# Fire Research Note No 1032

## GAS VELOCITY MEASUREMENT IN FIRES BY THE CROSS-CORRELATION OF RANDOM THERMAL FLUCTUATIONS

by

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SUMMARY

Thermal fluctuations are employed as natural tracers to determine gas flow velocities in fire gases channelled under a ceiling. Results obtained using this cross-correlation technique are in reasonable agreement with those obtained by more conventional methods where interpretation in the presence of turbulence is difficult.



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## INTRODUCTION

There are many examples in fire research where gas velocity determination in flame and smoke is desirable but, because the gas temperature is high (up to 1000°C) and the velocity low ($\sim$1 m/s) and turbulent, has not been possible other than by indirect (eg $CO_2$ concentration[1]) or limited techniques (streak camera or vane anemometer) or by employing a method at the extreme limit of its sensitivity (pitot tube).

All these techniques, except the visual methods, have the fundamental disadvantage that interpretation is difficult where turbulence is present, some averaging procedure is necessary (see for example ref 2). Further, they require a knowledge of ancillary parameters such as temperature, gas composition etc. Simple visual techniques can only be applied to flames.

Recent developments involving Laser Doppler[3] or photon auto-correlation[4] techniques have been applied to laboratory flames on burners but are probably too cumbersome for large scale fire research.

One solution to the problem is to employ the turbulence as a tracer and to time its movement. The general problem of dealing with random fluctuations by cross-correlation techniques has been the subject of several reviews[5,6,7]. A cross-correlation technique is described in this paper where only cheap, easily replaceable thermocouple probes are exposed to the possibility of damage and deterioration in the rigorous environment experienced in fires.

The technique described here, which is analogous to flow measurement by artificial tracer, is an absolute measurement of the transit time of some naturally occurring fluctuating pattern in the fluid flow. This could be an optical[8], velocity[9,10], concentration[11] or as discussed here, thermal fluctuation. The pattern is assumed to be convected with the mean flow of the fluid between two measurement probes.

Data obtained by this method in some corridor fires are compared with those obtained by more conventional techniques. Comparisons have been made with pitot tube, vane anemometer and $CO_2$ concentration measurements in hot smoke and additionally with drum camera and a visual measurement using closed circuit television equipment (CCTV) for flames.

PRINCIPLE

The correlation concept is common in statistics where the degree of association of certain variables is to be measured. The analysis described here is an extension of this concept to establish the similarity of signals in the time domain. Signal statistics are employed to recognise a fluid fluctuation and to time its movement. For small separation between sensing probes this pattern changes little (see for example plate 1). The transit time $\tau_m$ is that value of time shift for which the delayed version $x(t-\tau)$ of signal $x(t)$ from the first measuring point is almost equal to the signal $y(t)$ from the second point

ie when $\lim_{T\to\infty} \frac{1}{T}\int_0^T x(t-\tau)y(t)\,dt$ is a minimum

where $T$ is the averaging time,

or when

$$R_{xy}(\tau) \equiv \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t-\tau)y(t)\,dt \qquad (1)$$

has a maximum value. This function, the cross-correlation function, must be computed for all values of $\tau$ and will have a maximum value when $\tau = \tau_m$. This may be written as $R_{xy}(\tau) = \overline{x(t-\tau)y(t)}$ implying a continuous averaging process. This function is often expressed in normalised form as the correlation coefficient $\rho_{xy}(\tau)$ where:

$$\rho_{xy}(\tau) = \frac{R_{xy}(\tau)}{\left[\overline{x(t-\tau)^2}\right]^{\frac{1}{2}}\left[\overline{y(t)^2}\right]}$$

If $y(t) = x(t)$ the cross-correlation function becomes the auto-correlation function of $x(t)$

$$R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t-\tau)x(t)\,dt \qquad (2)$$

The auto-correlation function describes the relationship between a signal and a time-shifted version of itself, and serves as a useful indicator of the validity of the assumption of 'frozen' turbulence. Should the turbulence be rigidly convected at the mean gas velocity then the cross and auto-correlation functions would be identical except for the time shift. However, in real situations the delayed correlation is always poorer because of the viscous dissipation of eddies. A measure of the departure from this assumption is obtained by the degree of inequality of the relationship.

$$R_{xx}(\tau_m) \doteq R_{xy}(0)$$

A slightly different approach described for example by Stegen and van Atta[12] is to measure the phase speed of the Fourier components of the velocity fluctuations. The frequency components of $y(t)$ are simply regarded as phase-shifted versions of those of $x(t)$. The phase lag is then proportional to the transit time of that component of frequency.

The cross spectral density $G_{xy}(f)$ is readily computed from the cross-correlation function $R_{xy}(\tau)$ since for stationary phenomena they are a Fourier transform pair (Wiener-Chinchin theorem),

$$G_{xy}(f) \equiv C_{xy}(f) - i\,Q_{xy}(f) = 2\int_{-\infty}^{\infty} R_{xy}(\tau)\, e^{-i2\pi f\tau}\, d\tau$$

$C_{xy}(f)$ and $Q_{xy}(f)$, the real and imaginary parts of the cross spectrum, are known as the co- and quad-spectra. Again, if $y(t) = x(t)$, the cross spectral density becomes $G_{xx}(f)$ the power desnity spectrum, a real number. The phase of the cross spectrum

$$= \tan^{-1} \frac{Q_{xy}(f)}{C_{xy}(f)}$$

The phase lag $\phi(f)$ of a component of $y(t)$ behind $x(t)$ will be related to $v(f)$, the phase speed, by

$$v(f) = 2\pi f \frac{d}{\phi(f)} \qquad (3)$$

where $d$ is the spacing between sensors.

This approach was adopted in early experiments but was abandoned in favour of 'real time' digital correlation. Some results obtained by the method are presented in Appendix 1.

EXPERIMENTAL PROCEDURE

(i) General

The corridor used as a vehicle for gas velocity determination was 2.5 m high, 1.3 m wide and 6.35 m long, constructed of asbestos wood with a lining of refractory felt (Fig 1). The fire was set near a closed end and combustion gases were channelled along under the ceiling to pass out of the open end.

Table 1

A summary of measurements made

| Test | Fuel | Thermal Output (MW) | Max mean Temp °C | Velocity measurement | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Pitot | $CO_2$ | CCTV | Drum | Vane | Correlation |
| 1 | i.m.s. | 1.03 | 1000 | ✓ | ✓ | – | ✓ | – | ✓ |
| 2 | | 0.89 | 1000 | – | ✓ | ✓ | ✓ | – | ✓ |
| 3 | | 0.89 | 980 | ✓ | ✓ | ✓ | ✓ | – | ✓ |
| 4 | | 1.20 | 770 | ✓ | Monitored | – | – | – | – |
| 5 | | 1.18 | 720 | ✓ | | – | – | – | ✓ |
| 6 | Wood | 1.20 | 750 | ✓ | | – | – | – | ✓ |
| 7 | | 1.18 | 700 | ✓ | – | – | – | ✓ | – |
| 8 | | 1.12 | 700 | ✓ | – | – | – | – | ✓ |

Two fuels were employed to generate different types of fire behaviour. Three tests were conducted with a circular pool, 0.92 m diameter of industrial methylated spirit (i.m.s), which reaches a constant thermal output with time. This tray was raised to 1 m below the ceiling to provide flames passing along the whole length of the corridor. Five tests were conducted with a wooden crib (seven layers of ten sticks/layer of Baltic Redwood, each stick 38 mm square and 1 m long) the output from which is not constant but has commonly been used in fire research to simulate real fires in buildings. This fire was designed to give flames just reaching the measurement plane. Temperature measurement in the vicinity of the measurement area was effected by two vertical columns of ten thermocouples, 0.1 m apart extending 1 m down from the ceiling (Fig 1). The thermal output from each fire was estimated by continuous monitoring of weight loss of fuel by strain-gauge load cells. Measurements of velocity were made at a distance of 3 m from the closed end of the fire chamber and close to the centre line of the corridor. It was not always possible to simultaneously measure velocities by techniques involving the immersion of probes (vane, pitot and correlation) because wake interference from one technique may deceive another. This was a problem mainly with wooden crib fires where velocity could not be assumed constant with time. Reference to temperature-time profiles indicates slight differences in the rate of growth of fires which were nominal repeats. A summary of measurements made appears in Table 1.

