# Design of an Actively Cooled Plate Calorimeter for the Investigation of Pool Fire Heat Fluxes*

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## INTRODUCTION

For final qualification of shipping containers for transport of hazardous materials, thermal testing in accordance with regulations such as 10CFR71 must be completed. Such tests typically consist of 30 minute exposures with the container fully engulfed in flames from a large, open pool of JP4 jet engine fuel. Despite careful engineering analyses of the container, testing often reveals design problems that must be solved by modification and expensive retesting of the container. One source of this problem is the wide variation in surface heat flux to the container that occurs in pool fires. Average heat fluxes of 50 to 60 $kW/m^2$ are typical and close the values implied by the radiation model in 10CFR71, but peak fluxes up to 150 $kW/m^2$ are routinely observed in fires (Keltner, et al,

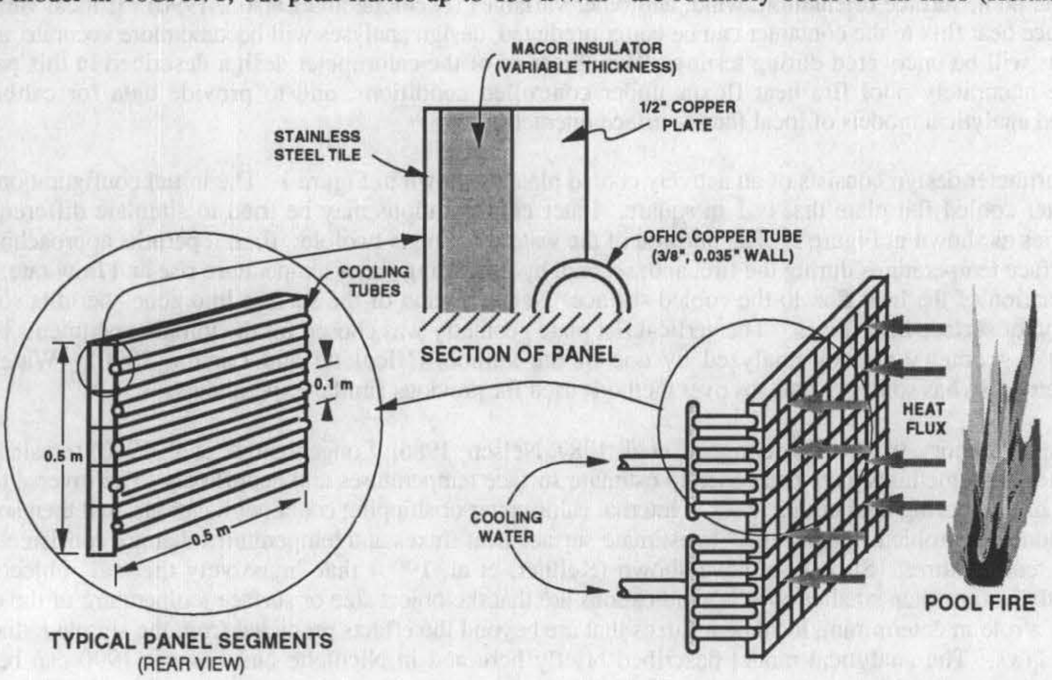


Figure 1. Sketch of actively cooled calorimeter experiment.

* This work supported by the U.S. Department of Energy under Contract No. DE-AC04-76DP00789.

