InTech®

August, 1986

TRANSPIRATION RADIOMETER IN FIRE CHARACTERIZATION

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AN ISA REPRINT

Transpiration radiometers have been used to measure radiative heat fluxes in large, sooty pool fires. These gages have been designed to withstand severe environments and to keep the sensing area soot free. The radiometers are described and information concerning response, sensitivity and various operating parameters is presented.

KEYWORDS: transpiration radiometers; transpiration heat flux gages; heat flux gages; radiative heat flux.

Transpiration Radiometer in Fire Characterization

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Extensive tests have been conducted at Sandia National Laboratories to evaluate various ramifications of severe transportation accidents. One such aspect being fuel-fed fires for which a large fire test facility has been developed (Fig 1).

Characterization of large open pool fires is required to improve predictions of shipping container response to such fire, which are used to simulate severe transportation accidents. Parameters which are important in establishing fire definition include:

- Temperature
- Thermal transport in the fire
- Fire dimensions
- Velocities in the fire
- Chemistry

It should be noted that all of these parameters are interdependent.

In addition to the instrumentation of the test unit a large amount of diagnostic instrumentation is installed in the 9m × 18m pool fires used for these tests. The types of instrumentation and their uses are outlined in Table 1.

Measurements of temperature and heat flux are particularly important in trying to define the fire environment and the response of the test item. Temperature measurements provide part of the primary definition of the fire environment. Test item temperatures define the response of the item to the fire environment, and the potential material failures that occur due to temperature. Heat transfer affects both the development of the fire and the response of the test item to the fire. The heat flux levels indicate how severely an item will be stressed by the fire and the integrated flux helps to define the total thermal insult. It is important to note that the presence of the test item affects the heat transfer in a fire and that the heat transfer to the test item is affected by the design of the item.

TRANSPIRATION RADIOMETER

One aspect of thermal transport in fires concerns the partitioning between radiative and convective heat transfer. Measuring radiative heat flux inside a large sooty pool fire requires care-

TABLE 1. Instrumentation used in large pool fire tests.

Instrumentation	Uses
Thermocouples mounted on towers	- Fire temperatures up to 20 feet - Velocity estimate from cross correlation - Amplitude and frequency fluctuations
Calorimeters Large cylinder, thick wall Small cylinder, thin and thick wall Large plate, thin and thick wall	- Transient hot wall heat flux and surface temperature data from inverse heat conduction codes - Heat flux data for comparison to similar measurements in other fires - Velocity estimates from cross correlation of thin wall temperature measurements - Amplitude and frequency fluctuations
Bidirectional velocity probes	- Velocity measurements from a pitot-type device designed for low Reynolds number flows
Infrared imaging cameras (3-5 & 8-12 micron) Optical pyrometers Narrow angle radiometers	- Mapping temperatures of the lower part of the fire - Partial estimates of the radiated power
Pressure static head in the pool	- Transient fuel consumption rate
Plate calorimeter at fuel surface	- Total heat flux to fuel surface
Smoke generators Neutral density balloons	- Flow visualization and entrainment of the fire
Video records from four directions	- Velocity of large turbulent structures around the outside of the fire - Plume shape for comparison with plume models
Tethered balloon at ~ 400m	- Plume velocity - Plume gas composition - Soot characterization and production
Airplane at ~ 600m Wind velocity and direction	- Compliance with test specifications - Correlation with thermal measurements
Transpiration Radiometers	- Radiation flux measurements to fuel surface and test item within fire

