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The Design and Application of Bi-Directional Velocity Probes for Measurements in Large Pool Fires

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The Design and Application of Bi-Directional Velocity Probes for Measurements in Large Pool Fires

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Sandia National Laboratories, Thermal Test and Analysis Division, performs large (9 by 18 meters), open pool-fire tests to simulate severe transportation accidents for evaluating shipping containers. In an effort to characterize the fire environment, a number of measurements were made in a 46-minute test that consumed approximately 48,500 liters of JP-4 fuel. The measurements included temperatures, heat fluxes, and velocities. This report addresses the fabrication and calibration of the velocity probes, their use in measurements of flame velocities in the large pool-fire test, and a comparison with a flame velocity correlation developed from measurements in smaller diffusion flames.

INTRODUCTION

The Thermal Test and Analysis Division of Sandia National Laboratories in Albuquerque, New Mexico conducts various fire tests in diverse facilities. These facilities may be wind shielded, where temperatures are controlled, or large pools where tests are performed under natural conditions. Fire tests are performed on a variety of test objects, including full-sized, spent fuel shipping containers in simulated severe transportation accidents.

One of these tests was performed in the large (9 by 18 meters) pool facility on a nuclear waste shipping container. Figure 1 is a photograph of the test in progress. In an effect to characterize the fire environment, a number of measurements were made.[1] These include temperatures, heat fluxes, and velocities. This report will address the velocity measurements made during the fire test.

There are several reasons for wanting to know the characteristic fire velocity. The primary importance of the velocity is that it controls the entrainment of air into the fire plume. The velocity also drives the convective heat transfer mechanism and determines the characteristic length scales for the chemical reactions within the fire plume.

VELOCITY PROBE SELECTION

Fire plume behavior in the open fire shown in Figure 1, has turbulence and fluctuations caused by both combustion processes and wind perturbations.[2, 3] A low-velocity pitot-type probe, which is somewhat insensitive to changes in direction, was selected to measure the velocity in the fire plume. The probe is described in the following: "The probe consists of a section of circular tube with a barrier midway between the end points, which divides the tube into two chambers. The upstream chamber senses the pressure closer to the stagnation pressure of the flow. The downstream chamber senses a pressure slightly below the static pressure of the flow. The pressure sensing lines are tapped into the chambers close to the barrier and led to the recording device."[2] The velocity is calculated from the measured pressure difference.

Figure 2 shows the design of the bidirectional probes. The probes were manufactured from AISI 304 stainless steel. Previous experience with this material showed rapid deterioration of the material leading to mechanical failure. A post test analysis showed the deterioration was due to oxidization.[4] In order to prevent this deterioration, the

Figure 1. 9 × 18 meter, JP-4 fuel, open pool fire

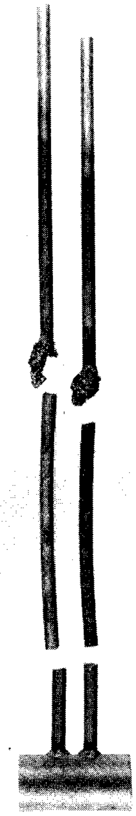

Figure 3a. Mechanically failed, uncoated probe

probes were coated with solgel/glass film[5] and the pressure sensing lines were water cooled. The cooling and pressure lines were insulated with several layers of blanket insulation. Figure 3 shows (a) a mechanically failed, uncoated probe from a previous test, (b) a used glass coated probe, and (c) an unused glass coated probe.

