Measurements in Large Pool Fires With an Actively Cooled Calorimeter*

J.A. Koski
Sandia National Laboratories

S.D. Wix
GRAM, Inc.

INTRODUCTION

The pool fire thermal test described in Safety Series 6 published by the International Atomic Energy Agency (IAEA) or Title 10, Code of Federal Regulations, Part 71 (10 CFR 71) in the United States is one of the most difficult tests that a container for larger "Type B" quantities of nuclear materials must pass. If retests of a container are required, costly redesign and project delays can result. Accurate measurements and modeling of the pool fire environment will ultimately lower container costs by ensuring that containers past the pool fire test on the first attempt.

Experiments indicate (see, for example, Gregory et al. 1989) that the object size or surface temperature of the container can play a role in determining local heat fluxes that are beyond the effects predicted from the simple radiative heat transfer laws. An analytical model described by Nicolette and Larson (1990) can be used to understand many of these effects. In this model a gray gas represents soot particles present in the flame structure. Close to the container surface, these soot particles are convectively and radiatively cooled and interact with incident energy from the surrounding fire. This cooler soot cloud effectively prevents some thermal radiation from reaching the container surface, reducing the surface heat flux below the value predicted by a transparent medium model. With some empirical constants, the model suggested by Nicolette and Larson can be used to more accurately simulate the pool fire environment. Properly formulated, the gray gas approach is also fast enough to be used with standard commercial computer codes to analyze shipping containers. To calibrate this type of model, accurate experimental measurements of radiative absorption coefficients, flame temperatures, and other parameters are necessary. A goal of the calorimeter measurements described here is to obtain such parameters so that a fast, useful design tool for large pool fires can be constructed.

The design of a 1 m x 1 m square actively cooled calorimeter intended for measurements in large pool fires was described at the 1992 PATRAM conference (Koski et al. 1992). Since that time, the calorimeter, together with other fire diagnostics, has been used to characterize surface heat transfer and other parameters in several large pool fires. Results from these experiments have been used to construct an initial computer model, and as additional data are analyzed, the model will be refined.

* This work was supported by the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

DESCRIPTION OF THE CALORIMETER

The calorimeter panel is composed of 20 0.1 m x 0.5 m copper plates with brazed copper cooling lines as shown in Figure 1. By varying the thickness of insulating tiles located between the copper plates and stainless steel surface tiles, the calorimeter surface temperatures can be changed on a test-to-test basis. Type K thermocouples and turbine type flow meters are used to measure the temperature rises and flow rates necessary for calorimetry. By dividing the water cooling into 10 zones, vertical spatial variation of the heat flux can be determined. The active calorimetry provides more uniform, quasi-steady-state boundary conditions than the more common approach with inertially cooled calorimeters, and leads to a different perspective on fires. The steadier boundary conditions also allow long-term fire trends and transients to be easily identified and isolated. For the initial tests in the series, the calorimeter face was located vertically as shown in Figure 1. In all tests the bottom edge of the calorimeter was located about 1 m above the pool surface.

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 surface that faces the fire. 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 through to the copper plates with Belleville type spring washers to preserve good thermal contact even when heating causes differences in thermal expansion between the tiles and the insulating substrate.

For the initial experiment, 6.4 mm thick Macor ceramic insulators were used. Analyses show (Koski et al. 1992) that the calorimeter with these tiles should reach steady state in 2 to 3 minutes. For later experiments, a 3.2 mm thick stainless steel feltmetal material, Technetics FR1109, was used as the insulator. The Macor tiles have a higher thermal resistance resulting in higher calorimeter surface temperatures than the feltmetal. Water