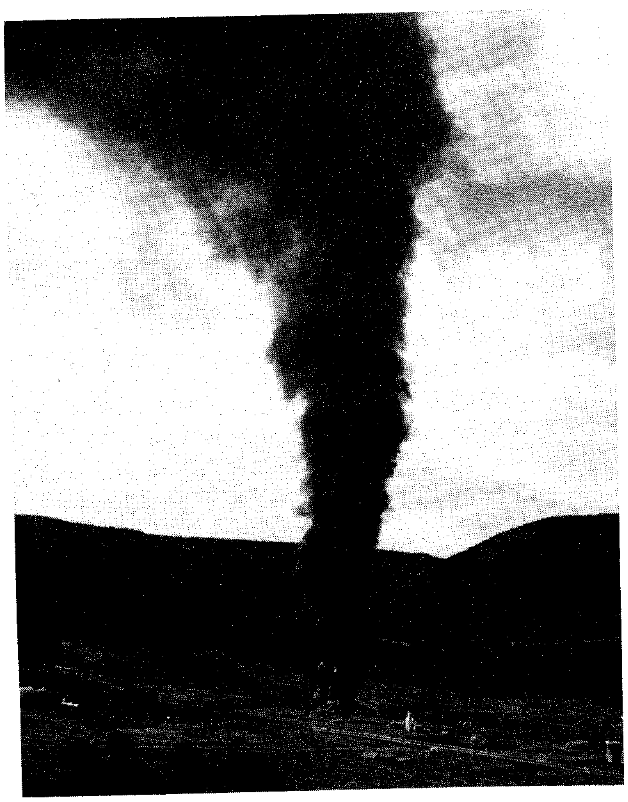

Figure 1A & 1B. Remote and close up photos of pool fire tests.

ful instrument design to minimize measurement errors and for sensor survival. In the pool fires conducted at Sandia National Laboratories, several techniques have been used to measure radiative flux. Inherent problems in designing an instrument that can be used in this environment include:

1. coating of the sensing area by soot
2. removing the convection component of the total heat flux
3. maintaining a 180 degree field of view
4. obtaining an accurate calibration that includes the spectrum of the fire
5. choosing a sensor surface that is repeatable, stable and sensitive to small changes in the fire environment
6. keeping the effect of the sensor on the fire environment to a minimum
7. surviving high temperatures present in the fire (1300 K)

One of the more successful designs used in pool fires has been a modification to the transpiration radiometer developed by Moffat, Hunn and Ayers (Ref 1). Figs 2, 3 and 4 show the radiometer as designed for the current application.

Moffat's transpiration radiometer was initially designed to measure radiative fluxes in hot gas flow environments such as combustion chambers. The radiometers were mounted with the sensing surfaces flush to the chamber walls with the majority of the radiometer body protected from high temperatures within the chamber. This is certainly not the case with pool fires. The radiometer must be totally engulfed in the fire when taking measurements. In addition, the described soot coverage problem is much greater in a pool fire.