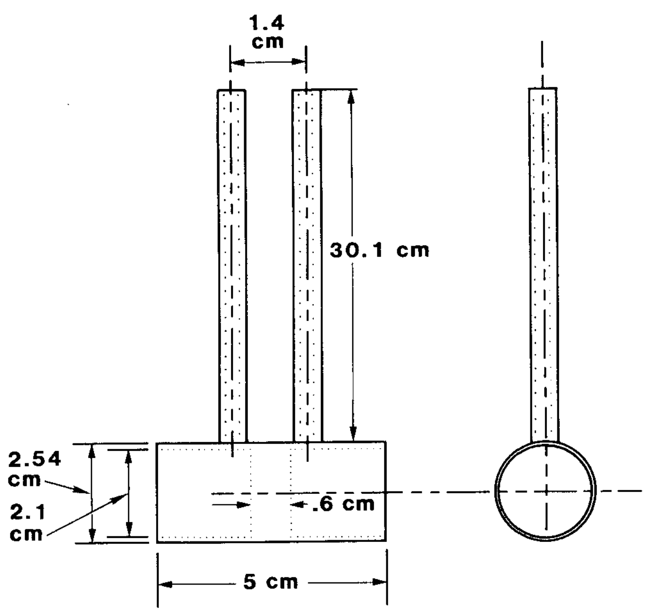

Figure 2. Bidirectional, low-velocity probe design

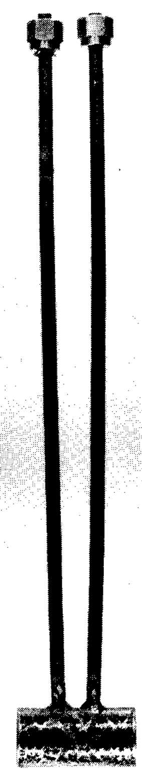

Figure 3b. Used glass coated probe

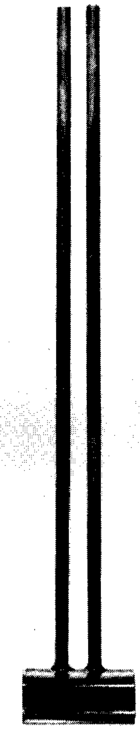

Figure 3c. Unused glass coated probe

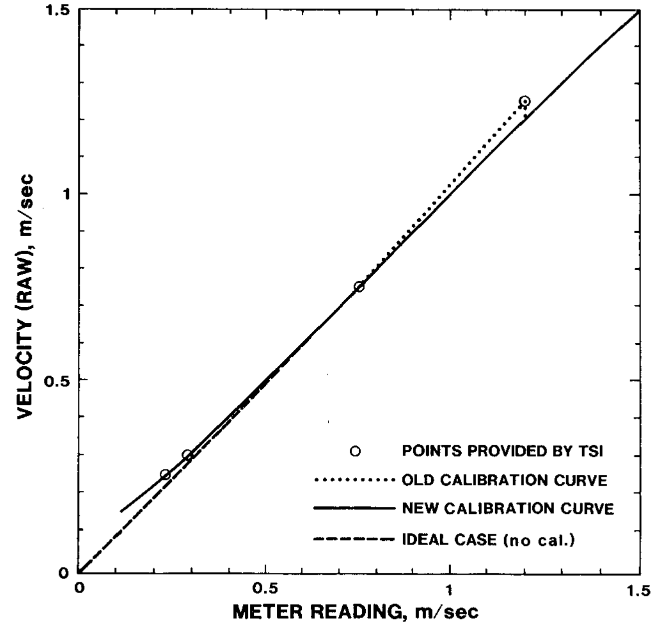

Figure 4. Calibration curve for the TSI anemometer

CALIBRATION OF VELOCITY PROBES

The bidirectional, low-velocity probes were calibrated[6] at low Reynolds numbers representative of those expected in the fire. The probes were calibrated in an existing subsonic wind tunnel at the University of New Mexico in Albuquerque. The following information is from the calibration report.[6] A probe mount was installed at the test section that allowed a probe to rotate so that the sensitivity of the probes to flow direction could be examined.

Calibration Instrumentation

(1) TSI anemometer, model 1650, used to measure the freestream velocity in the wind tunnel.
(2) MKS Baratron differential pressure transducer, type 90, used for pressure measurements.
(3) Keithley digital voltmeter, model 175, and a Nicolet digital oscilloscope, model 2090, used to monitor the DC output of the differential pressure transducer.
(4) Pitot-static tube, 16 mm outside diameter, used to check the performance of the TSI anemometer.

Calibration Measurements

The anemometer was not designed to measure low velocities. It was therefore necessary to calibrate it at velocities over the range of interest to agree with velocities measured by a standard pitot-static probe with a known calibration constant. Figure 4 shows the calibration points supplied by the manufacturer, the old calibration curve that was used initially, and the new calibration curve.

Each velocity probe was calibrated over the range of Reynolds numbers from 300 to 3900. The calibration constant, C(Re), versus the probe Reynolds number, Re_D, is shown in Figure 5. The uncertainties are indicated in the figure by the bars. The extrapolation of the calibration curve for air velocities below ~ 0.2 m/sec, Reynolds number below 400, is the single most important contributor to the uncertainty levels as shown in Figure 5.