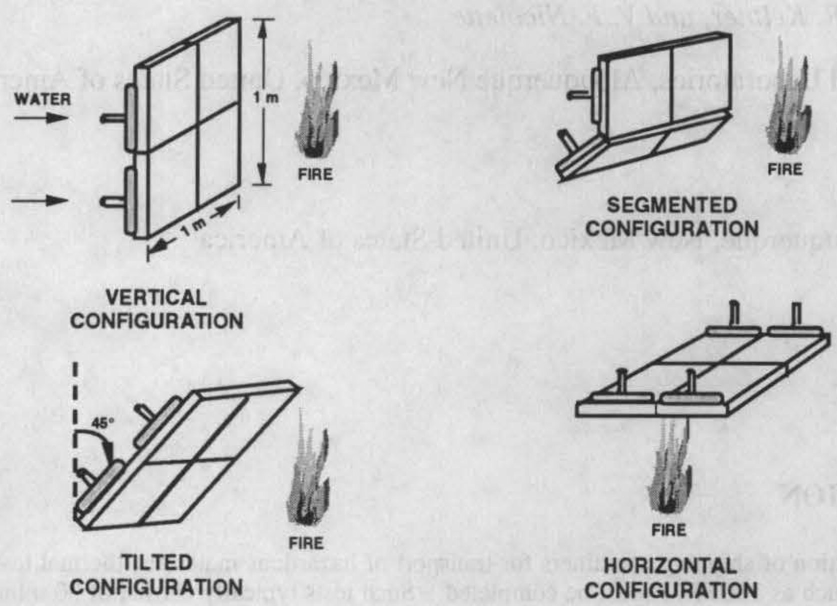


Figure 2. Future test configurations for actively cooled panels.

1990). Heat fluxes in pool fires have been shown to be a function of surface temperature of the container, height above the pool, surface orientation, wind, and other variables (Nicolette and Larson, 1990). If local variations in the surface heat flux to the container can be better predicted, design analyses will become more accurate, and fewer problems will be uncovered during testing. The objective of the calorimeter design described in this paper is to measure accurately pool fire heat fluxes under controlled conditions, and to provide data for calibration of improved analytical models of local flame-surface interactions.

The calorimeter design consists of an actively cooled plate as shown in Figure 1. The initial configuration consists of a water cooled flat plate that is 1 m square. Later configurations may be tried to simulate different surface geometries as shown in Figure 2. The purpose of the water cooling is twofold: first, it permits approaching steady state surface temperatures during the fire, and, second, by measuring water temperature rise and flow rate, it allows determination of the heat flux to the cooled surface. Segmentation of the surface into zones permits some local resolution of surface heat fluxes. The vertical flat plate geometry was chosen for the initial experiments because it matches a geometry already analyzed by one of the authors (Nicolette and Larson, 1990). Water cooled calorimetry also has some advantages over methods used for previous similar experiments.

In the past (Gregory, et al. 1989, Gregory, et al. 1987, Nelsen 1986, Longenbaugh, et al. 1990) transient inverse heat conduction methods have been used to estimate surface temperatures and heat fluxes. The inverse technique consists of monitoring temperature rises at internal calorimeter or shipping container locations, and then solving the heat conduction problem "backwards" to estimate surface heat fluxes and temperatures that are consistent with the internal temperatures. Such tests have shown (Keltner, et al. 1990) that "massively thermal" objects behave differently in fires than smaller objects. Indications are 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. The analytical model described briefly here and in Nicolette and Larson, 1990 can be used to understand many of 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 more careful 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 performing the initial tests in the Smoke Emissions Reduction Facility (SMERF), a wind shielded facility, a major source of test-to-test experimental variation will be removed. Later tests in open pools will be used to assess wind effects.

## DESIGN ANALYSES

To balance the various design choices for the calorimeter, finite element analyses were conducted with the Topaz2D computer code (Shapiro, 1986). Typical issues addressed were temperature uniformity of the actively cooled surface, time to reach steady state conditions, selection of appropriate materials, temperature rise of the coolant, and methods for controlling surface temperature. Where necessary, hand calculations of the hydraulics and convective film coefficient augmented the finite element analyses.

Initial calculations indicated that simply varying the flow velocity of the cooling water could not provide the desired plate surface temperature range of 200°C to 1000°C. This led to a design where water velocities are held constant, but installations of insulating tiles of various thicknesses permit temperature control as shown in Figure 1. Tile thicknesses of 3.2 mm, 6.4 mm and 11.7 mm permit the controlling surface temperatures as shown in Figure 3 where constant heat fluxes have been applied to the actively cooled surface. As indicated in the figure, the calorimeter surface temperature is a function of the surface heat flux, so that in practice, insulating tile thickness will be chosen based on previous experimental results. Transient calculations indicate that all configurations reach steady state surface temperatures in less than 10 minutes. To prevent heat flux to the rear surface of the calorimeter, the piping manifold and other components behind the actively cooled surface will be enclosed in a heavily insulated support frame and box. All instrumentation leads will be routed along cooling pipes and wrapped with commercial high temperature insulating material.

