermocouple is provided in each inlet manifold, while each of the ten tubes exiting the calorimeter has a separate thermocouple. To insure measurement consistency, all thermocouples were specified to be produced from the same batch of thermocouple wires. Water flow is measured in the upper and lower tube

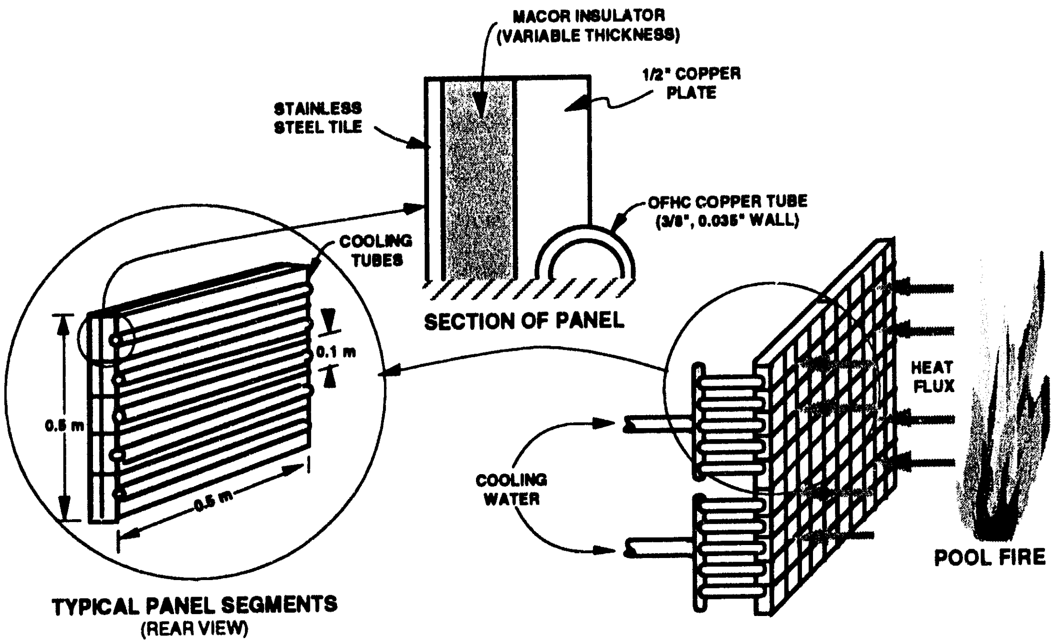

Figure 1. Sketch of actively cooled calorimeter experiment.

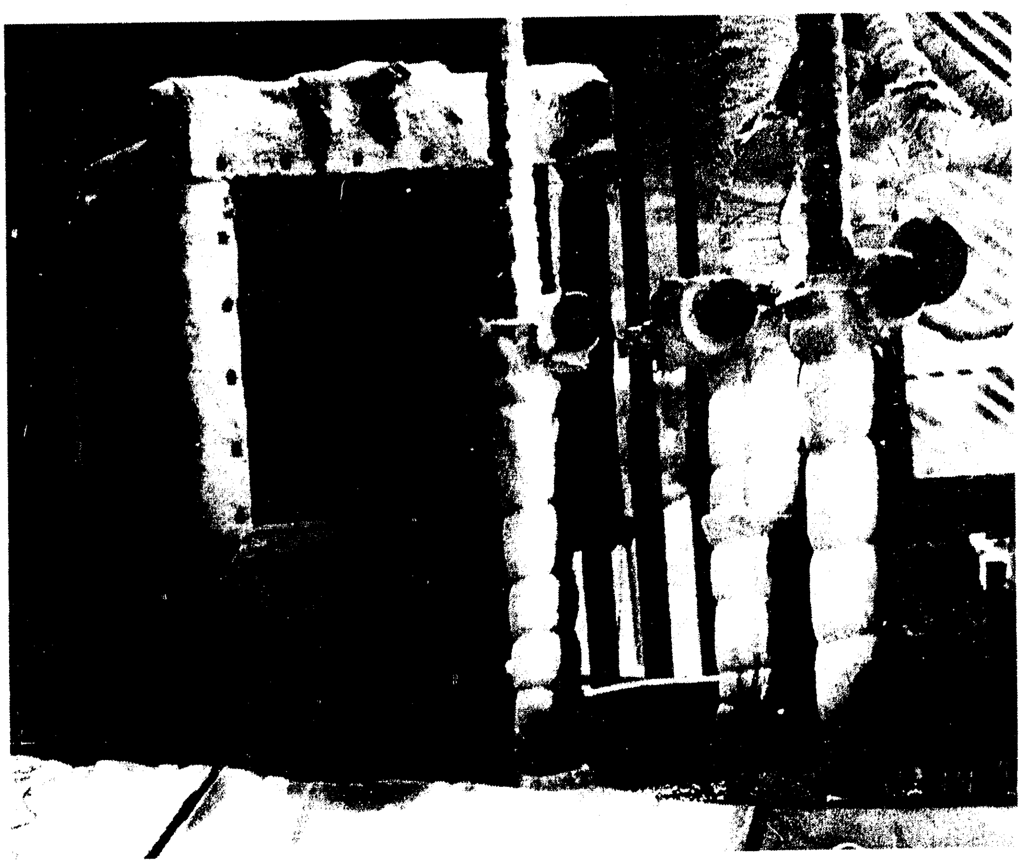

Figure 2. Calorimeter after fire. Calorimeter face is black square at left in photo. The directional flame thermometers are visible as black disks to the right of the face.