Angular sensitivity was checked for two probes at a probe Reynolds number of 900. The results shown in

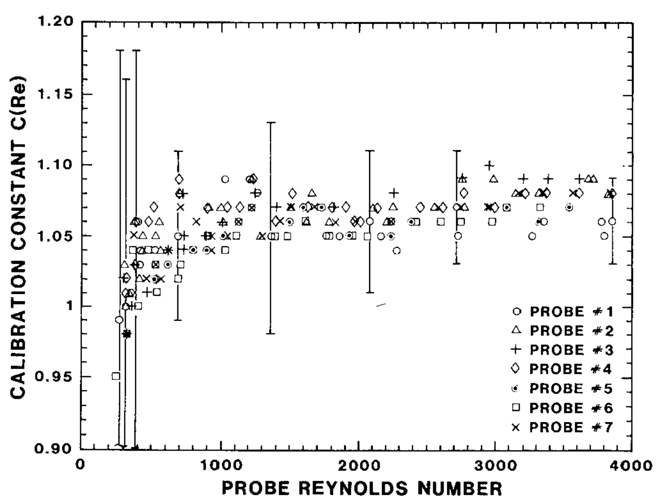

Figure 5. Calibration "CONSTANT" versus probe Reynolds number for all the probes data

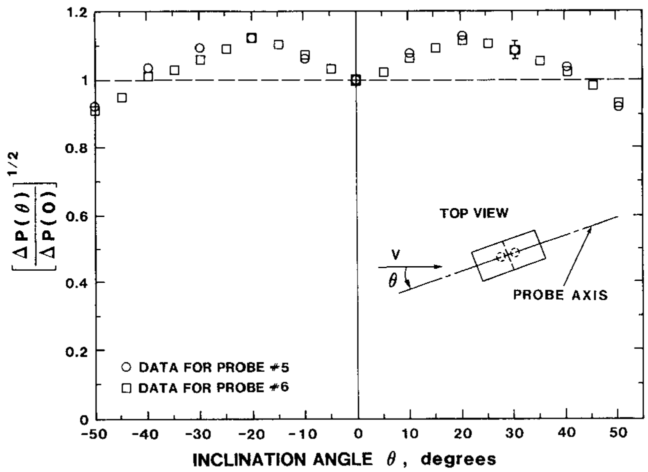

Figure 6. Angular sensitivity of the probes to the inclination angle for the probe Reynolds number of 900

Figure 6 agree within experimental uncertainty with earlier measurements at the National Bureau of Standards[2] and Factory Mutual Research.[3]

VELOCITY PROBE CALIBRATION UNCERTAINTY

Small fluctuations in the measured pressure differences at low velocities caused a large uncertainty in $C(Re_D)$ at small Reynolds numbers. For the probes, however, the uncertainty of the pressure difference measurements were smaller than for the pitot-tube measurements.

To estimate the uncertainty of the resulting calibration constant $C(Re_D)$, consider the following equation:

$$C(Re_D) = \left[\frac{\Delta P}{\frac{1}{2}\rho V^2}\right]^{1/2} \qquad (1)$$

The uncertainty in the results, $C(Re_D)$, caused by the uncertainties in measuring the independent variables (i.e., P, V, ρ) can be written as[7]

$$\delta C(Re) = C(Re)\left[\left(\frac{\delta V}{V}\right)^2 + \left(\frac{1}{2}\frac{\delta \Delta P}{\Delta P}\right)^2 + \left(\frac{1}{2}\frac{\delta\rho}{\rho}\right)^2\right]^{1/2} \qquad (2)$$

where δ(*) denotes the uncertainty of (*) quantity measurement.

$\delta\rho$ = The uncertainty value for density was estimated using the maximum error caused by readings and/or variations of the local temperature. The maximum uncertainty in density was calculated to be 0.01 kg/m^3 (about 1% of local typical density).

$\delta(\Delta P)$ = The larger of the observed fluctuation of the MKS Baratron differential pressure measurement or the smallest division on the MKS unit (i.e., 0.00001 mm of Hg).