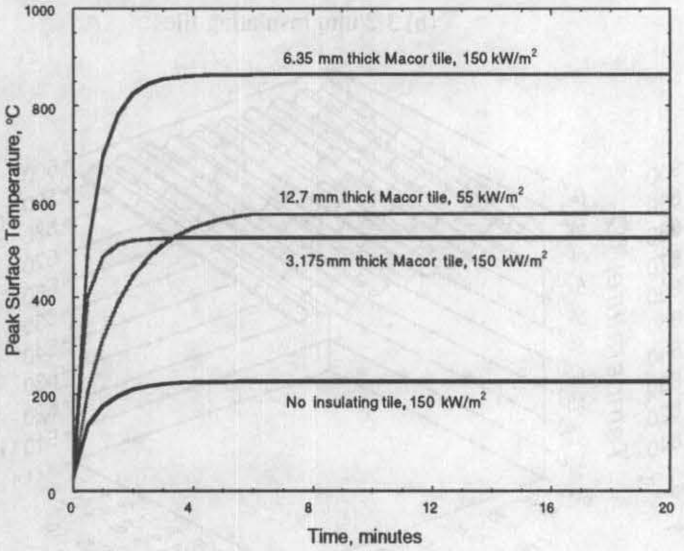


Figure 3. Time to reach steady state for constant heat flux to calorimeter surface

Early calculations showed that, because of relatively low ther nal conductivity, the use of stainless steel tubes and base plates would lead to variations in surface temperature of hundreds of degrees unless very close tube spacing and a thick plate was used. Since copper is widely available, easy to join to tubing by brazing, and has a high thermal conductivity, it solved this problem. With copper, even with a 10 cm tube spacing, surface temperatures could be held within 40 to 50°C across the entire plate as shown in Figure 4. This includes the effect of temperature rise in the cooling tubes as water flows across the plates. The calculations demonstrate that more uniform surface temperatures occur for the thicker insulating tiles and the low surface heat fluxes.

In early designs, the actively cooled 1 m x 1 m surface was broken into four equal quadrants, each with its own insulating tile and a 6 mm thick stainless steel cover plate as shown in Figure 2. Analysis of thermal stresses during heating of the stainless steel plates led to concerns about bowing of the center of these plates toward the fire when heated. This would create a significant gap between the stainless steel and the underlying ceramic. The solution to this problem was to break the stainless steel surface and underlying ceramic tiles into smaller 10 cm x 10 cm tiles, use thinner 1.8 mm thick stainless steel tiles, and to provide the attachment bolts near the center of the tiles to resist the bowing tendency. Infrared thermography of the tiles during radiant heat testing will be used to assure that no surface tile temperature variations occur due to thermal bowing. The underlying copper cooling plates were broken into 20 segments that are 0.5 m x 0.1 m as shown in Figure 1.

For the maximum anticipated heat flux of 150 kW/m$^2$, the water temperature rise through the tubes for a 2 m/s flow velocity is about 30°C. This difference can be accurately measured by thermocouples. If experimental heat fluxes prove to be lower, the water flow velocity can be reduced to achieve the desirable temperature rise necessary for good measurements.