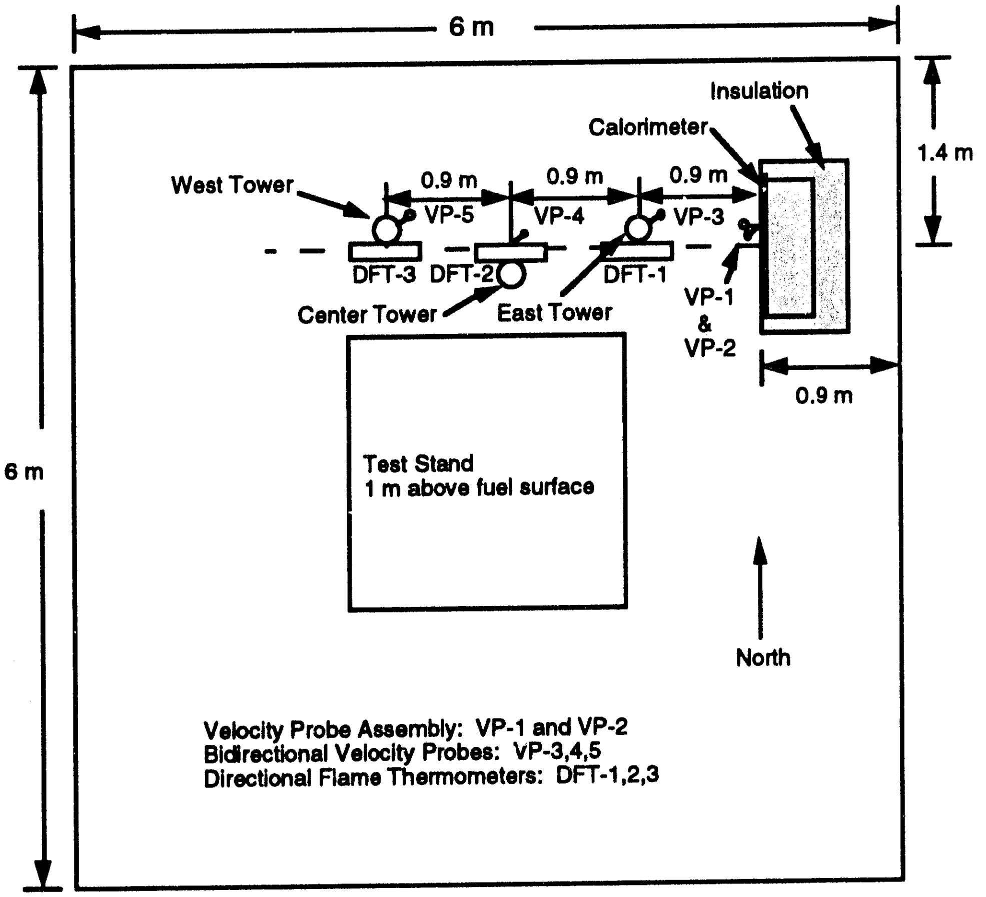

Figure 3. Location of calorimeter and diagnostics in 6 m x 6 m pool.

banks of five tubes each with two turbine type flow meters. To create an even flow distribution among the five tubes in each bank, large diameter inlet and outlet manifolds are used to assure uniform tube entrance and exit pressures, and care was taken during assembly to assure that all copper tubes havethe same shape and routing between the manifolds. Further details of the analysis leading to the design are provided in Reference [7].

Before making any fire measurements, the calorimeter was tested in the Sandia radiant heat facility where banks of halogen filled quartz lamps behind a steel shroud simulated the fire environment. Absorbed heat fluxes of 70 to 80 kW/m^2 were recorded. Under these conditions, the maximum recorded variation from a measured heat flux data point to a cubic polynomial fit through all ten data points was 2.7 %, with a rms variation of 0.5 % for the ten channels. The variations are most likely caused by small tube-to-tube differences in the water flow. The radiant heat testing also served to cure the Pyromark paint on the surface of the tiles. For the 500°C surface temperatures anticipated during testing, Pyromark 2500 paint has a surface emittance in the 0.7 to 0.75 range.

For the experimental results presented here, the calorimeter was mounted facing west near the northeast corner of the 6 m x 6 m pool (see Figure 3). The vertical plane of the face was 0.9 m west and parallel to the east edge of the pool. The center of the vertical face was located 1.3 m above the pool initial fuel level and 1.4 m from the northeast corner. The location was chosen to reduce interference with a test object at the center of the pool.