δV = Velocity measurement uncertainty was based on calibration curve used to interpolate raw velocity measurements at low velocities and on the manufacturer's accuracy guarantee at higher velocities. The values listed in Table 1

VELOCITY (m/sec)	UNCERTAINTY (m/sec)
0 - 0.28	0.036
0.28 - 0.75	0.024
0.75 - 3.00	0.072 = 2% full scale reading (given by manufacturer)

Table 1. Uncertainty velocity measurements for TSI meter (corrected for non-standard conditions)

were used to estimate the uncertainties of the velocity measurements by the TSI velocity meter.

For velocity points corresponding to probe Reynolds numbers of approximately 600 or less, high uncertainties in the calibration constant exist, as seen in Figure 7. Probe Reynolds numbers for the shipping container test were calculated from measured temperature and velocity histories. The values ranged from 700 to 2000. Thus all probes were operating in the range of low uncertainty.

An average of $C(Re_D)$ for all data points above the probe Reynolds number of 600 is shown in Figure 5. The average value is 1.07 with a standard deviation of 0.015. This average value, which is in good agreement with the value of C=1.08 given in reference 1, was used as the calibration "constant" in calculating the velocities for the large pool-fire test. Probes 4, 5, 6, and 7 were used to obtain data for the shipping container test.

TEST AND INSTRUMENTATION OVERVIEW

The velocity probes were mounted on a 6.1 meter high, water-cooled tower at locations: 2.2, 3.4, 4.8, and 6.1 meters above the pool floor as shown in Figure 8. The "east" tower was located near the center of the 9 by 18 meter pool as shown in Figure 9. A 1.6 mm outside diameter, inconel sheathed, type K, ungrounded junction thermocouple was placed at each probe location to mea-

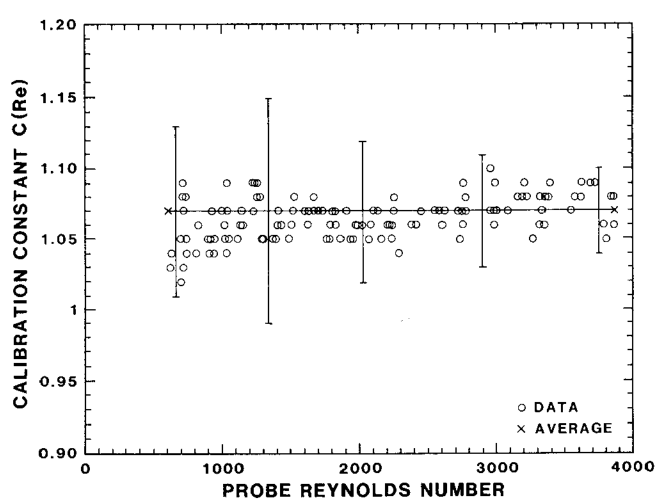

Figure 7. Calibration "CONSTANT" versus probe Reynolds number above 600

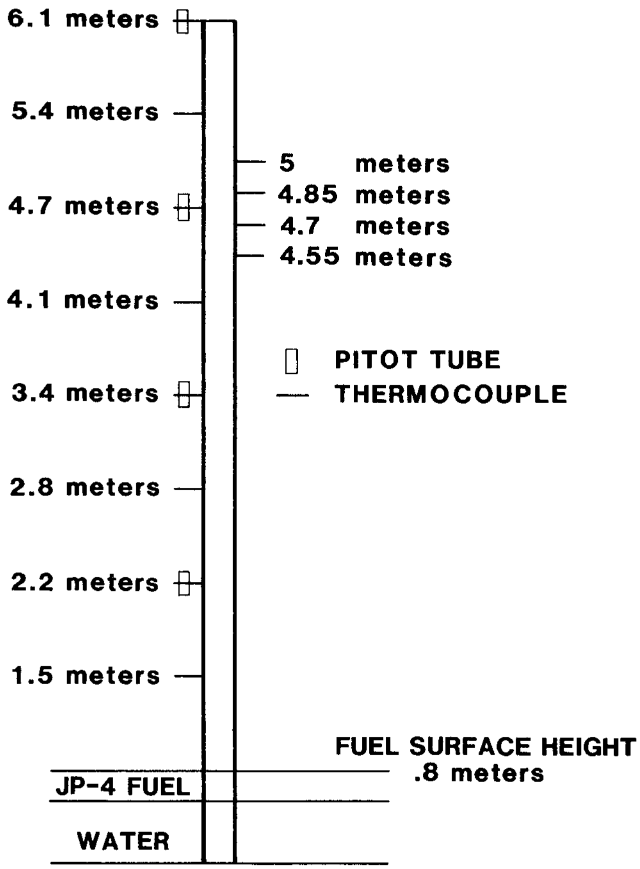

Figure 8. East tower instrumentation scheme

sure the temperature of the gas. These temperatures were used to calculate the density (ρ) of the gas that is used in the velocity equation.