(ii) Flow determination

(a) Correlation measurements

Thermal fluctuations along the centre line of the corridor and parallel to the ceiling were detected by two 40 SWG (0.12 mm diameter) chromel-alumel thermocouples. The thermocouples were mounted 38 mm apart in a reversible probe capable of scanning the hot gas layer. The probe, Fig 2 was constructed of cylindrical steel tube with circumferential grooves cut at 0.1 m intervals along its length so that location in a sprung support could readily be made during the experiment and so that the probe could easily be rotated through $180^{\circ}$. The thermocouple wires were insulated by ceramic twin-bore tubing supported by refractory cement.

The natural thermal time constant of these sensors was about 0.5 s so it was necessary to improve their response by resort to a simple analogue circuit based on that described by Praul and Hmurcik[13]. The circuit (Fig 3) combines the thermal emf at the thermocouple junction with its rate of change with time. If the response is exponential with time then this gives an 'instantaneous' measurement of temperature dependent only on the electronic time constant. With the above thermocouples the time constant was improved typically to 5 ms. Care was taken to ensure similarity of the two sensing probes and associated circuitry (ac decoupling, thermocouple junction size etc). However, should the response time of one limb differ from that of the other, for example the junction size may change due to corrosion, oxidation soot accumulation etc then the measured delay times will be in error. This is allowed for by reversal of the probes in the flow and taking the mean delay for calculation of gas velocity.

The data from each thermocouple were recorded on two tracks of a frequency modulated tape recorder. Data was then re-played at a later stage for analysis by a Hewlett-Packard 3721A Digital Correlator. Measurements of velocity were made at 0.1 m intervals from 0.075 - 0.575 m below the ceiling. Each measurement involved recording data for 1 min before probe reversal or movement to a new position.

(b) Comparative techniques

Pitot tube

A pitot tube was mounted through a side wall of the corridor (see Fig 1) and pivoted at the wall 0.5 m beneath the ceiling. The pitot head (9.5 mm dia) swept out an arc of radius 0.7 m about the pivot to measure velocity at six levels below the ceiling. Differential pressures were measured with an electrical micromanometer and recorded on a heavily damped chart recorder (response time $\sim$1 sec).

Streak camera and closed circuit television (CCTV)

In tests 1 2, 3 a drum camera mounted above a CCTV camera observed the images of flames moving horizontally over a length of 0.5 m under the ceiling as reflected through a right angle by mirrors situated beneath the ceiling. The image of the flames is thrown onto a photographic film moving at known speed perpendicular to the flames and a mean velocity is determined from the slope of these tracks. This method was devised by Hinkley et al[14].

The output from the TV camera was recorded on a video tape recorder and rough estimates of velocity obtained by timing the transit of a recognisable flame front across the field of view, by counting frames. An initial calibration was conducted for these techniques by recording the positions of lamps at known intervals 0.15 m below the ceiling; this depth was chosen as being the approximate location of the lowest flames. This could be seen clearly by observation of flames around the correlation probe during experiments. Clearly the spatial resolution of these techniques is poor and for flames closer to the ceiling than 0.15 m, velocities will tend to be underestimated by up to 10 per cent because of the angle subtended by the calibrated length at the camera.

Carbon dioxide concentration

It is possible for chemically simple fuels to estimate mass flow rates of combustion products by examination of measured carbon dioxide concentrations[1]. The yield of carbon dioxide per unit mass of i.m.s.* completely burnt is well known[15] and the rate of weight loss is measured. Thus a simple calculation (Appendix 2) allows

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*Ethanol constitutes about 95% of i.m.s.

local measurements of $CO_2$ concentration to be converted to gas flow rates. Carbon dioxide concentrations were continuously monitored at three levels beneath the ceiling (0.05, 0.20, 0.35 m) by infra-red analyser. Periodically samples of gas were taken for later analysis for $CO_2$ and CO by gas chromatograph. Since the composition of the combustion products from wood fires is difficult to define, the velocity analysis was only applied to the i.m.s. fires.

Vane anemometer

Finally a water-cooled vane anemometer described by Palmer and Northcutt[16] and supplied by the US Department of Agriculture was used in some later tests at a fixed position below the ceiling. The centre of the rotor was 0.23 m below the ceiling and the outside diameter of the blades was 0.15 m.

This anemometer employs reed switches operated by magnetic slugs in the rotor to provide a pulse output. This is converted to a continuous voltage output by a simple digital to anologue circuit. The device was calibrated at room temperature in a wind tunnel. The modification required to interpret results obtained at elevated temperatures is given in Appendix 3.

RESULTS AND DISCUSSION

The results are presented in two forms

(i) measured velocities as a function of distance below the ceiling for liquid pool fires where the thermal output reaches a reasonably constant level with time

(ii) measured velocities as a function of time at a fixed distance below the ceiling for wooden crib fires where the thermal output is a continuously varying function of time.

Figure 4 summarises the time variation of thermal output for the two types of fire investigated. Velocities determined by cross-correlation as a function of position are plotted in Fig 5 for a pool fire (test 2) together with the temperature distribution below the ceiling in the measurement plane. The measurements were made from the time (3 min) that the thermal output had reached the plateau indicated in Fig 4. Points obtained with either thermocouple downstream are given at each position to indicate the error caused by unequal response times. This error which is eliminated by taking the mean delay time would be less than ± 6% for these measurements. It would appear that, at least over the region 0–0.2 m, the exact vertical positioning of the comparative devices is unimportant.

Typical thermal fluctuations as measured by the thermocouples are displayed in Plate 1. It can be seen that fluctuations up to, perhaps, 100 Hz have been observed. Plate 2 exhibits the cross-correlation function of the above signals computed for two hundred values (positive and negative) of time delay after $2^{16}$ display updatings (or 65 seconds). The delay time for these signals is 12 ms yielding a mean velocity of 3.16 m/s for the probe spacing of 38 mm. The autocorrelation function of the upstream signal is shown in plate 3, again after $2^{16}$ display updatings. It can be seen from these photographs that $R_{xy}(0) \doteqdot R_{xx}(12\text{ ms}) \doteqdot 5.5 \times 10^{-2} V^2$ apparently supporting the assumption of frozen turbulence.

A typical set of pitot results is given in Table 2.

Table 2

Pitot tube – i.m.s. fire, test 3

| Distance below ceiling (m) | Time (mins) | Mean differential pressure (mm $H_2o$) | Temp ($^oC$) | Vel (m/s) | Re |
|---|---|---|---|---|---|
| 0.05 | 1 | 0.17 | 700 | 3.06 | 269 |
| | 3 | 0.12 | 850 | 2.76 | 191 |
| 0.10 | 4 | 0.12 | 910 | 2.84 | 180 |
| | 12 | 0.17 | 875 | 3.28 | 223 |
| 0.20 | 5 | 0.11 | 825 | 2.62 | 191 |
| | 11 | 0.08 | 800 | 2.20 | 164 |
| 0.30 | 6 | 0.10 | 675 | 2.32 | 215 |
| | 10 | 0.08 | 700 | 2.10 | 202 |
| 0.40 | 7 | 0.08 | 525 | 1.90 | 232 |
| | 9 | 0.08 | 425 | 1.78 | 270 |
| 0.50 | 8 | 0.07 | 250 | 1.44 | 360 |

Interpretation of pitot measurements becomes difficult at a pitot head Reynolds number below about 500[17]. Hinkley et al[14], however obtained good agreement with streak camera results for flames down to a Reynolds number of 250 using the simple theory and this is the method employed here.