Additional diagnostics included in the calorimeter structure itself are intrinsic thermocouples, radiometers, and various thermocouples for checking internal temperatures. The intrinsic thermocouples are formed by spot welding closely spaced type K thermocouple wires to the back of 18 of the stainless steel surface tiles. Locations of the intrinsic thermocouples are shown in Figure 4. During radiant heat testing the intrinsic thermocouples performed well with zones of higher temperature consistently coinciding with zones of higher heat flux. Four Schmidt-Boelter type radiometers with an 11° field of view are mounted (see Figure 4) behind holes in the copper plates and tiles. These radiometers have a much faster response than the water calorimetry, and are intended to provide a measure of the time variations of surface heat flux. Space limitations do not permit reporting the radiometer results in this paper. Type K thermocouples monitor copper plate temperatures and frame assembly temperatures at locations shown on Figure 4.

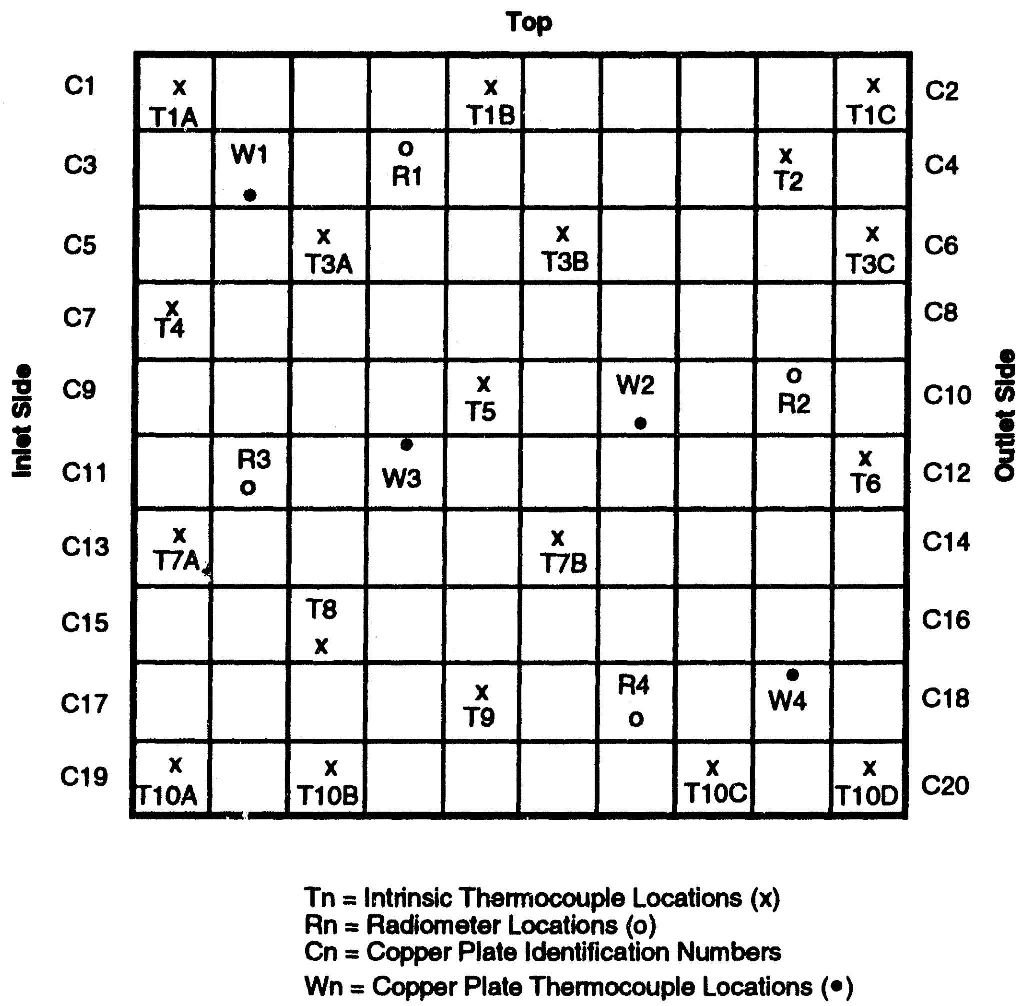

Figure 4. Location of diagnostics on front face of calorimeter. Small squares represent stainless steel tiles that face fire.

General fire diagnostics included a meteorological tower with wind velocity and direction measurements at various heights above the pool, and video records of the fire from three directions.

Velocity Probes

There are several problems in measuring the gas velocity in the fire plume of an open pool fire. The fire plume is very turbulent with large fluctuations caused by air entrainment, mixing, combustion processes, and wind perturbations [1,2]. Typically the gas velocities are low, the gas density is low and the temperatures are high. To avoid these problems a bi-directional, low-velocity pitot type probe designed for use at low Reynolds numbers was selected. Bi-directional probes have been used to measure velocities in large open pool fires because they are relatively insensitive to changes in flow direction [8].

To interpret the results from the vertical plate calorimeter, it is necessary to understand the flow velocity and direction across the face. The design and application of these "multi-directional probe assemblies" are described in detail in [9].