$$V = \left[\frac{\Delta P}{\frac{1}{2} \rho C^2} \right]^{1/2} \tag{3}$$

The pressure differences (ΔP) in inches of water were detected by electronic manometers. Both the temperatures and pressure differences were recorded by an automatic data acquisition/control system.

The four velocity histories are shown in Figure 10. The large fluctuations in the velocities are primarily due to wind effects. The velocity depends upon the vertical temperature profile. The wind affects the vertical temperature profile thus changing the buoyancy of the fire and the velocity. The effects of the wind on the temperature history of the 6.1 meter thermocouple on the east tower are quite pronounced. The low temperature dips were found to correspond to times when the tower tip was visible, uncovered by flame, and times when wind measurements commonly indicated a strong component of wind blowing from the south.

To examine the wind effects on the temperatures and velocities, a conditioning signal was generated from the thermocouple temperature history located at the 6.1 meter station. The conditioning signal is at a high state when the temperature is above the average temperature, and a low state when the temperature is below the average. This

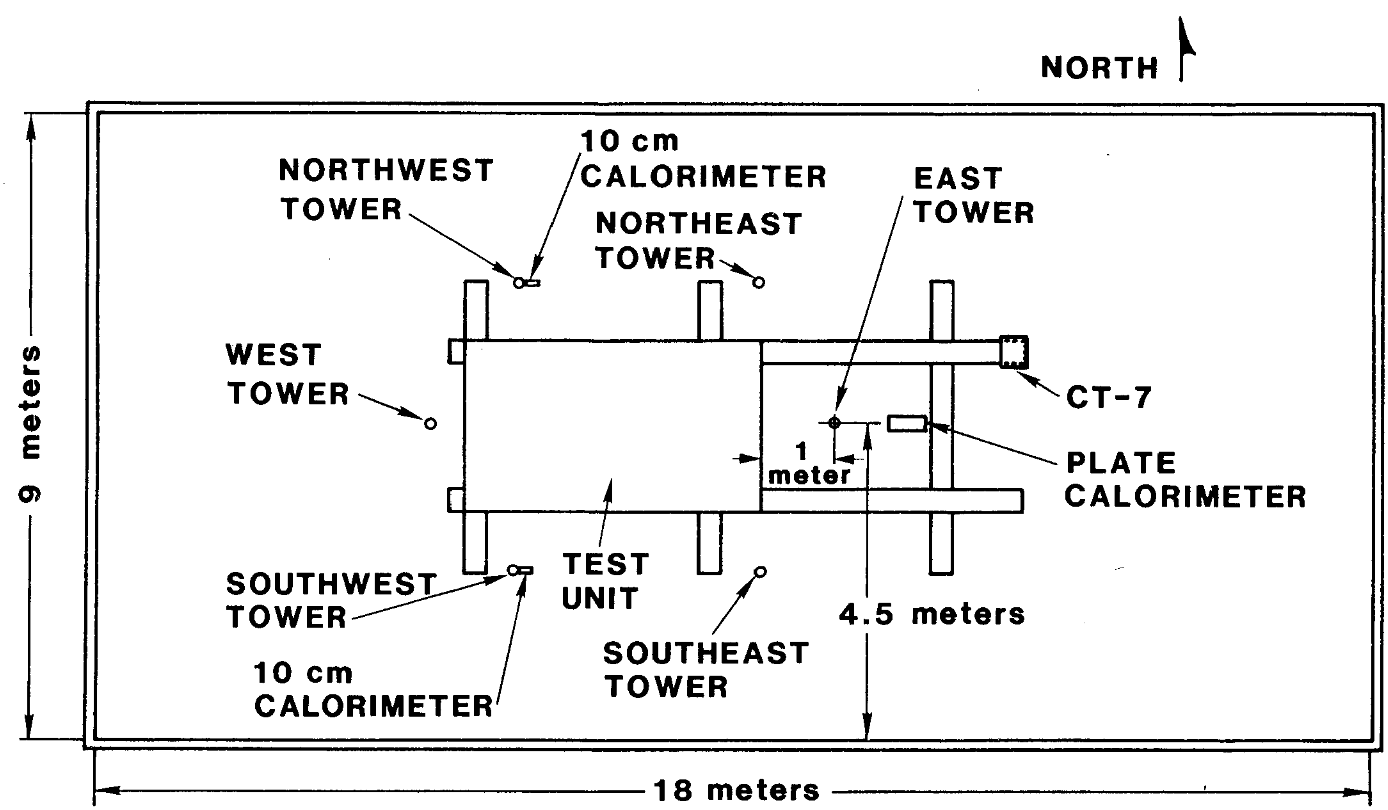

Figure 9. Open pool fire test facility

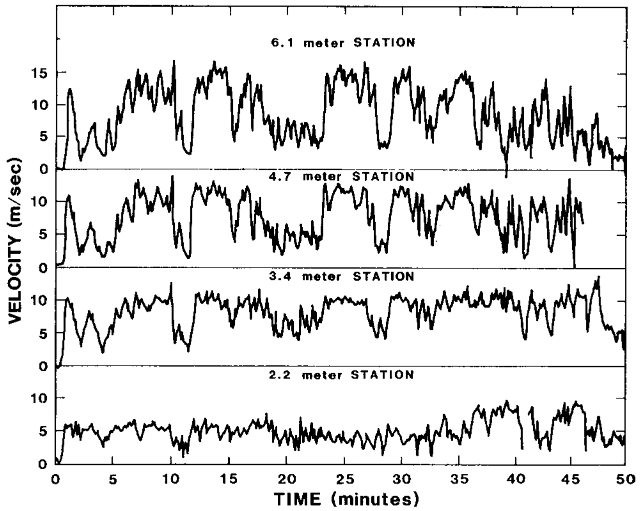

Figure 10. Velocity history at each station

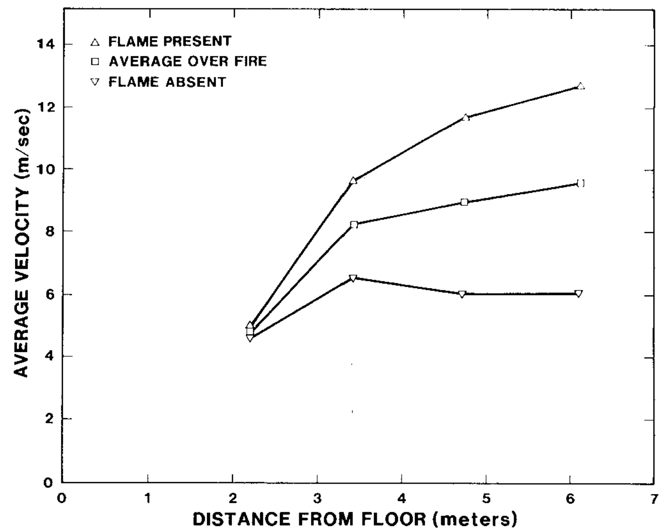

Figure 12. Average and conditional average velocities

corresponds to a signal representing the "presence" or "absence" of the flames. This correspondence is not exact; however, this is a simple starting place to help in examining the fire data with an attempt to account for the variability of wind effects. The temperature history and conditioning signal are shown in Figure 11. The velocity and temperature data were conditioned with this signal. The average and conditional average velocities are presented in Figure 12. The velocities during flame presence are significantly higher than those during flame absence. Table 2 summarizes the average temperatures and velocities from the east tower. The uncertainties in these measurements have also been included in the table. These uncertainty calculations will be discussed in detail in the upcoming section.