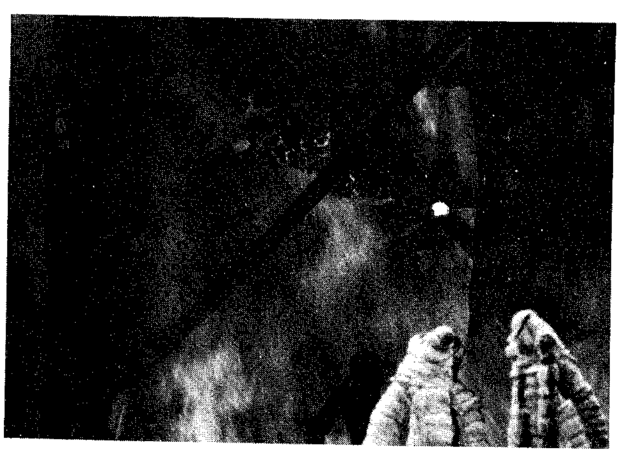

Figure 1C. Radiometers mounted in the fire environment

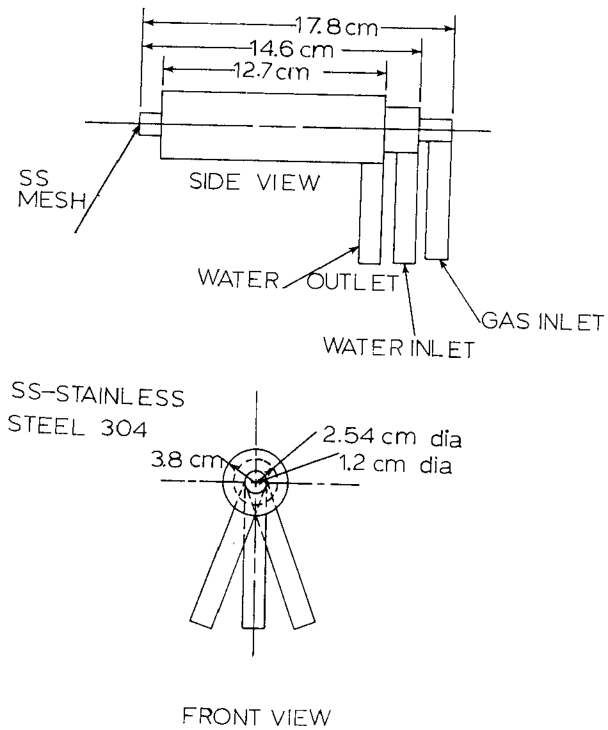

Figure 2. Basic radiometer structure sketch

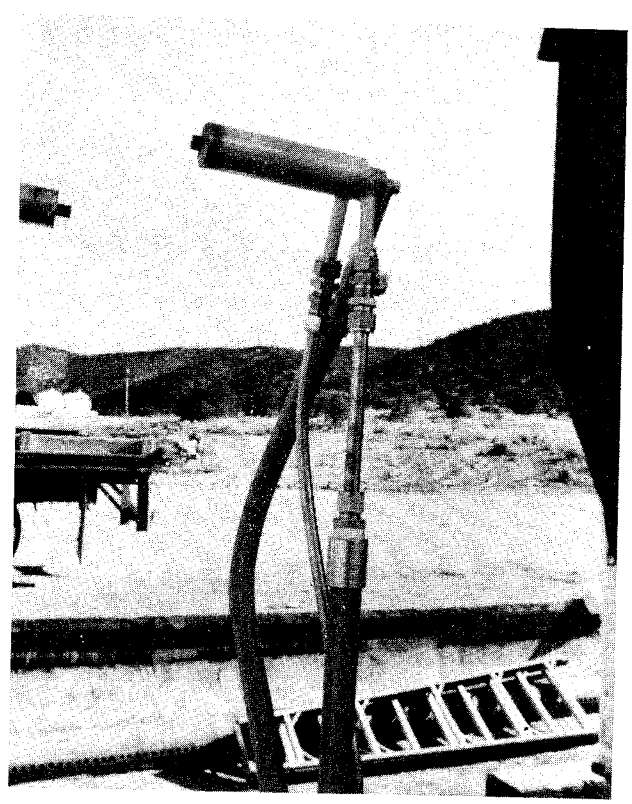

Figure 3. Assembled radiometer - uninsulated

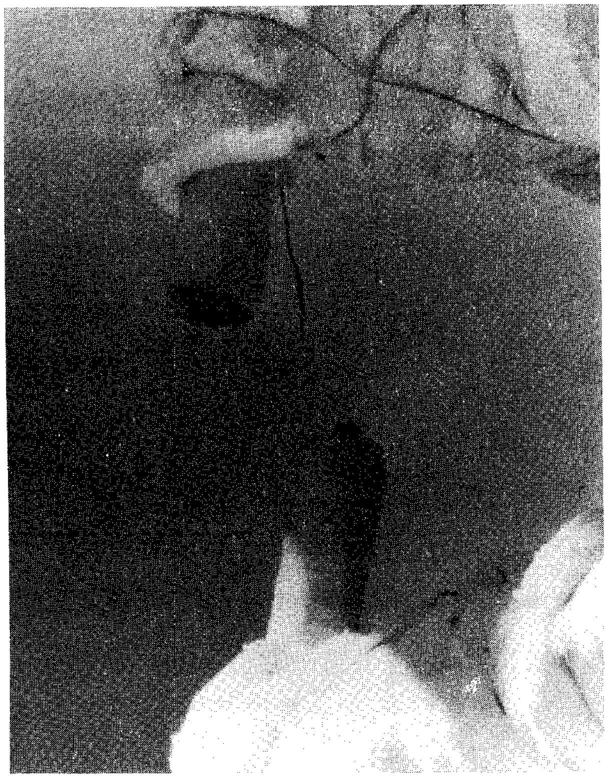

Figure 4. Insulated radiometers.