Since a 'plug flow' situation cannot be assumed in these experiments the results obtained from $CO_2$ analysis have assumed a velocity profile as measured by the correlation probe. The position of the profile on the velocity axis is determined from $CO_2$ analysis (see Appendix 2).

The data from three fires 1, 2, 3 (nominal repeats) are combined in Fig 6 with those measurements made by pitot, CCTV, streak camera and $CO_2$ concentration.

For the visual measurements the approximate limits of uncertainty are shown. It can be seen that there is good consistency between the results from each fire and that over a two-fold range of gas velocity there is reasonable agreement between the techniques employed, considering the limitations of the comparative methods, with the exception of those obtained from $CO_2$ analysis. It is suggested that incomplete combustion at the measurement plane (flames passing the probe) may explain this discrepancy.

Fig 7 displays measured velocities with time obtained by cross-correlation and pitot tube at 0.075 m below the ceiling for the fires from a wood crib. Measurements from the vane anemometer centred 0.23 m below the ceiling, have been temperature corrected following the procedure outlined by Ower and Pankhurst[2] (see Appendix 3). Points are included for either thermocouple upstream, again, to indicate the magnitude of the error caused by asymmetry in the measuring limbs. The error here, if the mean were not taken, would be less than $\pm$ 15%, significantly higher than the previous series, probably reflecting unequal soot deposition on the sensors.

Cross-correlation and pitot measurements made at the same distance, 0.075 m below the ceiling are in excellent agreement. It takes over a minute for the gas momentum to overcome the inertia of the vane anemometer, situated 0.23 m below the ceiling. The output then quickly rises to indicate a velocity somewhat lower than those above. This is explained by the location of this anemometer below the ceiling. It is clear from the temperature-time profile, that the growth of this fire, test 8, was slow compared with test 5 where the correlation and pitot measurements were made.

CONCLUSIONS

(1) This paper has illustrated the considerable advantages of the cross-correlation technique described here over many alternative methods employed hitherto for the measurement of hot gas flow velocities. The sensors are robust and simple and can be used in flame and smoke. It is the signal processing that is relatively sophisticated and, though quick to use, should properly account for turbulence by statistical averaging of the data instead of relying on anemometer time-constant averaging.

(2) Without recourse to the measurement of ancillary parameters it has been possible to measure absolutely the transit times of thermal fluctuations in the flow. Pitot tube and vane anemometer measurements require a measurement of temperature, velocity determination from $CO_2$ concentration is difficult where the velocity distribution is not known or the $CO_2$ yield of the fuel difficult to define (eg wood) and the streak camera has poor spatial resolution.

(3) It has been shown for these crib and pool fires that where the above techniques can be compared there is a reasonable level of agreement between mean velocity and the convection velocity of thermal fluctuations. The technique may therefore now be used with some confidence to investigate flame and smoke movement.

(4) Clearly there is scope for improvement in the sensor design. Probe reversal is a nuisance and though this could be mechanised, a shift to noble metal thermocouples should help to eliminate any changes in time constant due to contamination of junctions. Further it is conceded that these measurements have only been made in a system where the mean flow direction is clear. A probe with four sensors to measure the components of velocity along three orthogonal axes should help determine vector velocities in flows where the direction is less clear.

ACKNOWLEDGMENTS

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APPENDIX 1

Some early experiments were conducted with hot-wire sensors before being abandoned in favour of more robust thermocouples. Conventional hot-wire probes (typically 0.01 mm diameter) are too fragile for use in hot gases and flames so more sturdy hot-wires (0.06 mm diameter) were used with some loss of high frequency response.

These have been employed to measure the phase speed of the Fourier components of velocity fluctuations for example in the cold flow from a wind tunnel (Fig 8). These phase-lag/frequency results were computed using the spectral analysis program of Roberts and Surry[18] at the National Physical Laboratory using a small digital computer with analogue-to-digital access. The velocity of 2 m/s obtained from this data using equation 3 for probes 20 mm apart agrees with that obtained by cross-correlation analysis (see Fig 9).

APPENDIX 2 - $CO_2$ ANALYSIS METHOD

Let $y$ be the volume of $CO_2$ produced at ambient/unit mass fuel burnt

$\frac{dx}{dt}$ be the rate of mass loss of fuel burnt

$\rho a$ be the density of $CO_2$ at ambient temperature and pressure

then $\frac{ydx}{dt} \cdot \rho a$ is the mass $CO_2$ produced/unit time

At the measurement plane, consider the i th hot gas layer beneath the ceiling

where $Ai$ is the cross-section area of that layer

$c_i$ is the volumetric $CO_2$ concentration measured in a dried sample of gas from that layer produced by complete combustion of the fuel

$\rho i$ is density of $CO_2$ at absolute temperature $T_i$ in that layer

$r_i$ is the volumetric concentration of water vapour in that layer

and assume that the gas velocity, $u_i$, does not vary across the width of the layer then for conservation of $CO_2$

$$y \rho a \frac{dx}{dt} = \sum_{i=1}^{j} c_i \; A_i \; u_i \; \rho_i \; \left[ 1 - r_i \right]$$

or rewriting

$$\frac{ydx}{dt} = T_a \sum \frac{c_i A_i}{T_i} \left[ 1 - r_i \right] \; u_1 \cdot \frac{u_i}{u_1}$$

Since for these experiments unlike those of Heselden[1] et al $u_i \neq u_j$ this can only be solved knowing $\frac{u_i}{u_1}$ from another measurement eg cross-correlation.

Complete combustion has been assumed but it can readily be shown that if CO is produced but all fuel is burnt then

$$c_i \doteq d_i + e_i$$

where $d_i$ and $e_i$ are the concentrations of $CO_2$ and CO measured

and that $r_i = \frac{3}{2} \left[ d_i + e_i \right]$ .

RESULTS

The measurements made in test 2 appear in Table 3; $\frac{dx}{dt}$ = 0.037 kg/sec, y = 1.02 $m^3/_{kg}$

Table 3

| Depth below ceiling of sampling (m) | $d_i$ % | $e_i$ % | $T_i$ $^oK$ | $\frac{u_i}{u_1}$ | $u_i$ (m/s) |
|---|---|---|---|---|---|
| 0.05 | 9.0 | 2.05 | 1250 | 1 | 3.82 |
| 0.20 | 9.0 | 0.45 | 1125 | 0.98 | 3.74 |
| 0.35 | 3.0 | 0 | 925 | 0.81 | 3.09 |

APPENDIX 3

VANE ANEMOMETER

A correction to the room temperature calibration must be made to allow for gas density changes when using a vane anemometer in high temperature gases. If the frictional torque in the bearings is linearly proportional to the resultant wind force then Ower and Pankhurst[2] have shown that the calibration curve for a density $\rho t$ is parallel to that obtained at room temperature density $\rho o$, but displaced along the ordinate by $q\sqrt{\frac{\rho o}{\rho t}}$, where q is the ordinate intercept at $\rho o$.

The room temperature calibration and correction for 1000°C are displayed in Fig 10. Below about 1 m/s the calibration ceases to be linear.