MEASUREMENT	HEIGHT FROM FLOOR (METERS)	AVERAGE	STD.DEV.	FLAME PRESENT	FLAME ABSENT
VELOCITY [m/sec]	6.1	9.5±.70	4.2	12.6±.88	6.0±.52
	4.7	8.9±.70	3.4	11.6±.82	6.0±.55
	3.4	8.2±.67	2.2	9.6±.73	6.5±.61
	2.2	4.8±.70	1.7	5.0±.70	4.6±.70
EAST TOWER TEMPERATURES [°C]	6.1	725±6.9	276	974±8.8	458±4.2
	4.7	810±7.6	281	1025±9.2	579±5.1
	3.4	891±8.2	231	1022±9.2	751±7.1
	2.2	949±8.6	133	949±8.6	949±8.6

Table 2. Summary of results

Figure 13 compares the average measured velocities during the "flame present" state with the mean centerline velocity data of McCaffrey for a number of much smaller fires.[8] The vertical distance, z, has been scaled in a way

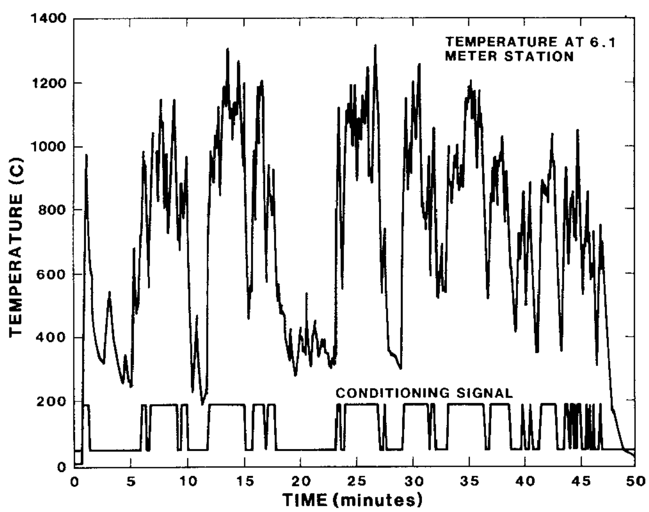

Figure 11. Temperature history at the 6.1 meter station and conditional signal

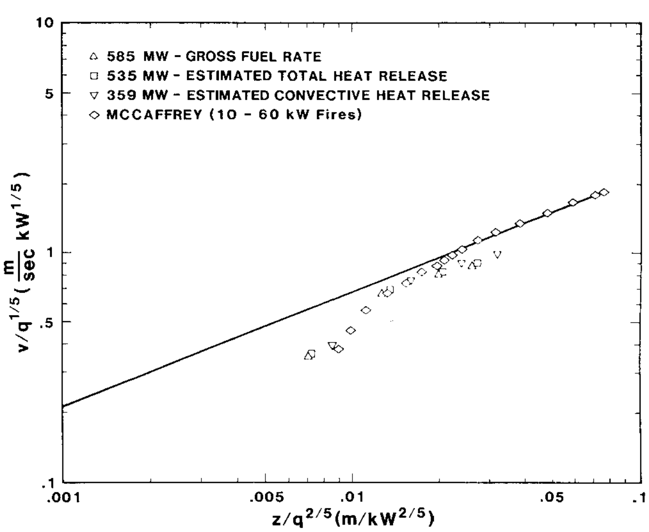

Figure 13. Comparison of measured velocities with other published results

that normalizes the flame height with the thermal power of the fire. McCaffrey defines three zones in the fire: flame, intermittent flame, and plume. The point $z/Q^{2/5} = 0.08$ is the end of the continuous flame region, $z/Q^{2/5} = 0.20$ is the end of the intermittent flame region. The vertical velocity should vary as

$$\frac{V}{Q^{1/5}} = 6.83 \left(\frac{z}{Q^{2/5}} \right)^{1/2} \qquad (4)$$

in the continuous flame region. The value of Q used in these relations by McCaffrey was the estimated total heat release. In McCaffrey's work, the flames studied were nonluminous methane flames. In this case the theoretical maximum heat release (from gross fuel consumption), the estimated total heat release (considering combustion efficiency), and the convective heat release were very near the same values for a given flame. In the case of a sooty pool fire with a luminous flame, these values will differ considerably from each other. It is likely that only the convective heat release contributes to the buoyancy, and thus to vertical velocities. As a result of this uncertainty, in the most appropriate value for the heat release, velocities normalized for all three heat release rates are plotted in Figure 13.