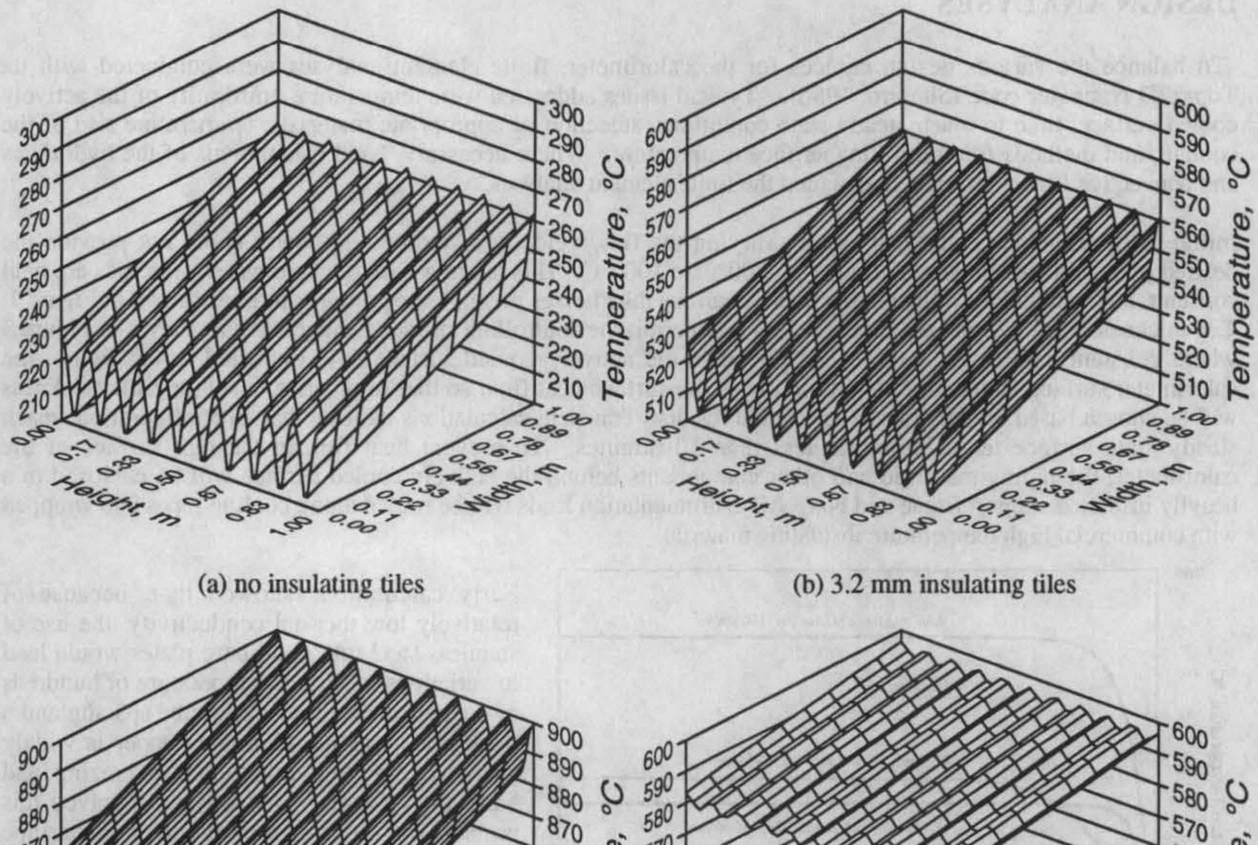


Figure 4. Calorimeter surface temperature distribution for constant heat flux to surface. Upward slope across width is due to heating of water. For (a), (b), and (c) a surface heat flux of 150 $kW/m^2$ is assumed. For (d) the surface heat flux is 55 $kW/m^2$.

## INSTRUMENTATION AND DIAGNOSTICS

The calorimeter diagnostic instrumentation includes intrinsic thermocouples, radiometers, turbine flow meters, thermocouple probes and washer thermocouples. Since the primary function of the calorimeter is water calorimetry, selection of the instrumentation used to measure the flow rate and temperatures of the water through the calorimeter is very important. The turbine flow meters have a linearity of +/- 0.5 per cent and a repeatability of +/- 0.1 per cent over the calibrated flow rate range. A filter is used with the flow meter to prevent damage. The flow meter is located on the inlet of the calorimeter and straight lengths of pipe have been included both upstream and downstream of the flow meter to ensure accurate flow measurement. For water temperature measurement, Type K thermocouple probes were selected. There is a single temperature probe in the inlet pipe to the calorimeter and a probe in the outlet pipe of each section of the calorimeter. Type K thermocouples were selected because of the accuracy, (+/- 1°C), operating temperature range, and output voltage. A small diameter probe is used to ensure adequate transient response.

Radiometers are used to measure the radiative heat flux of the pool fire. Since the calorimeter measures total heat flux (radiation and convection), data from the radiometers will allow determination of the convective heat flux contribution. Previous experiments (Nakos and Keltner, 1989) indicate that the convective contribution is on the order of 10 to 20 per cent of the total surface heat flux for the fires of interest. The radiometers are also calibrated as optical pyrometers. This will permit data to be acquired on the black-body flame temperature during the open pool fire tests. The radiometers are the Schmidt-Boelter type. The Schmidt-Boelter type was chosen to minimize error due to convective effects are seen with a Gardon type gauge. The body of the radiometer is water-cooled to prevent damage to the instrument. The gauge range is 200 $kW/m^2$, which is well above the expected maximum heat flux of 150 $kW/m^2$ from the pool fire. The radiometers will be located behind the calorimeter copper plate and can see the fire through small holes (approximately 12 mm) in the calorimeter. The radiometer field of view is 11 degrees, which allows the radiometer to see the pool fire without seeing the calorimeter. A nitrogen gas purge nozzle is located next to the radiometer to prevent soot from accumulating on the radiometer window.