The velocity probe assembly was mounted above the center of the actively cooled surface as shown in Figure 3. At each DFT location, a bi-directional velocity probe was installed to measure the vertical gas flow component. To prevent deterioration, all the probes were coated with sol-gel/glass powder film [10] and the pressure sensing lines were water cooled and insulated with several layers of blanket insulation. The location of the instrumentation is shown in Figure 3.

A 1.6 mm O.D., Inconel sheathed, ungrounded junction, type K thermocouple was used at each probe location to measure the temperature of the gas. These temperatures were used to calculate the density of the gas (assumed to be air) which in turn was used to calculate the flame velocity. Assuming that the gas is air could lead to errors in the lower flame region where it is expected that significant fractions of unburned fuel vapors may be present.

Directional Flame Thermometers

Directional flame thermometers (DFTs) were included as part of the fire instrumentation package. A DFT consists of a plate that is insulated on the back side, and exposed to the fire on the other side. A thermocouple is mounted on the back face. The plate is a thin sheet of metal that rapidly reaches a thermal equilibrium with the heat flux incident on the front face. By assuming convection heat transfer is a small portion of the incident heat flux on the DFT surface, Fry [11] demonstrates that the temperature measured by the DFT approximates the black body temperature for the incident radiation on the DFT. Figure 5 shows a diagram of the DFT design used in these tests.

The test configuration consisted of three DFTs in an east-west line located 1.4 m from the northern edge of the fire fuel pool. The DFTs were spaced 0.9 m apart and were located 1.3 m above the fire fuel pool. DFT 1 was the easternmost and was 0.9 m from the front face of the calorimeter. DFT 3 was the westernmost sensor and DFT 2 was located between DFT 1 and 3. Each DFT had an eastern and a western facing sensor plate. The location of the DFTs relative to the calorimeter is presented in Figure 3.

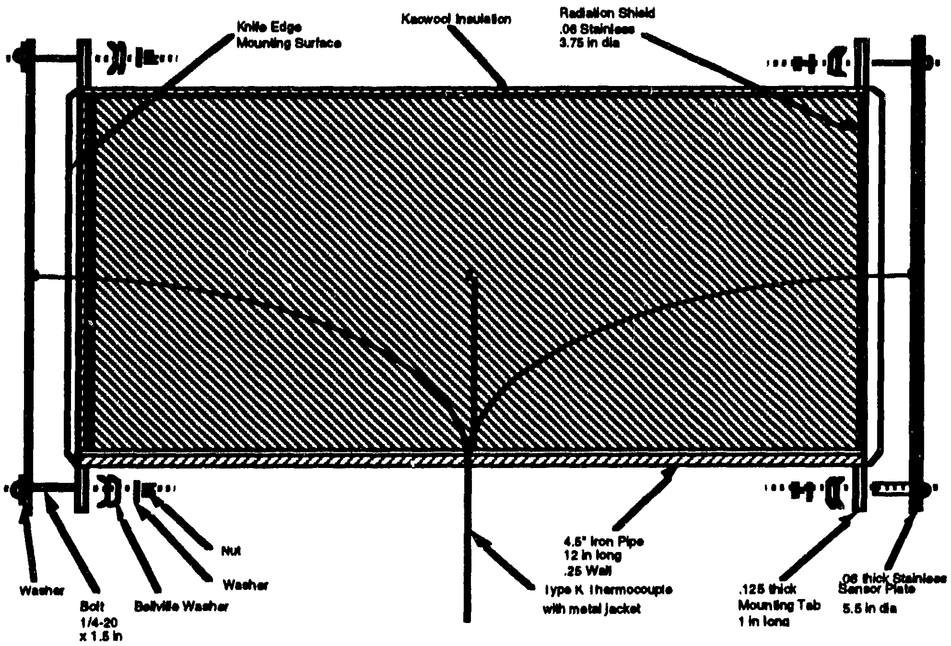

Figure 5. Sketch of Directional Flame Thermometer construction.

RESULTS

Calorimeter

Heat fluxes calculated by water calorimetry for five zones ranging from 0.8 to 1.3 m above the fire for times from 10 minutes to 25 minutes after ignition are shown in Figure 6. The heat fluxes shown represent the absorbed energy to the water and were calculated from the equation

$$q'' = \rho V A_{tube}(h_{out} - h_{in}) / A_{plate} \qquad (1)$$

where q" is the heat flux to the zone in kW/m^2, ρ is the inlet water density in kg/m^3, V is the inlet water velocity in a tube in m/s, A_{tube} is the cross section area of a tube in m^2, h_{out} is the outlet enthalpy in J/kg, h_{in} is the inlet enthalpy in J/kg, and A_{plate} is the surface area of the copper plate facing the flames. Water enthalpies were evaluated from a polynomial fit to steam tables data for subcooled water at 0.2 MPa, close to the actual pressures in the tubes.

Two trends are visible in the data shown in Figure 6. First, with the exception of a period near 20 minutes after ignition, the heat flux generally decreases with height above the pool, and, second, the heat flux levels decrease with time. The observed decrease of heat fluxes with time, when correlated with several other measurements, is thought to be related to a decrease in wind speed that was observed during the fire. Further discussion of wind speed during the test is presented later. The small channel-to-channel increases and decreases in heat flux at various heights indicated in Figure 6 are probably caused by flow variations between the coolant tubes, and are not considered to be significant.