VELOCITY MEASUREMENT UNCERTAINTY

Measurement uncertainties caused by component inaccuracies are small, not easily detected, and are often overlooked. Listed in Table 3 are the error sources associated with the velocity measurement. The largest source of uncertainty is the difference in thermoelectric properties of the thermocouple. The uncertainty shown conforms to the specifications for thermocouple accuracy given by the American National Standards Institute for Chromel-Alumel (Type K) thermocouples. An estimate of the uncertainty in the velocity results, caused by the uncertainties in measuring the independent variables (i.e., T, ρ) can be written as

$$\delta V = \left[\left(\frac{\delta V}{\delta T} \delta T \right)^2 + \left(\frac{\delta V}{\delta \rho} \delta \rho \right)^2 + \ldots \right]^{1/2} \qquad (5)$$

where δ(*) denotes the uncertainty of (*) quantity measurement.

The results of the uncertainty calculations for each station are shown in Table 2. The uncertainty values indicated in the table were calculated considering the uncertainties in measured temperatures, pressure, and in the pitot-tube calibration.

Three effects were not considered in the calculation of the uncertainty in the velocity measurements:

(1) The choice of the conditioning signal may affect the calculated conditional values of the velocity.

(2) In the calculation of velocity from pressure difference, the combustion products are assumed to have the same density as air at the known pressure and temperature.

DESCRIPTION	ERROR SOURCE	ERROR MAGNITUDE
• Thermocouple	Difference in thermoelectric properties of wire.	0°- 293°C ±2.2°C 293°-1288°C ±.75% of reading.
• Noise	Ground plane noise after input filter	5μV, peak to peak or 2.5μV→ ±.07°C
• Reference Junction	Software Compensation	±.10°C
• DVM	ADC card Manufacturer's specification	±.007%, FSD+5counts Resolution 1μV ±.31°C
• CPU Hardware and Software	Accuracy of temperature conversion program	10°- 288°C ± .33°C 288°- 704°C ± .17°C 704°-1066°C ± .89°C 1066°-1288°C ±1.56°C
• Electronic Manometer	Manufacturer's specifications	±1% FSD chosen 0-.5 in. wg ±.005 in. wg

Table 3. Sources of uncertainty in velocity measurement

(3) The measured temperatures were not corrected for radiation errors or transient effects.

The choice of the temperature used at a cut-point for the determination of the flame presence will have an effect on the calculated conditional values. The magnitude of this effect was examined by recalculating the conditional values using a different temperature as the transition between flame presence/absence. For a 40°C change in the transition temperature, an average change of 1.5% was seen in the calculated average flame present velocities. The errors due to this problem are expected to be less than 3%.

The assumption that combustion products behave as air is common and leads to very small errors in most cases. In this case, however, some question exists due to the probable presence of unburned hydrocarbons in the lower flame region. NASA/White Sands[9] experimenters have measured some chemical species present in the lower flame region of a 15.3 meter (50 foot) diameter JP-4 pool fire. Alger et al.,[10] have also measured chemical species in a 3.05 meter diameter JP-5 fire. These results show extreme variability in gas composition. The occurrence of unburned fuel vapor in concentrations as high as 20 to 40% near the pool surface have been measured.

From these results it is expected that the current measurements below the 6.1 meter station will be affected by the presence of some unburned hydrocarbons. The effect of these hydrocarbons on the gas density will depend on the extent to which the original fuel has been broken down into smaller hydrocarbon groups. This is an area where very little information is available, thus an estimate of these effects was not attempted. It can be noted, however, that velocity data taken by other researchers in this region of the flames is also not corrected for this effect, thus the comparisons made with previous studies are hopefully valid.

Temperatures measured near the flame boundary are expected to be biased by radiation effects. Well within the flames the thermocouples will not be affected by the radiation losses to the ambient. These effects should be noted since the density used in the calculation of velocities is based on the measured temperatures. Another consideration is that the thermocouples used have time constants ranging from 1 to 4 seconds, depending on the local gas velocities and temperatures. This is slow in comparison to the response of the pitot tubes. Calculations of bias errors resulting from either of these sources have not been performed.

SUMMARY

The bidirectional velocity probe has been proven to be an excellent instrument to measure velocities in the hostile environment of a large open pool fire. The probe is rugged, insensitive to angle of approaching flow (from 0-50 degrees), and requires a minimum of signal processing. The average value of the measured velocities during "flame present" condition ranged from 5.0 m/sec at 2.2 meters above the pool floor to 12.6 m/sec at 6.1 meters. These values compare favorably with previously published data from smaller fires.

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