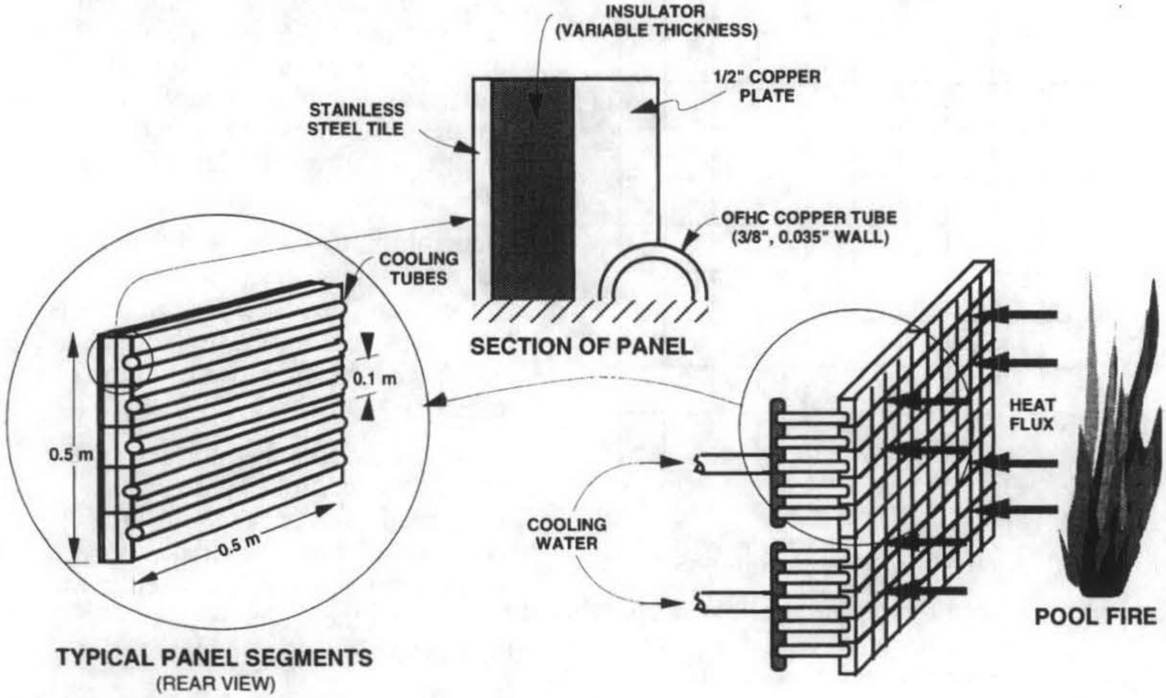

Figure 1. Sketch of actively cooled calorimeter.

flow is distributed into upper and lower banks of 5 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 10 tubes exiting the calorimeter has a separate thermocouple. Water flow is measured in the upper and lower tube banks of 5 tubes each with two turbine type flow meters. To create an even flow distribution among the 5 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 ensure that all copper tubes have the same shape and routing between the manifolds. Further details of the analysis leading to the design are provided in Koski et al. (1992).

FIRE INSTRUMENTATION AND DIAGNOSTICS

Other diagnostics used for fire characterization include intrinsic thermocouples, directional flame thermometers (DFTs), and velocity probes. The intrinsic thermocouples, made by attaching Type K thermocouple wires to the back of the stainless steel calorimeter surface tiles, allow calorimeter surface temperature distributions to be estimated via polynomial surface fits to the data. The specially designed and fabricated directional flame thermometers permit measurement of flame temperatures and estimation of local flame emissive powers. The specially designed velocity probes permit measurement of gas flow velocities in fires as well as flow directions across the calorimeter face.

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 2. 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 2) 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. Type K thermocouples monitor copper plate temperatures at the locations shown on Figure 2.

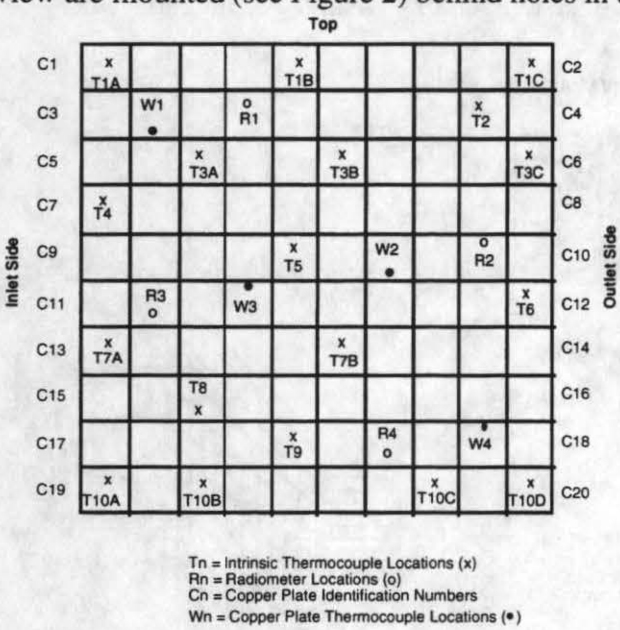

Figure 2. Location of diagnostics on front face of calorimeter. Small squares represent stainless steel tiles that face fire.

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.

Directional flame thermometers were included as part of the fire instrumentation package. A DFT consists of a thin plate that is insulated on the back side, and exposed to the fire on the other side. A type K 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 convective heat transfer is a small portion of the incident heat flux on the DFT surface, Burgess and Fry (1990) demonstrate that the temperature measured by the DFT approximates the black body temperature for the incident radiation, and hence the incident flux, on the DFT.