Moffat designed transpiration radiometers to blow off the boundary layer from the sensing surface. The effect was to eliminate the convection contribution to the measured heat flux. Blowing off the boundary layer was achieved by forcing a transpiration gas through the porous sensing surface. When used in the correct manner, the radiometer acts as a differential thermocouple measuring between the sensor temperature and the transpiration free stream temperature. This is different from a more conventional circular foil heat flux gage which measures the differential temperature between the center of the foil to the edge of the foil. To achieve the correct operation of the transpiration radiometer, Moffat described a blowing parameter which must be kept above a certain value,

$$BP = \left[\frac{m'' \ Cp \ R^2}{4 \ k \ \Delta} \right]^{1/2}$$

where Cp = specific heat of the gas
k = thermal conductivity
m″ = mass flux flow rate
R = sensor disk radius
Δ = sensor disk thickness

Moffat suggests keeping BP above 3.0. Given the above information, the authors redesigned the radiometer, so that it could be used in the more severe environment of a large sooty pool fire. In addition, the radiometer was characterized completely.

Gage description and characterization

As shown in Fig 2 the radiometer is constructed of three concentric cylinders. The center cylinder channels transpiration gas (nitrogen) to the porous mesh. The mesh is 304 stainless steel with 85 μm wire and a thickness of 0.25 mm. Radiometer body temperatures are monitored during both use and calibration by a wall thermocouple mounted on the inner cylinder. The body temperature is maintained at a constant value by passing water through the annuli between the three cylinders.

Before the radiometers are calibrated or used in the pool fire they are insulated with an aluminasilica batting material. This helps to reduce the lateral heat gain as well as the effect of the radiometers on the local fire environment by the radiometers.

The stainless steel sensing surface is a mesh and must be darkened to increase the sensitivity to the incoming radiation. Several methods have been suggested for increasing the absorptivity (and hence, the sensitivity) of the mesh including chemical deposition, painting, oxidation and others. The current study used the oxidation approach. Oxidizing the mesh surface is relatively easy and the end product is a stable surface that has not had small openings clogged by paints or other coatings. The radiative properties of stainless steel are given in several sources including Touloukian and DeWitt (Ref 2).

Clearly the oxidized surface will have a greater absorptivity but the actual effect of oxidation on the radiometer needed to be quantified. Fig 5 shows how surface oxidation affects the output of the differential thermocouple. The mesh was oxidized by heating it to approximately 1000 K for a fixed period of time. No transpiration gas or cooling water was supplied to the radiometer during this process. Once the surface is oxidized it is assumed to be stable since its temperature never exceeds 500 K during calibration or use in the pool fire.

The heat flux incident on the radiometer during the testing represented by Fig 5 was 150 kW/m^2. As seen from the figure, the output from the radiometer more than doubled, clearly indicating an improvement over the original unoxidized mesh. Several radiometers have been tested using this procedure and the results are very similar to those shown in Fig 5. In

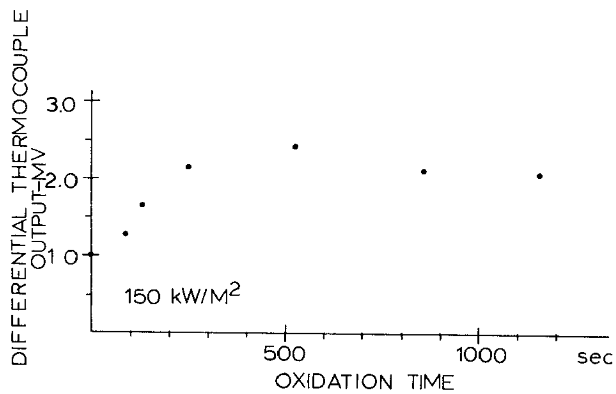

Figure 5. Change in radiation absorptivity with degree of stainless steel mesh oxidation

addition, once the radiometers are oxidized they have remained stable, showing no noticeable changes after being in use for several tests.