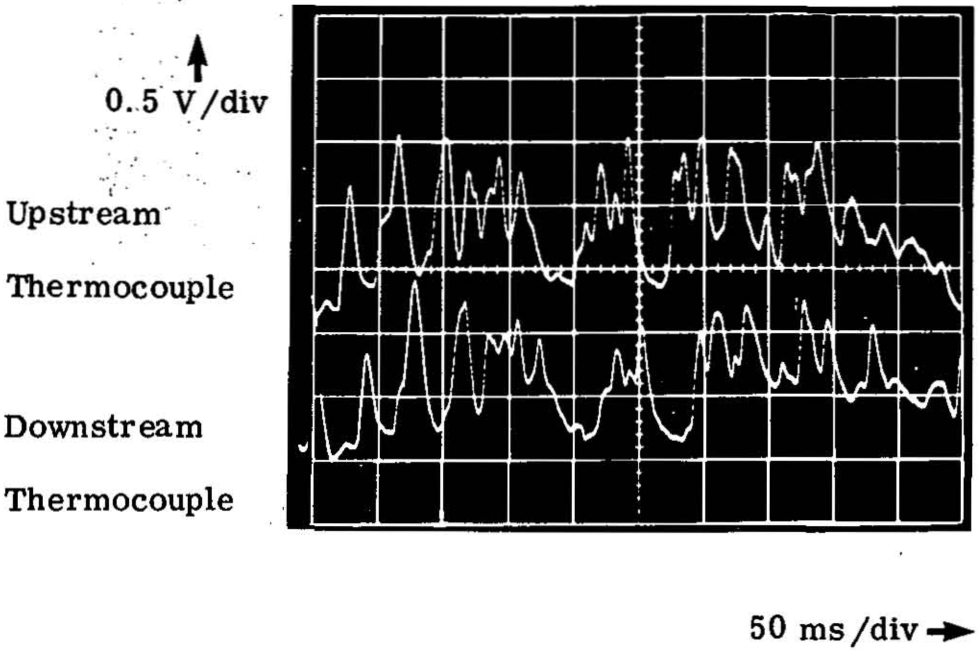


PLATE 1 TYPICAL AMPLIFIED THERMOCOUPLE RESPONSES IN FLAME (PROBES 38 mm APART)