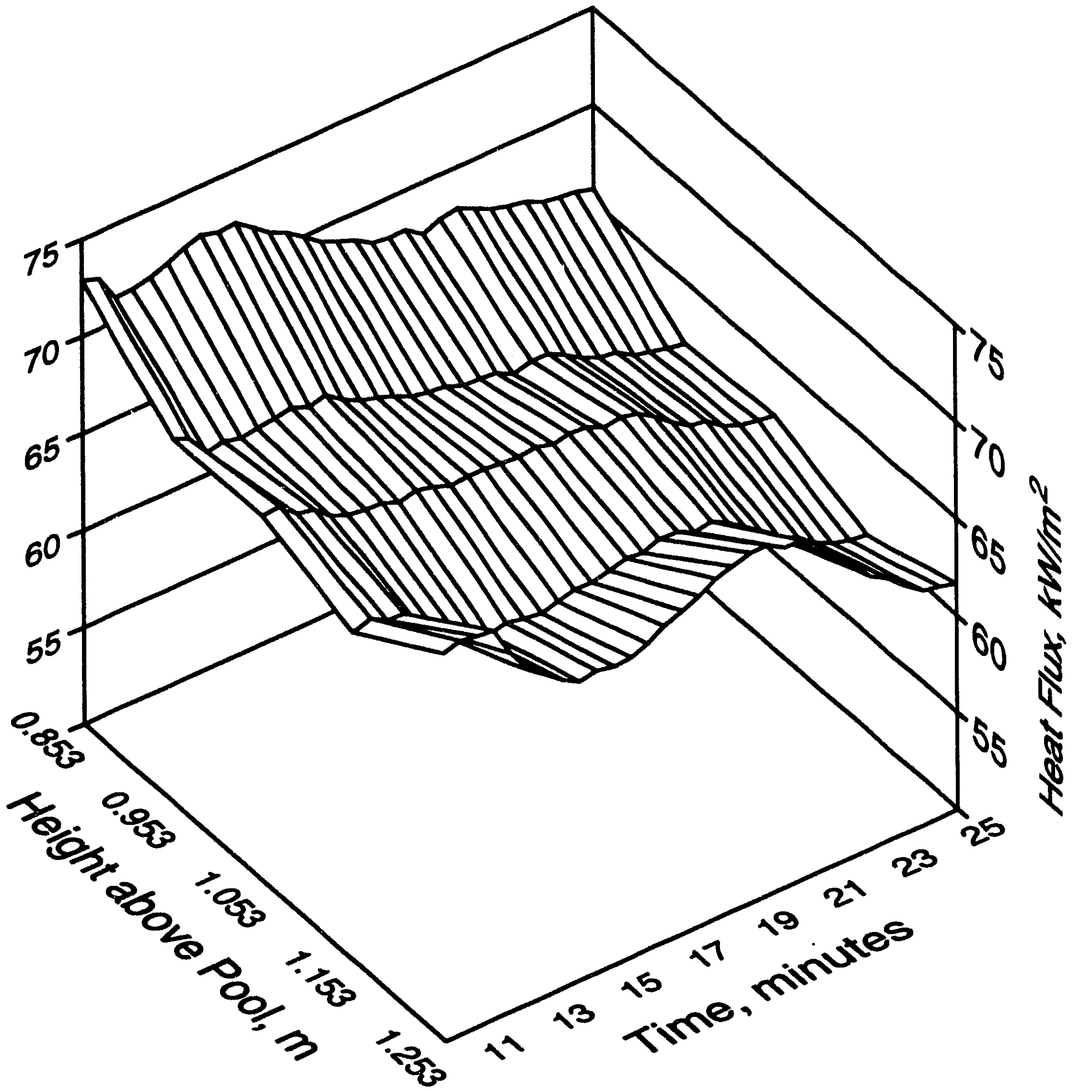

Figure 6. Heat flux to surface as a function of time and distance above pool surface.

The heat flux data shown represent only five of the ten channels available. The data from upper five channels representing heights of 1.3 to 1.8 m above the pool were discarded after examination revealed two problems. First, a flow blockage due to debris in the water caused abnormally high temperature rises in the zone just above the center of the calorimeter surface. Since this tube was manifolded with the four tubes above it, this cast doubt on the accuracy of all these data. Second, video observations showed that the upper half of the calorimeter, particularly the upper corner nearest the corner of the pool, was frequently not in contact with the flames during the fire. Data traces from the upper channels showed much wider variations of heat flux with time than the lower channels. In future tests, procedures to prevent blockages and to assure that the calorimeter is fully covered by flame will be used.