Intrinsic thermocouples are used to measure the back surface temperature of the stainless steel plates. An intrinsic thermocouple consists of two thermocouple wires welded near each other to the stainless steel plate. Properly used, this technique produces a good estimate of the rear surface temperature of the plate. By knowing the back surface temperature of the stainless steel plate, the heat flux on the front surface of the plate, and the thermal conductivity of the plate, the front surface temperature can be estimated. This will provide data on localized cooling zones near the surface of the calorimeter. The surface temperature and heat flux measurements will also provide indirect data on the effect of soot particles on surface heat flux.

Type K washer thermocouples are used to monitor the back side of the copper plate temperature. This temperature measurement is used as a safety feature and a data check to determine that the copper plates remain cool at all times during the test.

## GRAY GAS MODEL

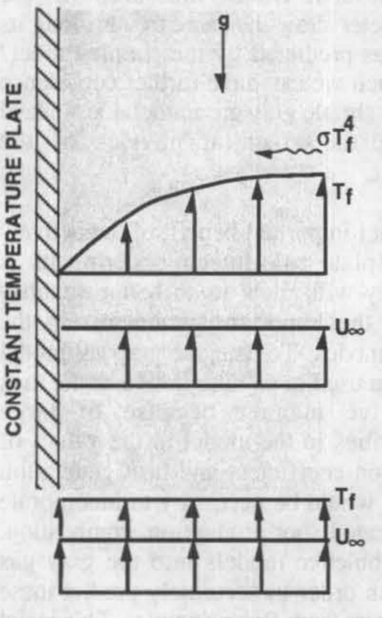


Figure 5. Model for study of effects of gray gas on radiation heat transfer.

Measurements made with the calorimeter can be used to calibrate analytical models of the geat flux to an object in a fire. There are many instances where it would be advantageous to have a simple analytical model to calculate heat fluxes to large objects in pool fires. For small objects in a fire, heat fluxes are reasonably approximated by assuming a simple $\sigma T^4$ radiative boundary condition. However, as discussed above, large objects can significantly influence the local fire environment, resulting in reduced heat fluxes to the large object. An analytical model that could model the interaction between a large object and a fire, and calculate an appropriate heat flux for such an object in a fire would be of great benefit to shipping container designers. The calculated thermal boundary conditions could then be used with a finite element model of a shipping container to predict its thermal response in a fire.

In order to capture this influence of a large object on the local fire environment, a model should have the following features: 1) It should focus on the radiative interaction between the large object and the fire (since 80-90 per cent of the heat transfer is radiative for the pool fires of interest to shipping cask designers); and, 2) It should account for the influence of object size and orientation on the fire.

Such a model has been developed previously (Nicolette and Larson, 1990), and will only be summarized here. The model consists of a vertical flat plate at constant uniform temperature completely engulfed by flames of large thickness (Figure 5). Combustion gases flow upward along the plate at a specified uniform velocity. Thermal radiation exchange between the surface of the plate and the combustion products is modeled assuming 1-D gray gas radiative heat transfer normal to the plate surface. The gray gas is assumed to have a constant, uniform absorption coefficient. For fires of this type, scattering can be neglected, and the extinction coefficient is well approximated by the absorption coefficient. The combustion source term can be modeled in a variety of ways, including: 1) a uniform heat generation rate, 2) an Arrhenius-based heat generation rate, or 3) zero heat generation (representative of large quenched regions near the object).