Moffat et al described reasons for having the blowing parameter, BP, greater than three. The primary reasons were to blow off the convection boundary layer and to reduce the effects of radial conduction in the mesh. An important part of characterizing the radiometers is to determine the sensitivity of the sensor output to transpiration gas flow. Obviously, as gas flow is reduced, sensor millivoltage output will increase. Fig 6 shows how the radiometers perform relative to gas flow and flux level. For BP equal to 3, the output is twice that for BP equal to 4.2. Clearly the radiometers are sensitive to the blowing parameter and care must be taken to insure that the same value is used during calibration as in a pool fire.

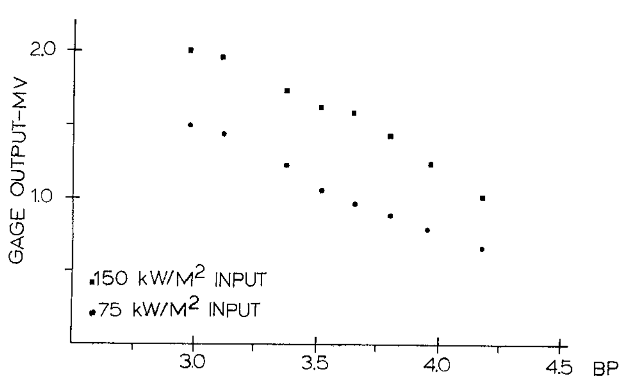

Figure 6. Effect of transpiration gas flow rate

Actual calibration of the radiometer was performed by Sandia National Laboratories at its Radiant Heat Facility. The radiant elements can be set to approximately the same temperature as the pool fire, thereby rendering a similar spectrum. Sooty pool fires are strong thermal emitters with band emission processes making only a small contribution to the total thermal output. Fig 7 is a sample calibration curve of one of the radiometers. The output of the differential thermocouple is essentially linear with input heat flux. From past experience with calibrating heat flux gages, the uncertainty band was given as ±5%. Of course, in a sooty pool fire the flame fluctuation and nonhomogeneous soot concentration add additional uncertainties to a measured heat flux.

In addition to the effects of oxidation and transpiration gas flow on the radiometer, the effects of sensor body temperature must be considered. A radiometer was tested at various body temperatures as measured by a thermocouple mounted on the inner wall of the inner stainless steel tube. As the temperature increased, the output from the sensor increased. Fig 8 shows the difference in sensor output versus temperature for a constant input heat flux of 150 kW/m^2.

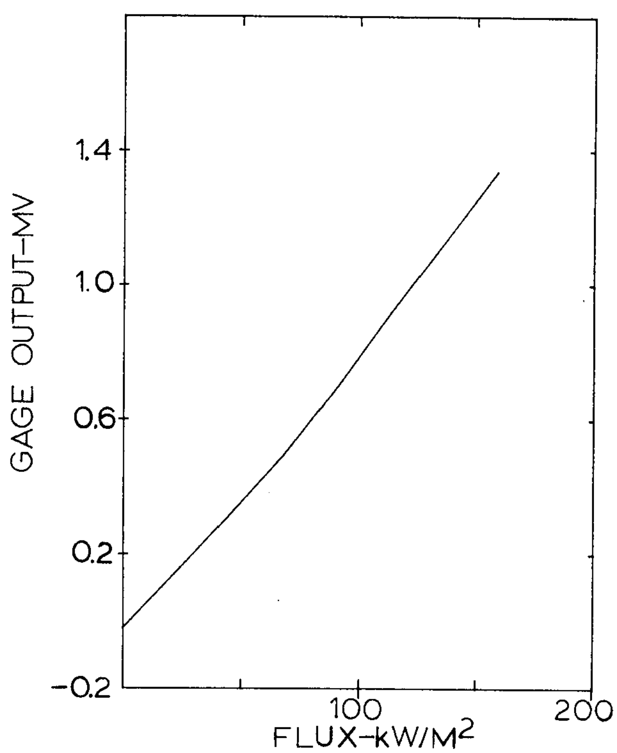

Figure 7. Radiometer calibration curve shows linear output with increasing heat flux rates