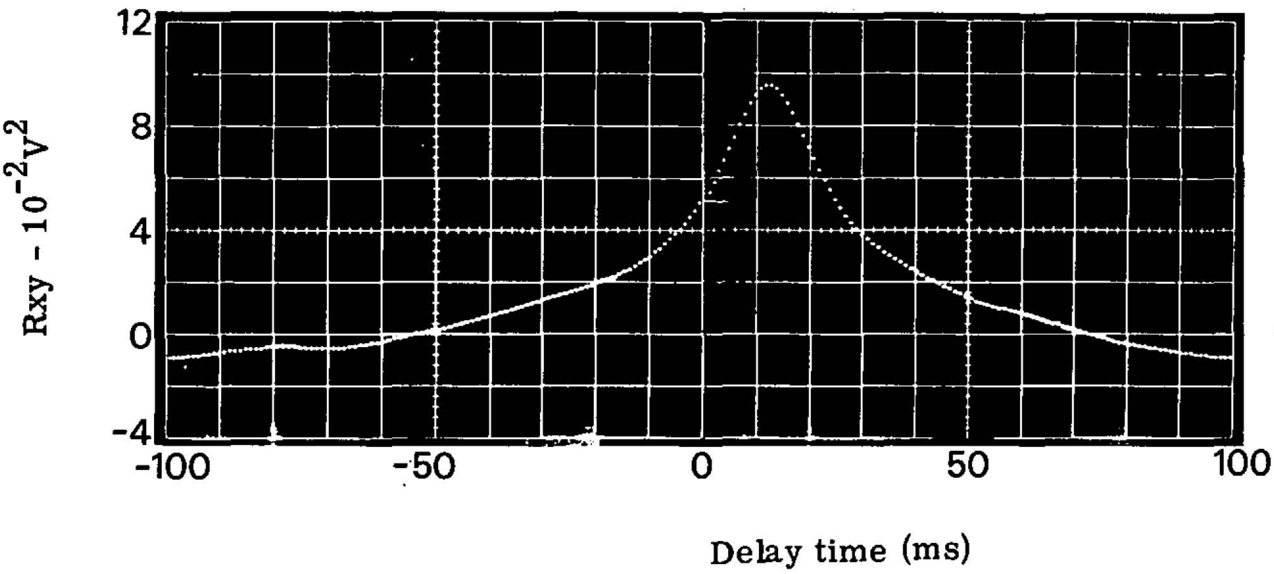


PLATE 2 CROSS CORRELATION FUNCTION OF ABOVE SIGNALS

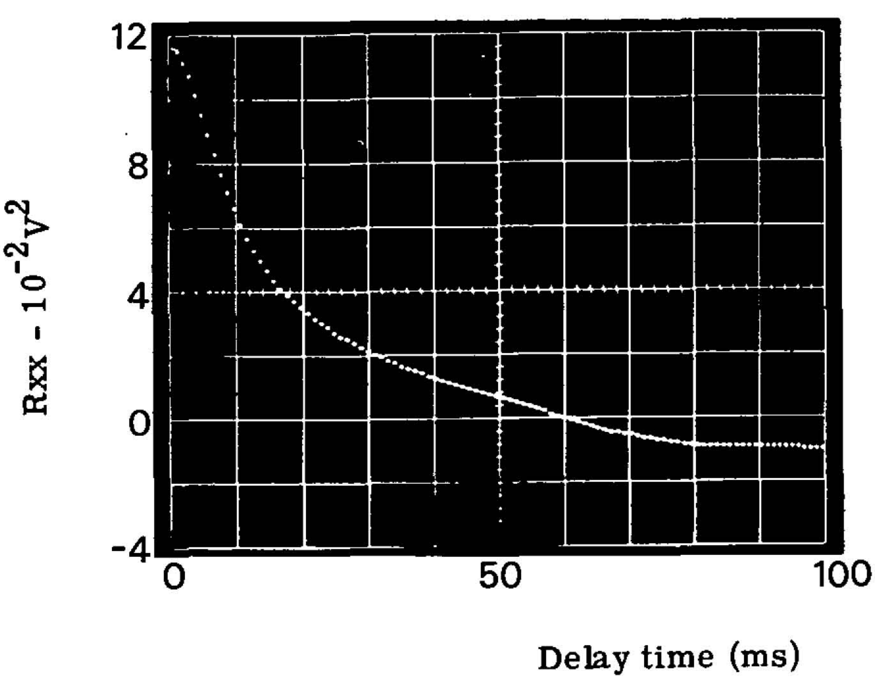


PLATE 3 AUTOCORRELATION FUNCTION FOR UPSTREAM PROBE

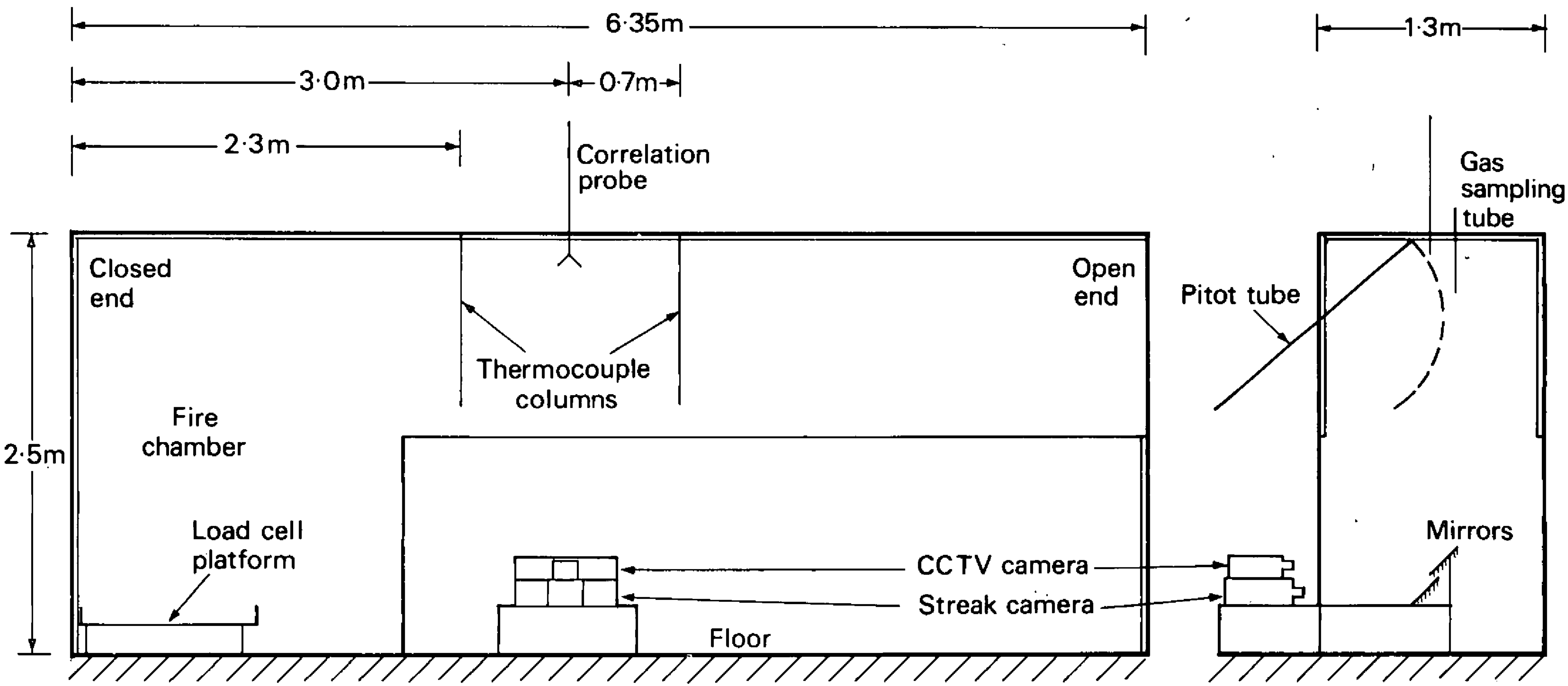


Figure 1 Schematic of corridor and instrument locations

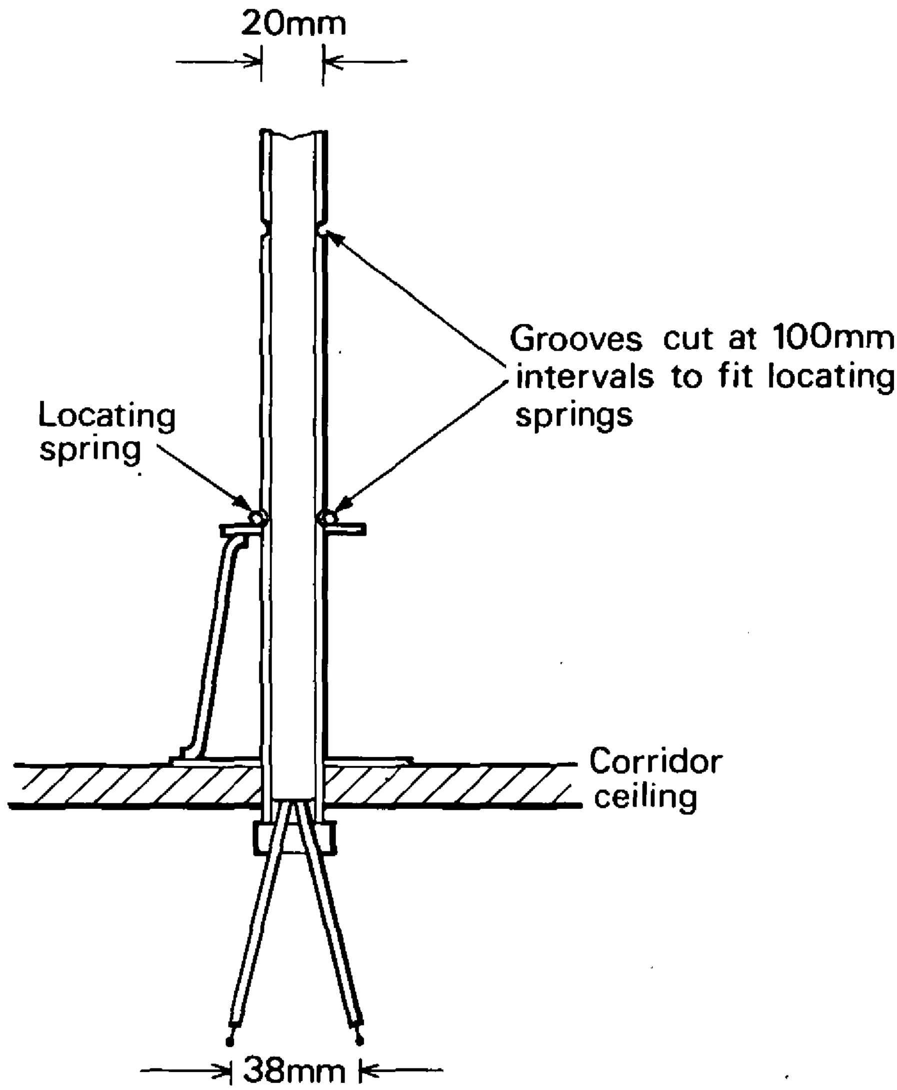


Figure 2 Correlation probe