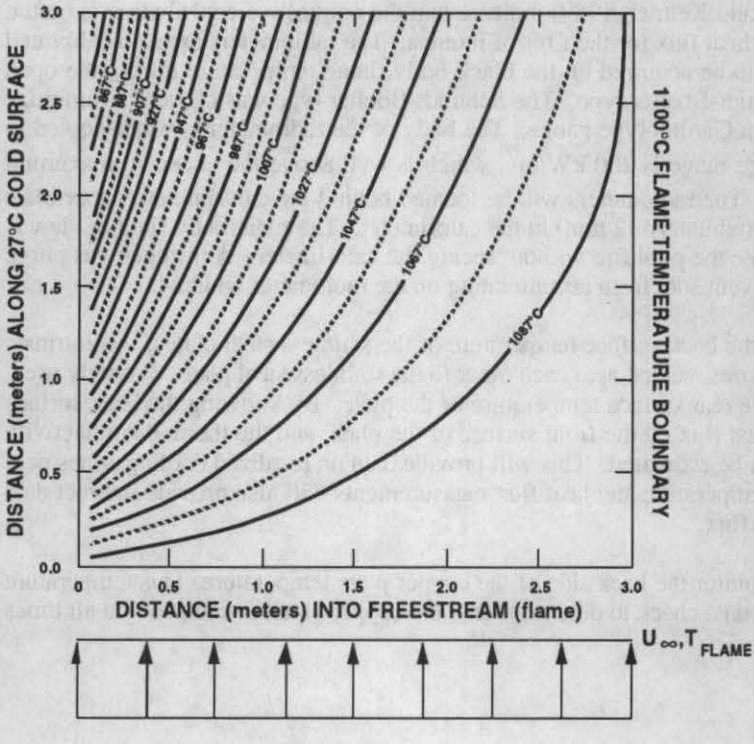


Figure 6. Typical isotherms calculated with gray gas model.

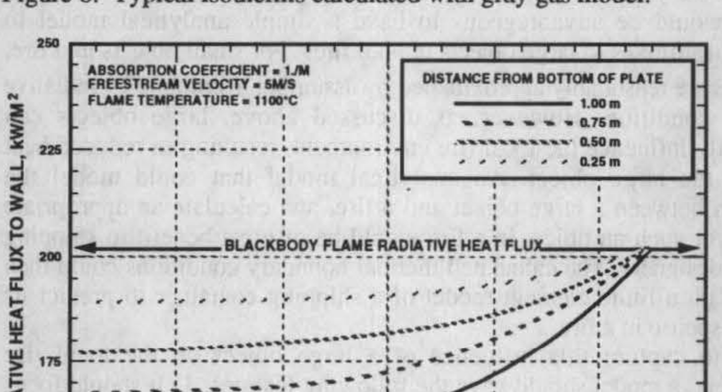


Figure 7. Incident heat fluxes to surface calculated with use of gray gas model.

This simple model predicts the development of a radiation boundary layer (Figure 6) as a result of the radiation/convection interaction between a large, cold plate and a fire. This boundary layer lowers the combustion gas temperatures near the plate, which results in a reduction in the incident radiative heat flux to the plate. Larger plates show a greater reduction in the incident radiative heat flux. For a 1 meter long plate, the reduction in incident radiative heat flux is calculated to be almost 25 per cent near the end of the plate for typical pool fire conditions (Figure 7).

With an actively cooled plate calorimeter, we can assess whether or not we are capturing the essential physics with our simple gray gas model. Since the gray gas model presently uses a constant and uniform plate temperature, the actively cooled plate calorimeter (with its relatively constant and uniform surface temperature) can provide an appropriate test for the analytical model. In particular, do the incident heat fluxes measured by the calorimeter show the same trends along its length as predicted by the simple model? If so, then we can have further confidence that our simple gray gas model does indeed capture the essential physics of the problem.

The other important benefit of the actively cooled plate calorimeter experiments is that they will allow us to better quantify two of the important parameters in the simple model. To date, the gray gas model has been used in an interpretive rather than predictive manner because of large sensitivities in the model to the values of extinction coefficient and heat generation rate. It would be necessary to incorporate complicated soot production, combustion, and turbulence models into the gray gas model in order to accurately predict these parameters from first principles. This is not desirable for such a simple model. Instead, data from the actively cooled calorimeter experiments will allow us to estimate the magnitude of these sensitive parameters that best enable the gray gas model to match the experimental heat fluxes. Our intent is that we will then be able to use the gray gas model to predict with confidence the heat fluxes to a large object in a pool fire.