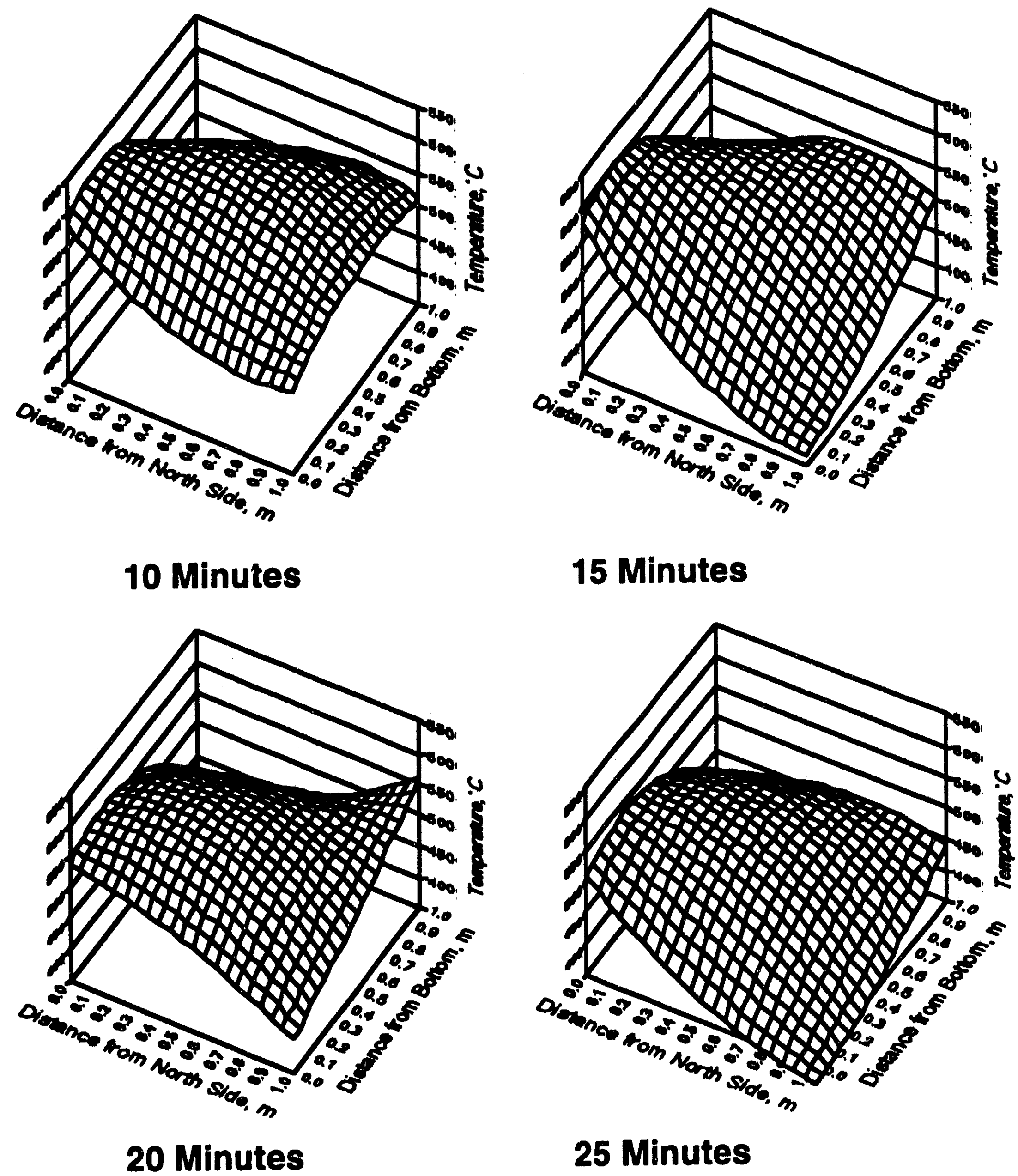

Figure 7. Surface temperatures estimated from intrinsic thermocouples at four different times.

As shown in Figure 7, calorimeter surface temperatures, as estimated from the intrinsic thermocouples, ranged from 350°C to 650°C. The temperatures, in a manner consistent with the heat flux record, showed a gradual decrease with time during the test. The central area of the calorimeter typically exhibited the highest temperatures with the upper left and lower right corners (as viewed from the front) exhibiting lower temperatures.

The plots in Figure 7 were prepared by fitting a polynomial expression in the least squares sense to the data from 17 of the intrinsic thermocouple locations shown in Figure 4. The polynomial expression used was

$$T_1 = b_{00} + b_{10}\,x + b_{20}\,x^2$$

$$T_2 = b_{01}\,y + b_{02}\,y^2 \qquad (2)$$

$$T_3 = b_{11}\,xy + b_{12}\,xy^2 + b_{21}\,x^2y + b_{22}\,x^2y^2$$

$$T = T_1 + T_2 + T_3$$

where T is the temperature estimate, the b_{nm} are the fit constants, and x and y are the horizontal and vertical distances from the lower left corner of the calorimeter as viewed from the front. With this technique, the maximum residual (i.e., the difference between fit value and measured value) was typically 70°C, with most residuals running in the 10 to 20°C range. The data from thermocouple T2 in Figure 4 was discarded because it consistently read about 100°C higher than surrounding thermocouples, indicating a high contact resistance between the stainless steel tile and the ceramic substrate.