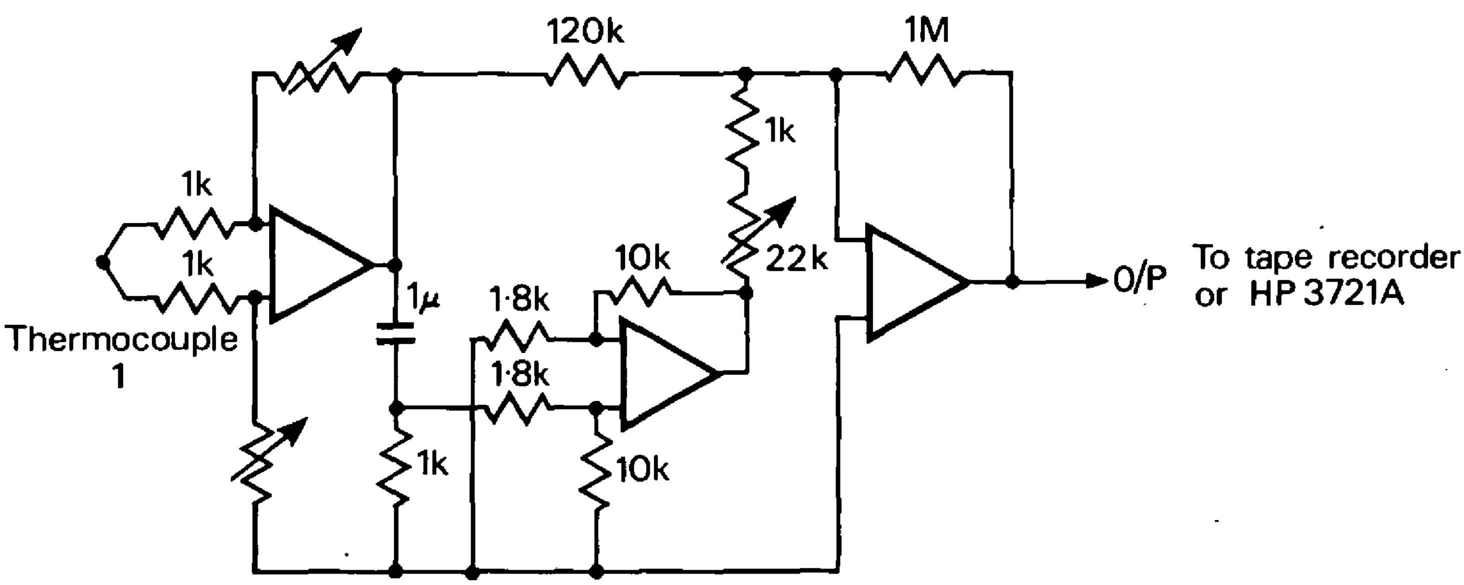


Figure 3 One channel of fast response thermocouple circuit

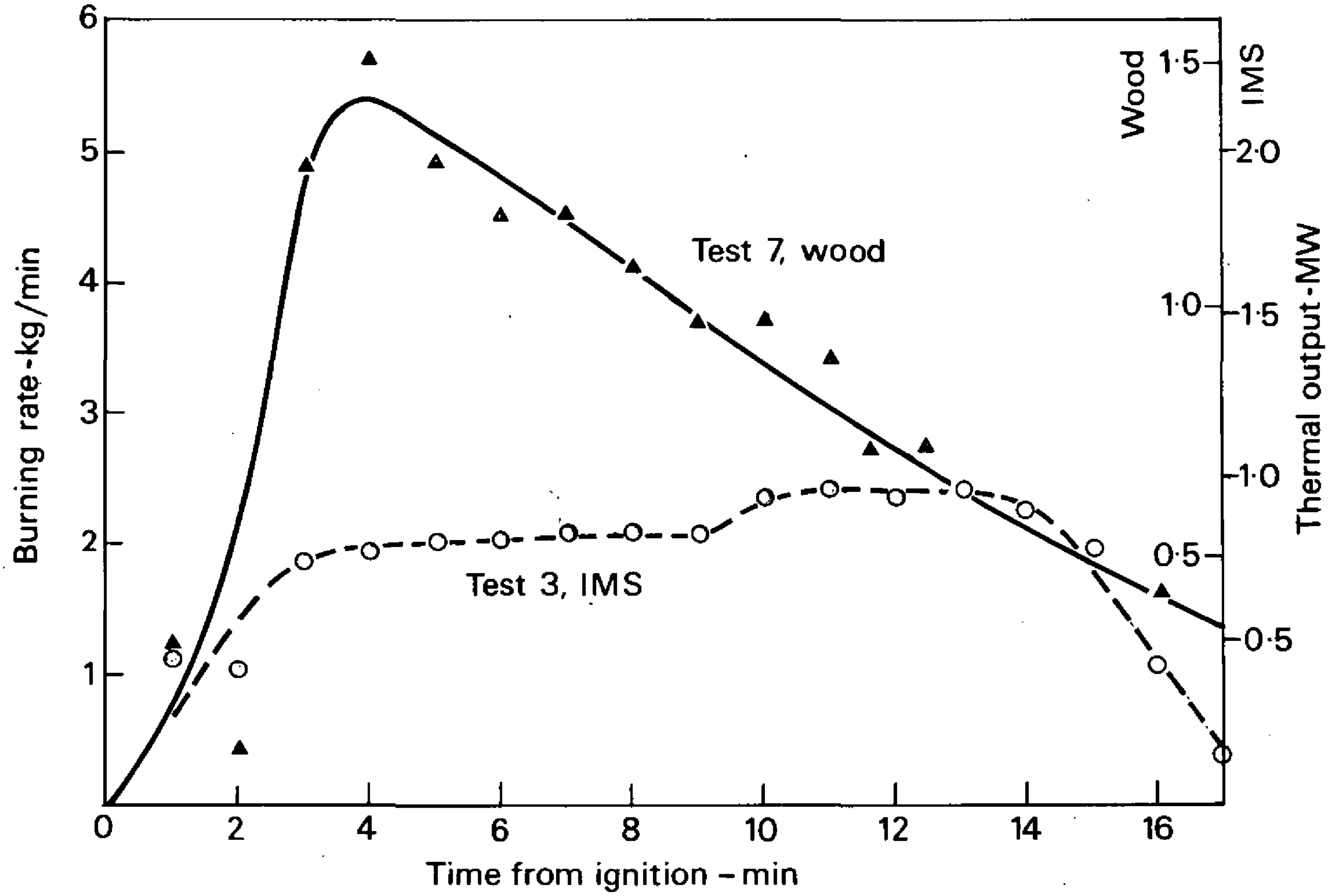


Figure 4  Variation of burning rate with time for tests 3 and 7

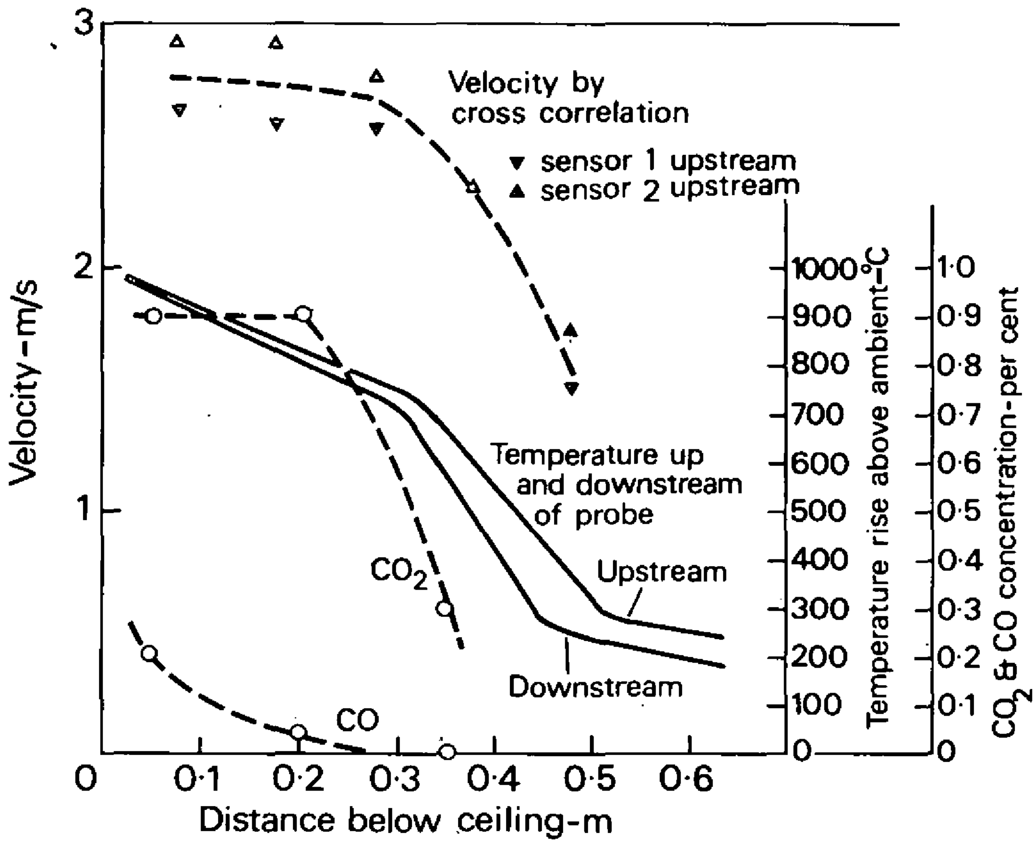


Figure 5 Velocity by cross-correlation as a function of position below ceiling for IMS fire no 2