## SMERF FACILITY

Initial tests with the calorimeter will be performed in the Smoke Emissions Reduction Facility (SMERF) at Sandia. This facility will permit elimination of wind as a variable during early tests. Wind produces the biggest, uncontrollable effect on open pool fires used to simulate postulated transportation accident environments. In developing wind shielded facilities, demonstration was necessary to prove that they closely simulate the environment in a large open pool fire. Demonstration tests in the Small Wind Shielded Facility (SWISH) have shown that it can reproduce the thermal environment of an open pool fire and comply with local air quality regulations (Keltner and Kent, 1989). The larger unit, SMERF, is based on a scale-up of SWISH. Certification tests of SMERF are underway.

SMERF has a 3 m x 3 m pool centered in the floor of a "cubical" test chamber that is approximately 6 m on a side. A sketch of the facility is shown in Figure 8. The walls of the chamber are water cooled to provide an appropriate boundary condition for radiative heat loss from the flames; this provides part of the control of the temperature in the flames. Air flow into the chamber is controlled by four variable speed fans.

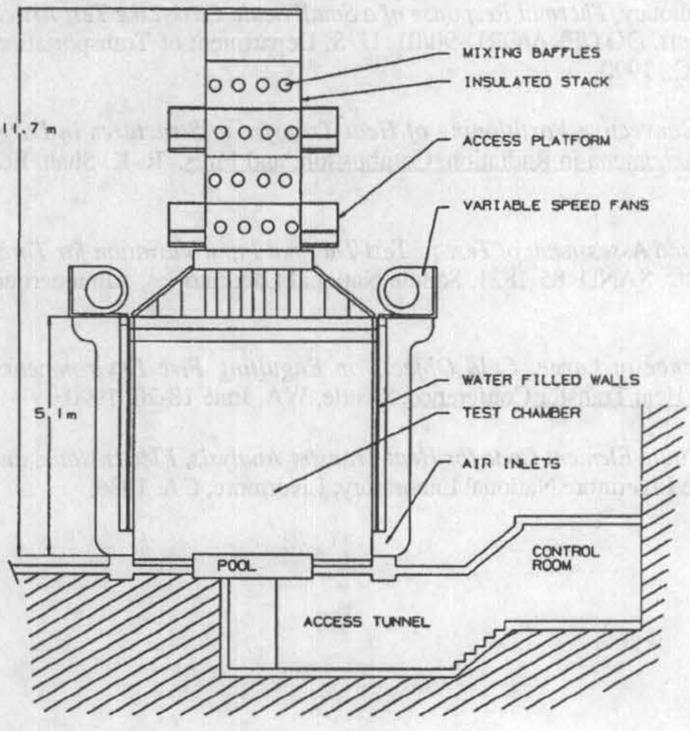


Figure 8. Smoke Emissions Reduction Facility (SMERF)

Control of the facility and data acquisition will be handled by a minicomputer based system with a total capacity of 140 channels of thermocouples and high level signals. Instrumentation or visual access to the test unit can be provided from a tunnel under the pool floor. There are observation ports in the walls of the facility to provide for viewing of the test unit, for real time or flash radiography, or for optical instrumentation.

A number of tests have been run using a 1.8 m circular pool in SWISH to define the thermal environment for comparison with extensive data from tests conducted at Sandia in a 9 m x 18 m open pool. The wind-shielded facility was shown to provide a stable environment for making detailed fire measurements. These tests were summarized for the 1989 PATRAM (Keltner and Kent, 1989).

The use of a wind-shielded facility, such as SMERF, offers significant advantages for studies of heat transfer in pool fires. The fuel recession rate is measured continuously. The current system uses hydrostatic pressure; an ultrasonic system is under development. The air flow rate is measured continuously and controlled. Measurements of these two parameters provide accurate inputs for fire models. By eliminating the wind effects, SMERF offers a fairly stable flame volume in which temperature, heat flux, velocity, and other parameters can be measured. This provides good data to compare with model predictions.

## SUMMARY

In order to better measure local heat fluxes in open pool fires, an actively cooled calorimeter has been designed and analyzed. As this paper is being prepared, the calorimeter is in fabrication. Following fabrication, testing in a radiant heat facility is planned to assure proper performance before introduction into the pool fire environment. Initially, testing in the SMERF facility will assure reproducibility of tests by removing wind effects. As the program progresses, tests in open facilities, and with different geometries are anticipated. Experimental data from the initial tests will be compared continuously to the gray gas model, and as experiments proceed, the gray gas analytical model will be refined with the goal of improving finite element code analysis of shipping containers.

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