Velocity Probe

The velocity history across the face of the calorimeter is shown in Figure 8 The flow velocity varies between 2 and 6 m/s. The flow direction varied in a sinusoidal fashion at angles ranging from 100 to 200°, where vertical upflow corresponds to 180°. This variation is probably due to changes in wind direction.

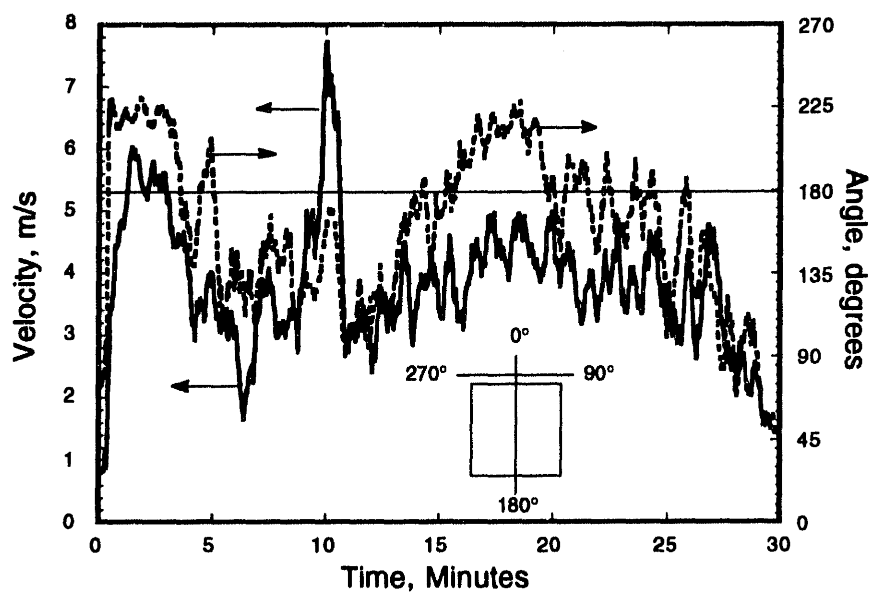

Figure 8. Velocity and flow angle from probes at top of calorimeter. Note that angle shows direction of source of flow, i.e., 180° represents vertical upward flow.

The velocity histories for the three towers are shown in Figure 9. These velocities agree in general with the velocity across the face of the calorimeter, especially for the East tower which is closest to the calorimeter.

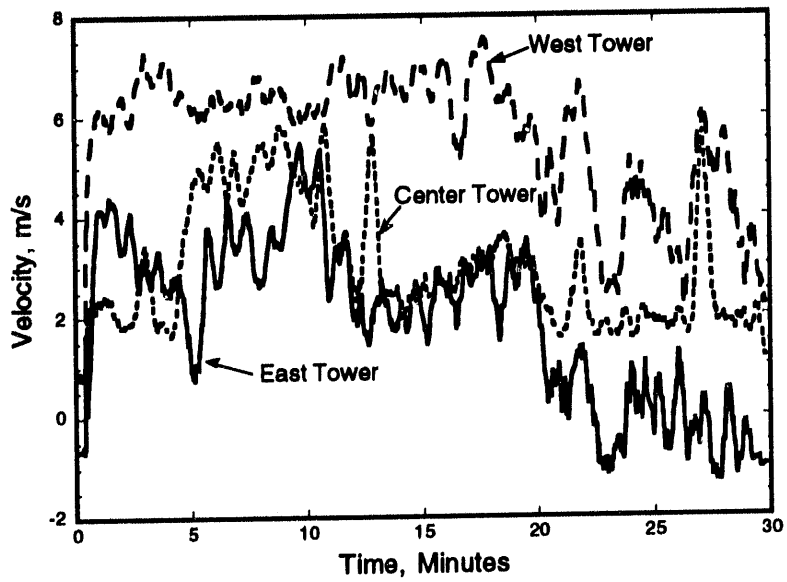

Figure 9. Velocities from bi-directional probes on towers in pool.