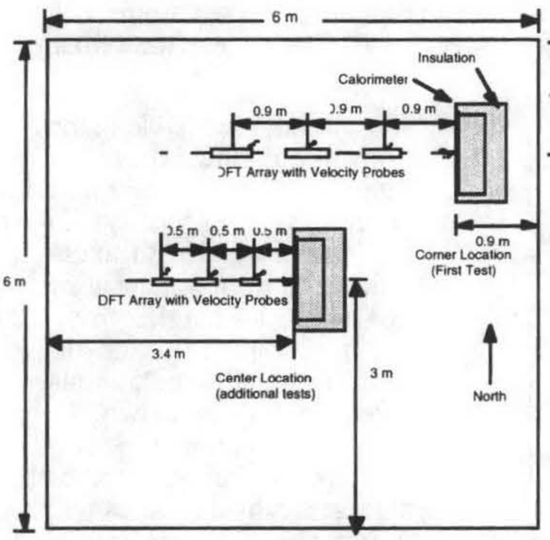

Figure 3. Locations of Calorimeter during tests.

The initial outdoor test configuration consisted of three DFTs in an east-west line located 1.4 m from the northern edge of the fire fuel pool as shown in Figure 3. The DFTs were spaced 0.9 m apart and were located 1.3 m above the fire fuel pool. For the later tests at the center of the pool, two horizontal rows of three DFTs each were used with sensors facing toward and away from the calorimeter face as shown in Figure 3. The rows of DFTs were located at one-third and two-thirds of the height of the calorimeter face.

In addition to the DFTs, 1.6 mm diameter, inconel sheath, ungrounded junction, type K thermocouples were supported in the flame region. For the outdoor tests, the thermocouples were located with tips facing upward in between the DFTs, at distances of 1.4 m and 2.3 m from the calorimeter front surface. The height above the pool for the thermocouples is the same as for the DFTs, 1.3 m. For the indoor tests two thermocouples were located between DFTs as shown in Figure 3.

Bi-directional velocity probes were used to measure velocities in the pool fires. For the tests, a bi-directional velocity probe was installed at each DFT location to measure the vertical gas flow component. To interpret the results from the vertical plate calorimeter, understanding of the flow velocity and direction across the face is useful. Two velocity probes oriented at different angles with respect to vertical were mounted above the center of the actively cooled surface. With proper data analysis, the crossed velocity probe arrangement yields both velocity and direction across the face of the calorimeter.

A 1.6 mm O.D., Inconel sheathed, ungrounded junction, type K thermocouples were used at each probe location to estimate the temperature of the gas. These temperatures were also used to calculate the density of the gas (assumed to be air) which in turn was used to calculate the gas 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.

FIRE TEST RESULTS

As shown in Figures 4, 5, and 6 measured heat fluxes ranged in the 60 to 100 kW/m^2 range depending on the test and the location in the pool. All tests were performed under conditions with low wind velocity, less than 3 m/s, to minimize fire-to-fire variations and simulate typical container test conditions. 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 in m^2 of the copper plate facing the flames. Water enthalpies were evaluated from a polynomial fit to steam table data for subcooled water at 0.2 MPa, close to the actual pressures in the tubes.

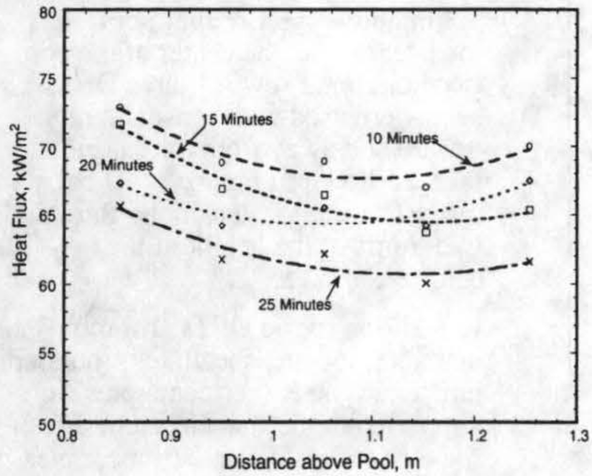

Figure 4. Heat flux vs. Distance above pool for test with calorimeter at corner of pool.