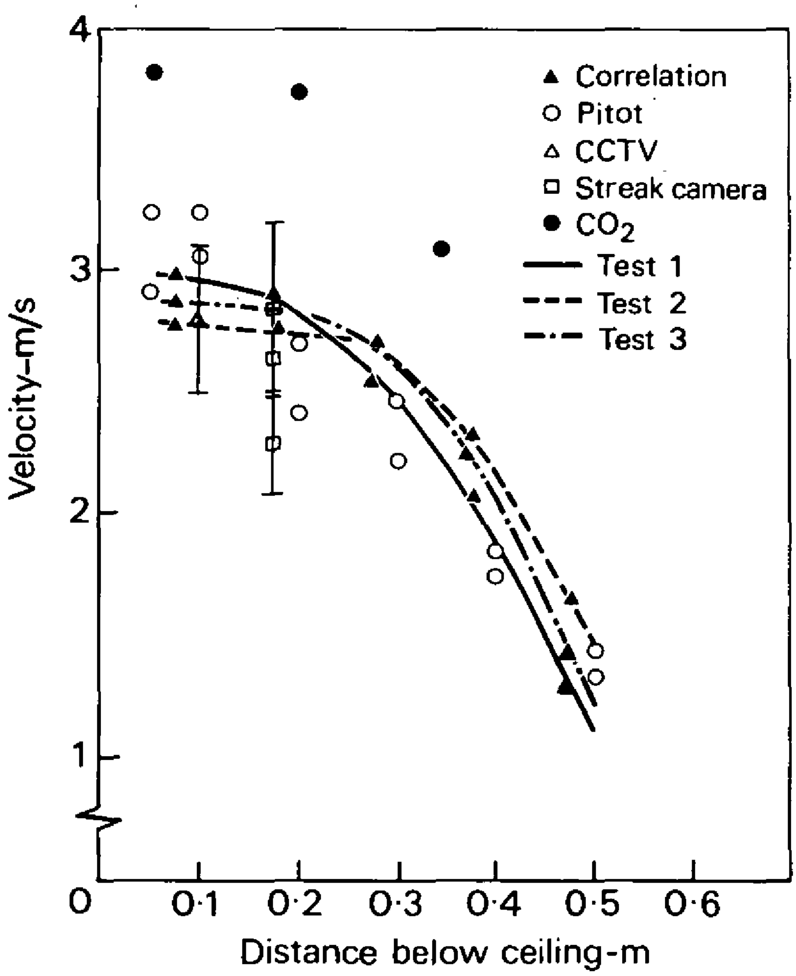


Figure 6 Vertical profiles of gas velocity for IMS fires 1,2,3

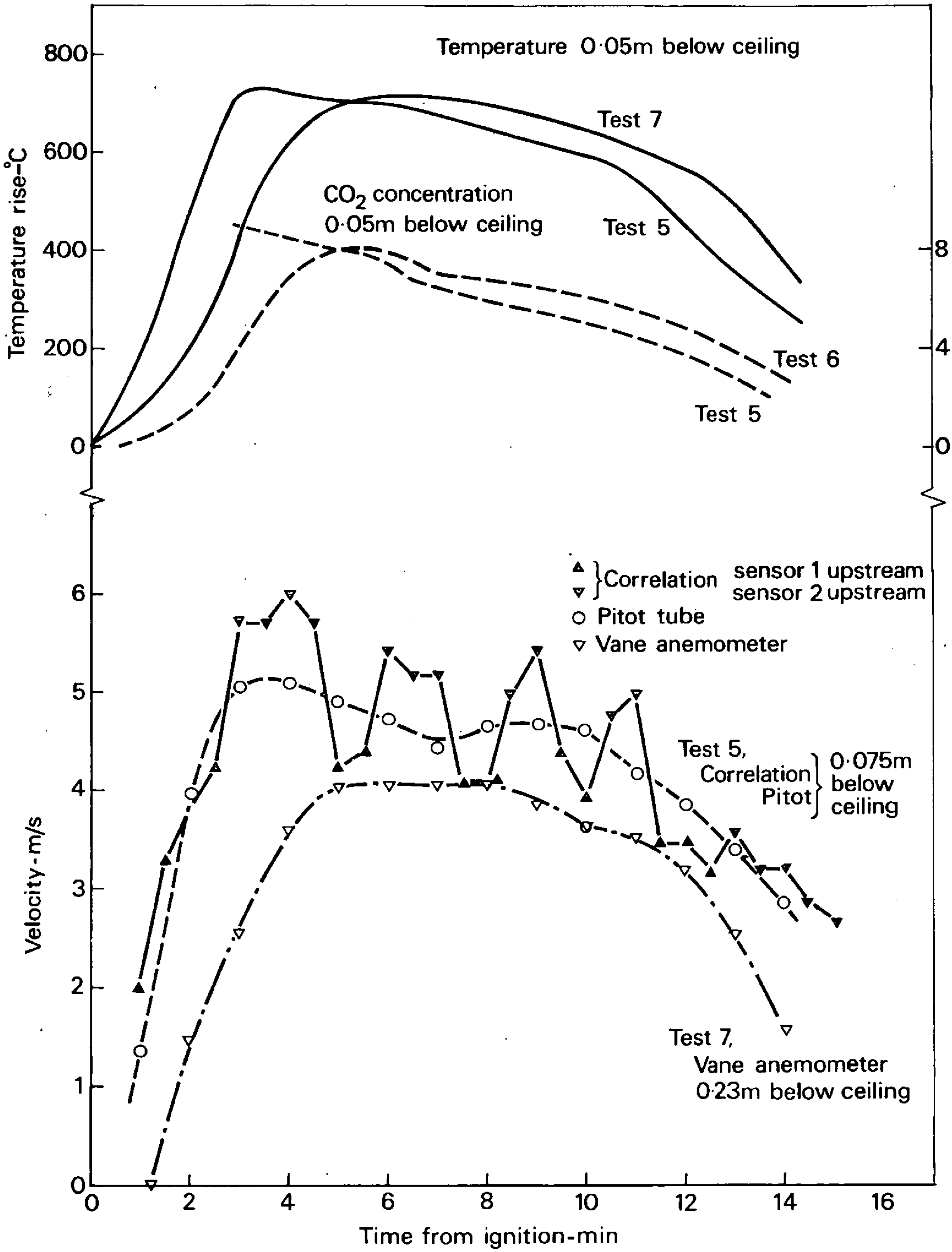


Figure 7 Gas velocity as a function of time for wooden crib fires

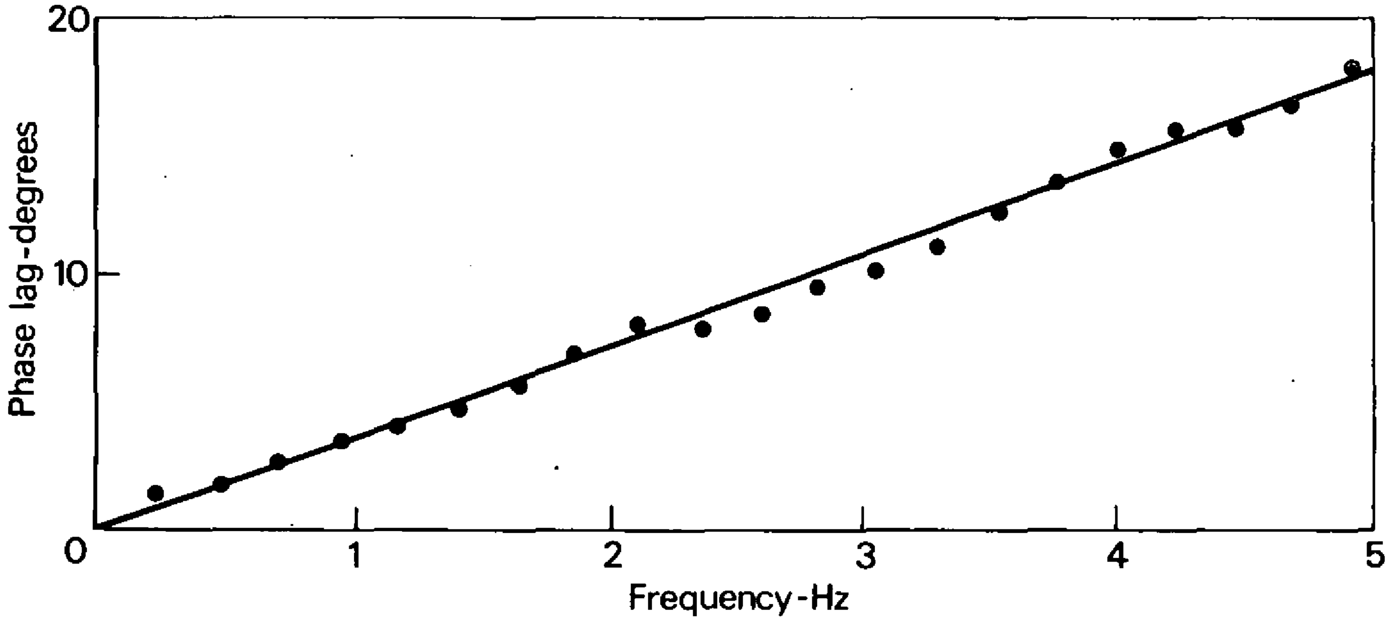


Figure 8 Phase lag/frequency for hot-wire sensors 20mm apart