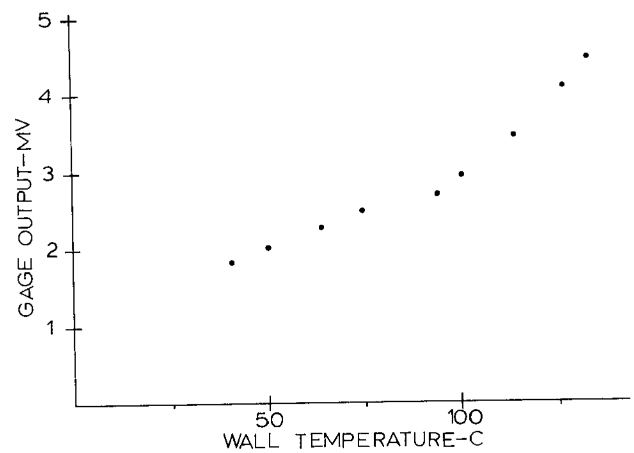

Figure 8. Radiometer sensitivity to wall temperature — controlled by a cooling water flow.

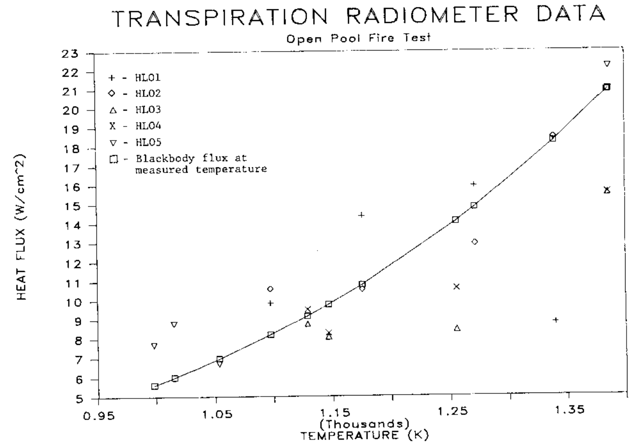

Figure 9. Measured fluxes compared with blackbody fluxes obtained from thermocouple temperature measurements.

Over a 40 K rise in body temperature the sensor output increased from 1.87 mV to 2.60 mV. Thus, the body should be cooled and held at a temperature similar to that which existed during calibration.

A new sensor geometry is currently being considered which couples five sensors together into a single unit not much bigger than the existing design. The sensors will be oriented in five different orthogonal directions.

An array of radiometers was used in the pool fire distributed from the edge to the center. Some of the radiometers were positioned looking towards the center of the fire and others were positioned looking in the opposite direction. Fig 9 shows results of one test where the measured fluxes are compared to the blackbody fluxes obtained from thermocouple temperature measurements. The HL01, HL02, HL03, HL04, and HL05 represent radiometer locations in the fire. More details can be found in Longenbaugh (Ref 3).

CONCLUSIONS

Measurements from the transpiration radiometers have been used to estimate radiative properties in a sooty pool fire. The results as stated by Longenbaugh (Ref 3) are:

1. the results obtained from the transpiration radiometer are repeatable and stable
2. the transpiration radiometer is a sturdy device that can be used in a fire environment
3. a transpiration flow rate of approximately 0.438×10^{-3} scms (standard cubic meters per second, which corresponds to a BP of 5.8) will eliminate the convection effects of a fire with an upward velocity of 4.57 mps (15 fps) or less
4. a 99% of full-scale response time to a step input of less than 2.0 was observed
5. soot build-up on the sensing surface was eliminated by the transpiration gas blowing through the mesh
6. the radiometer is inexpensive to build.

In addition, the transpiration radiometers should be considered as rugged, useful devices for measuring radiative flux in severe environment. The considerations needed for using this radiometer are very similar to those any other radiometer, namely:

1. maintain a constant body temperature
2. obtain an accurate calibration
3. obtain a stable and sensitive sensor surface
4. maintain a constant transpiration gas flow rate.

The added advantages of being rugged and having a 180 degree field of view make this radiometer a good choice for measuring heat flux in a fire.

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