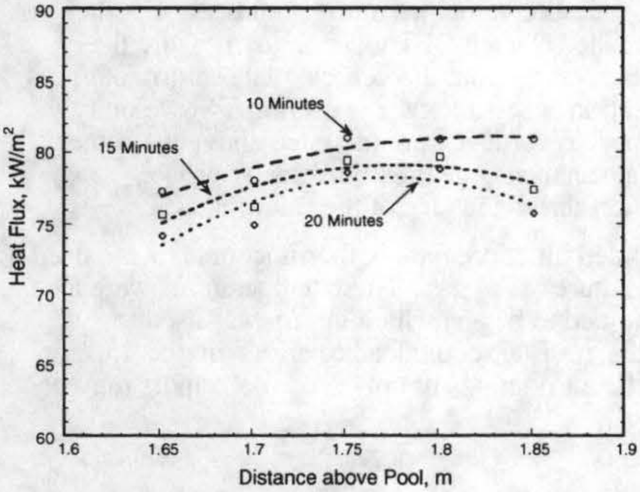

Figure 5. Heat flux vs. Distance above pool for first test with calorimeter at center of pool.

Two trends are visible in the data shown in Figure 4 for the calorimeter located near the corner of the pool. For this test JP4 jet fuel was used. Heat fluxes calculated from 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. 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. For this test calorimeter surface temperatures in the 500°C range were observed, which is somewhat higher than observed in later tests. The higher temperatures are attributed to the use of Macor insulators with higher thermal resistance under the surface tiles.

Figure 5 shows the heat fluxes for the first calorimeter fire tests conducted with the calorimeter located near the center of the pool. This fire exhibited several unusual features. First, an abnormally high burn rate for the combination of JP4 and JP8 fuel was observed. The 4.4 cm depth of fuel burned in about 20 minutes instead of the over 30 minutes times typical of this fuel depth. This indicates a larger power output than expected.

Second, the heat flux increases with height above the pool in conflict with other fire measurements. Reasons for these differences are not evident from the data. Calorimeter surface temperatures in the 300°C range were typical for this test series.

The results from the second test at the center of the pool are more consistent with the test in the corner of the pool. The heat fluxes decrease with height above the pool, and the burn duration exceeds 30 minutes. Two peaks of higher heat fluxes were observed during this test that are not shown in Figure 6. About 8 minutes into the test, heat fluxes peaked at 100 kW/m^2, and a second peak of 80 kW/m^2 occurred near the end of the test.

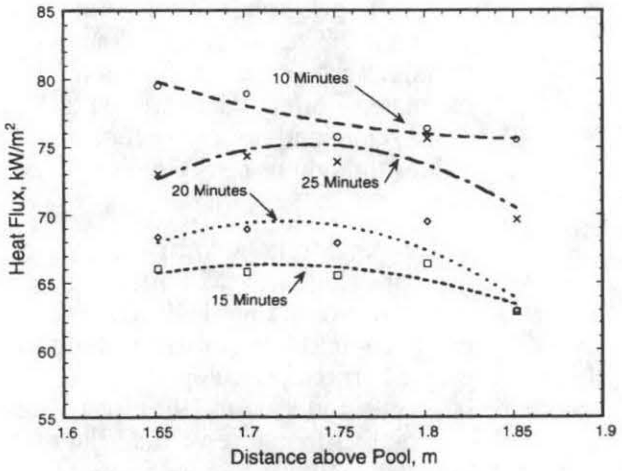

Figure 6. Heat flux vs. Distance above pool for second test with calorimeter at center of pool.

While the overall trends in heat flux shown by the fitted curves in Figure 4, 5, and 6 are considered significant, the small channel-to-channel scatter in heat flux at various heights is probably caused by minor flow variations between the coolant tubes that are not considered to be significant.

Many other results are obtained from the fire diagnostics installed in the pool and on the calorimeter. Figure 7 shows the flow velocities and direction across the calorimeter face for the test with the calorimeter located at the corner of the pool. Typical velocities in the 3 to 6 m/s were recorded.

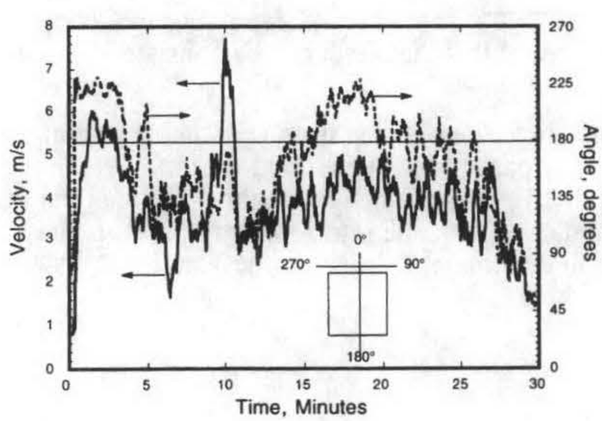

Figure 7. Velocity and flow angle in the plane parallel to the face of the calorimeter when located at the pool corner. Note that angle shows direction of source of flow, i.e., 180° represents vertical upward flow.