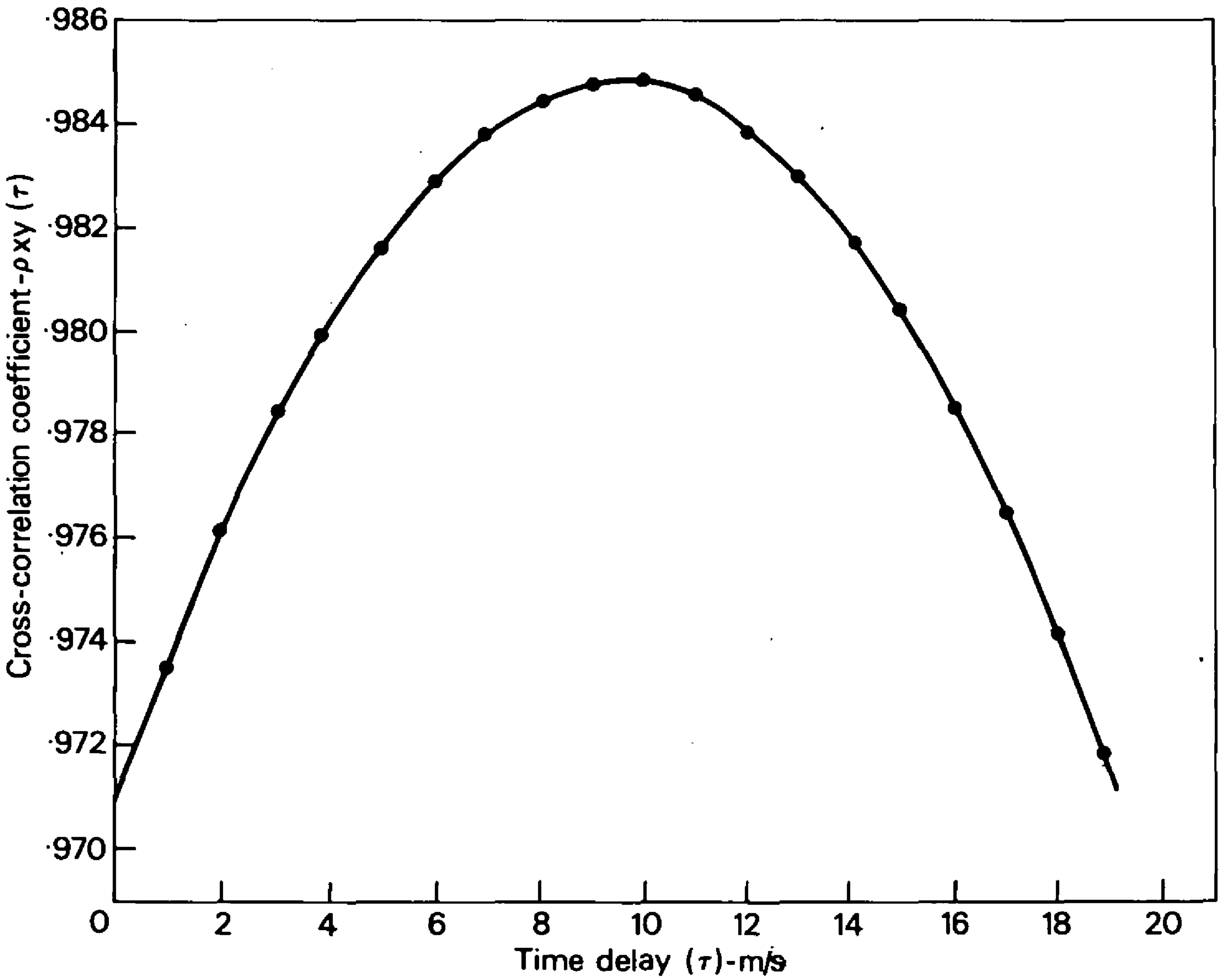


Figure 9 Cross-correlation function/time delay for hot-wire probes 20mm apart

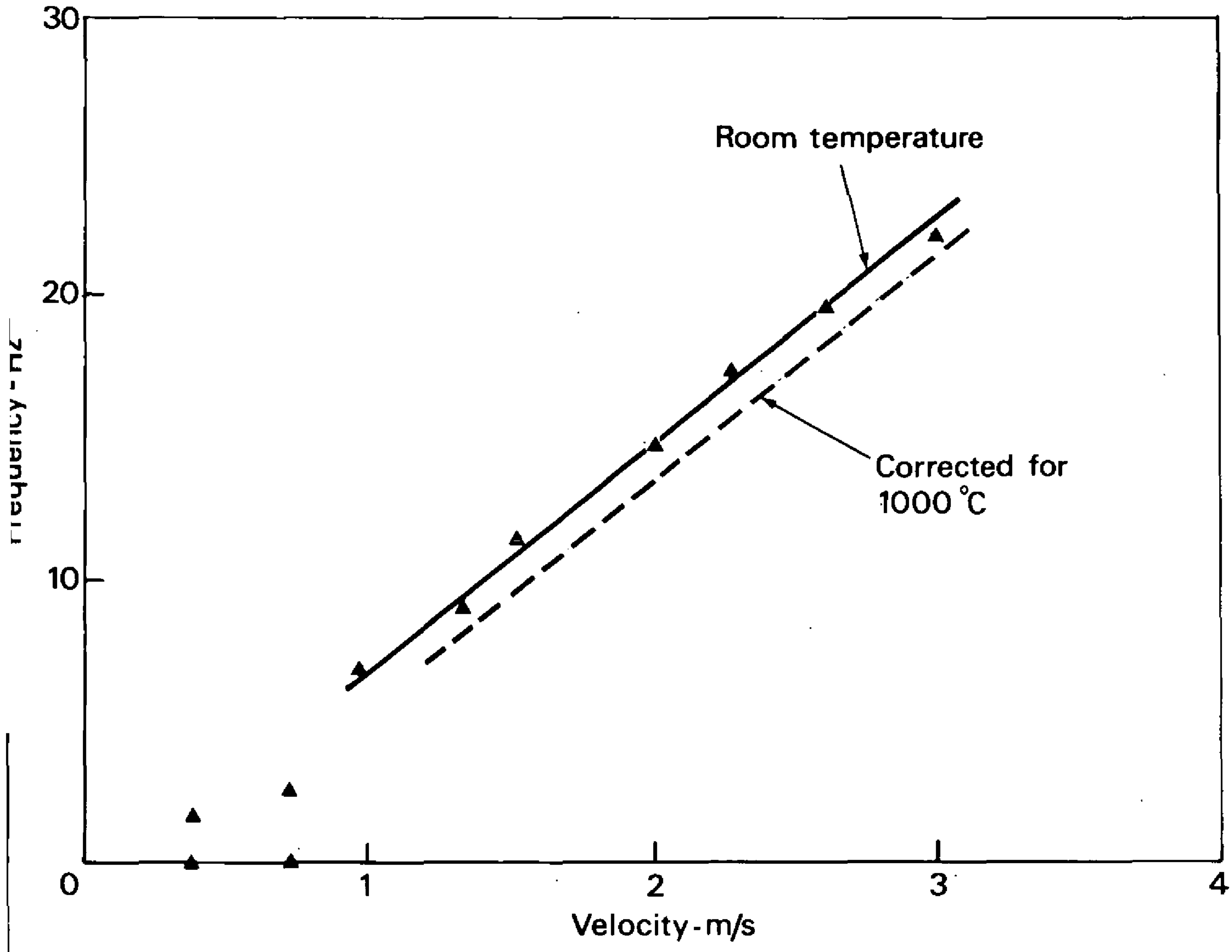


Figure 10 Calibration of vane anemometer at 15°C

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