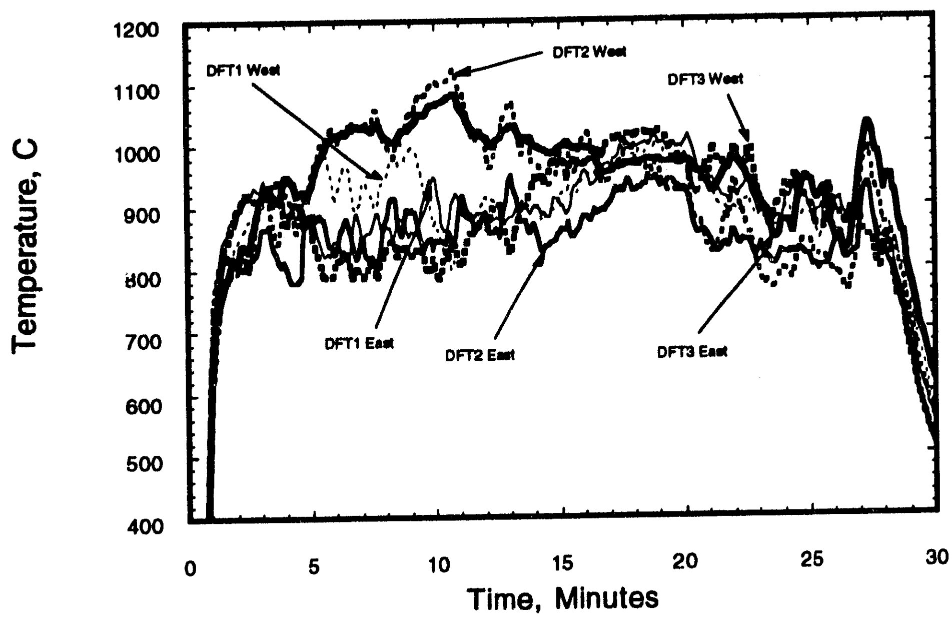

Figure 10. Temperatures measured by Directional Flame Thermometers.

Directional Flame Thermometers

Raw data from the DFTs are presented in Figure 10. The maximum temperature was 1122 °C and was recorded by the west face of DFT 2 at between 10 and 11 minutes into the test. The lowest temperature during the fire was 783 °C and was recorded by the west face of DFT 3, again at between 10 and 11 minutes.

DISCUSSION AND CONCLUSIONS

Use of the actively cooled calorimeter provides a different perspective on long term fire trends than an uncooled calorimeter based on transient analysis. As long as the actively cooled surface maintains a nearly constant temperature, trends can be observed without the necessity of first unraveling the interdependence between heat flux and surface temperature. In the first fire test of the calorimeter, several long term trends were observed, as well as some interesting transient responses.

The general trend toward a decrease in measured heat flux with increased height above the pool shown in Figure 6 is consistent with the gray gas model developed by Nicolette and Larson [4] for a constant temperature vertical flat plate. In that model, soot is modeled as a gray gas that participates in the radiant heat transfer between the core of the fire and a constant temperature plate. As soot laden gas moves up the front face of the vertical plate, the presence of the cold plate convectively and radiatively cools the soot. As the soot cools, it absorbs and emits radiation at a lower temperatures, and, as a result, heat flux to the wall decreases. While the initial testing is promising in confirming this effect, further tests with all ten water calorimetry channels in service and with the calorimeter at the center of a large pool will be necessary to ensure that the effect can be consistently measured. Further tests in a large indoor fire facility, SMERF [6], will also be performed to confirm the effect without the influence of wind. The calorimeter location and configuration will also be varied to explore the effects of other parameters. For example, the calorimeter will be installed at different heights above the pool to further explore heat flux variations. Different insulating tiles will be used to vary the calorimeter surface temperature during tests.

One trend observable in many diagnostics is a general decrease in fire intensity as the burn progressed. These decreases appear to be related to a decrease in wind velocity that led to less fuel mixing later in the test. Decreases in both heat flux and surface temperatures of the calorimeter are observed, as well as decreases in flame temperatures measured by the DFTs. This is the type of effect that could be difficult to confirm with uncooled calorimeters, but is easily discerned with active cooling.

Shortly after 10 minutes into the fire test, highly transient responses are visible on several diagnostic traces (see Figures 6,8,9,10). Heat flux and surface temperatures temporarily increased, as did flame temperatures measured by some DFTs. Flow velocities in the pool, as measured by the velocity probes at the East and center towers, dropped at the same time. Radiometer data not presented also indicate a significant drop in heat flux in this time frame. Inspection of the video record shows that flames appeared over the top of the calorimeter at this time in a region that was generally clear during the burn. No large changes in wind direction or velocity were observed during this period, so the cause of this behavior is uncertain.

Temperature distributions on the front face of the calorimeter also raise some questions. Both the upper left and lower right corners, as viewed from the front, exhibited lower temperatures than the rest of the face. This pattern was confirmed by differences in appearance of the stainless steel surface tiles observed after the test. The cooler corners appeared sooty and black, while the hotter regions appeared more reflective and metallic. The pattern in the tiles also indicated a general upward and to the right skew of the flow velocities across the face. The effect on the upper left corner can be explained by the fact that this portion of the calorimeter was in and out of the flame region during the test, but the cause of the effect at the lower right corner is more difficult to determine. One possible cause is a steel channel support that extended from the bottom of the calorimeter support table and sloped slightly outward toward the pool center. Although this support was centered on the calorimeter face, with measured velocities upward and across the face this support could shield the lower right corner of the calorimeter from the flames. Based on results from the first test, a support method for the calorimeter that does not include support legs that could potentially block gas flows across the front face will be used.

Further tests with the calorimeter will aim at producing an experimental data base that will be useful in constructing a simple large pool fire model for use in analyzing shipping containers for hazardous materials. The model should include major variables such as height above the pool, surface orientation, and surface temperature, and should be fast and simple enough to permit use as a subroutine to finite element thermal computer codes. The next step in our study will include comparison of the experimental data reported here to the existing gray gas analytical model [4].

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