With the use of the DFTs and flame thermocouples, estimates of the radiative absorption coefficient can be made. For example, Figure 8 shows the flame temperatures and emissive powers determined from the DFTs and thermocouples located in the pool during the test at the corner of the pool. Typical values in the 1 to 3 m^{-1} range have been determined as shown in Table 1. More details of this and other diagnostic results are given in Koski et al. 1995.

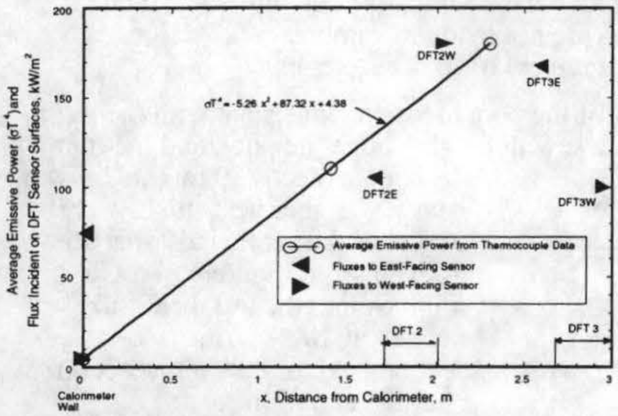

Figure 8. Emissive power estimated from thermocouples and Directional Flame Thermometers.

Table 1. Effective Absorption Coefficient Calculation

Zone	From Balance of Fluxes in Negative Direction	From Balance of Fluxes in Positive Direction	Average
0 <x< 1.85 m	0.7 m^{-1}	0.95 m^{-1}	0.83 m^{-1}
1.85 m <x< 2.38 m	3.1 m^{-1}	1.5 m^{-1}	2.3 m^{-1}

CONCLUSIONS

The actively cooled calorimeter approach has proven to be useful in observing heat transfer mechanisms in large fires. Large fire-to-fire variations in heat flux and other parameters have been observed, as well as large variations with time in a given fire. The effective radiative heat transfer absorption coefficients estimated from the data are in the 1 to 3 m^{-1} range and are consistent with values thought to be typical for large fires.

The general trend toward a decrease in measured heat flux with increased height above the pool shown in Figures 4 and 6 is consistent with the gray gas model developed by Nicolette and Larson 1990 for a constant temperature vertical flat plate. The test shown in Figure 5 exhibited an abnormally high burn rate when compared to the other fires, indicating significantly different fire conditions. While the initial testing is promising in confirming the gray gas modeling approach, further tests will be necessary to ensure that the effect can be consistently measured and quantified.

Additional tests with the calorimeter oriented at various angles from vertical have been conducted, and results will be reported in later papers. As mentioned, an initial version of a fire model called the Container Analysis Fire Environment is operational as a module that can be used with commercial thermal computer codes. The immediate goal is to include results from the experiments reported here in that model to improve the accuracy of container design computer codes.

REFERENCES

Burgess, M. H., and Fry, C. J., *Fire Testing for Package Approval*, Radioactive Material Transportation, Vol. 1, No. 1, pp. 7-16 (1990).

Gregory, J. J., Keltner, N. R. , and Mata, R., Jr., *Thermal Measurements in Large Pool Fires*, Journal of Heat Transfer, No. 111, pp. 446-454 (1989).

Koski, J. A., Keltner, N. R., and Nicolette, V. F. , *Design of an Actively Cooled Plate Calorimeter for the Investigation of Pool Fire Heat Fluxes*, in Proceedings of the 10th Symposium on the Packaging and Transportation of Radioactive Materials, Yokohama, Japan, September (1992).

Koski, J. A., Gill, W., Gritzo, L. A., Kent, L. A., and Wix, S. D., *Characterization of Indoor and Outdoor Pool Fires with Active Calorimetry*, American Society of Mechanical Engineers, HTD-Vol. 304, Book No. H00985 (1995).

Nicolette, V. F., and Larson, D. W., *The Influence of Large, Cold Objects on Engulfing Fire Environments*, in proceedings of AIAA/ASME Thermophysics and Heat Transfer Conference, Seattle, WA, June 18-20 (1990).