Fire Research Note

No. 812

THE PREVENTION OF FIRE SPREAD IN BUILDINGS BY ROOF VENTS AND WATER CURTAINS

PART 2. THE EFFECT OF AIR MOVEMENT ON WATER CURTAINS

by

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SUMMARY

The earlier part of this report showed how roof venting - if extensive enough - could remove all the combustion products of a fire. If this was not enough to prevent spread altogether, wetting down of fuels heated by radiation could prevent their ignition. However, venting induces draughts towards the fire and if these are strong, weak water sprays can be deflected into the fire, where they would be less effective.

An attempt to use the minimum effective water quantities for wetting down may thus be ineffective.

This report describes experiments on the deflection of water curtains by an air stream and shows how the effect can be calculated with the necessary degree of accuracy so that the data reported can be provisionally extrapolated to situations other than those examined experimentally.

With draughts of up to 1.2 m/s, a water flow of 0.5 l m^{-1} s^{-1} can give sufficient width of wetted fuel 5 m below the nozzles to prevent fire spread.

KEY WORDS: Water curtains, Fire spread, Building, Vents, Drops.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
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1. INTRODUCTION

Following the fire experiments described in Part 1 of this note[1], measurements have been made of the deflection of various water curtains produced by a cross wind to see whether the current of air induced by a fire could deflect a water curtain sufficiently to prevent it from forming an effective barrier to fire. Calculations of droplet trajectory, based on a simplified theory, have also been made and give deflections which are in agreement with those measured. The calculations enable the effect of curtain height and if necessary the effect of other wind speeds on deflection to be obtained for conditions other than the experimental ones.

Although the velocity of air flowing freely from all sides into a fully vented fire in a large compartment could be as low as 0.3 m/s, in other situations where the air approaching the fire is constrained to flow along a more restricted path much higher velocities could be attained. An example is discussed in Section 5.

2. APPARATUS AND EXPERIMENTAL METHOD

The water curtain was produced from the same 3 m (10 ft) long pipe that was used in the fire experiments[1]; Lechler flat jet nozzles F33/120°, F34/120° or F36/120° were spaced at 0.30 m (1 ft) intervals and turned so that the plane of the fan-shaped spray from each nozzle made an angle of 20° with the pipe. The pipe was erected about 3 m above the floor in the working space of the wind tunnel of the Models Laboratory[2] of the Fire Research Station at right angles to the direction of air flow. The water distribution at floor level beneath was measured in still air and for two wind speeds by weighing the water collected in a given time in 0.20 m diameter containers 2.7 m (9 ft) below the nozzles spaced at 0.30 m (1 ft) centres along a line at right angles to the curtain, halfway along its length.

Subsidiary experiments with extra lines of containers on either side of the central line showed that the curtain was long enough for a single line of containers to represent adequately the distribution across a much longer curtain.

Three nozzle sizes and two water pressures were employed in the balanced design shown in Table 1.

Since the containers were of equal size and were equally spaced the distribution of water at floor level was directly related to the distribution of quantities of water collected.

3. RESULTS AND DISCUSSION

3.1. General

The distributions obtained are given in Figs 1 and 2, where each ordinate is the fraction of the total output at zero wind speed, obtained from the water collected at zero wind speed. This procedure tended to average out the outputs of a number of nozzles, reduced bias introduced by the nozzles not being exactly vertical and showed up any loss of water carried by the wind beyond the furthest container.

Cumulative distributions are shown for the extremes of water flow rate (3 mm (0.12 in) nozzle at 7×10^4 N/m^2 and 6 mm (0.24 in) nozzle at 17×10^4 N/m^2) in Fig.3. The deflections of the peaks and the medians of the water distributions are given in Table 2.

3.2. Effect of wind velocity

The water curtain was indeed deflected by the wind; not only was the centre of the distribution moved downwind, but the distribution was broadened due to the elutriating (particle sizing) action of the wind discussed in Section 3.3. This led to a decrease in the rate of water application per unit floor area.

The deflection of both the peak of the water distribution and the median (not usually coincident) were roughly proportional to the wind velocity (Table 2).

3.3. Effect of water flow and nozzle diameter

For a given pressure, decreasing the nozzle diameter and hence the water flow rate gave greater deflections (Table 2). Not only was the peak of the distribution moved further from the curtain but the peak was lowered and the distribution broadened (Figs 1 and 2). The broadening of the distribution is due to the particle sizing action of the wind. The finer drops are slowed down in their vertical motion more rapidly than the coarser drops so that the cross wind can act on them for a longer time before they reach ground level. They are also more rapidly accelerated horizontally by the cross wind so that on two counts they are carried further than the coarser drops.

The difference in the deflections produced by the different water flows is almost certainly due to the higher momentum in the higher water flows, since for the same nozzle pressure the initial velocity and probably the droplet size distribution will be fairly constant. A higher jet momentum, even for the same initial jet velocity, will however lead to larger downward air velocities and hence less vertical deceleration of the droplets, which are therefore not deflected so far horizontally.

Fig 3 gives the distributions for two nozzles as a cumulative percentage of the water collected with no wind. The curve for the F36/120 nozzle at 3 m/s finishes at about 115 per cent, and this probably represents experimental error, which it was not thought profitable to try to reduce in this kind of experiment. However the curve for the F33/120 nozzle at 7.7 m/s only rises to about 65 per cent at a distance of 5 m and this is thought to represent a real effect of water loss to beyond 5 or 6 m (15 or 18 ft).

3.4. Effect of nozzle pressure

For any given nozzle diameter the effect of nozzle pressure on the spray deflection is very small (Figs 1 and 2), at least over the range of pressures employed in these experiments. This might appear curious in view of the importance of jet momentum mentioned in Section 3.3 however the higher pressure not only gives a higher jet momentum but also smaller droplets, which will be more readily deflected by the wind than the larger droplets.

4. CALCULATIONS OF DROP TRAJECTORIES

Since it was clear from the results that the curtain could be substantially deflected by the winds applied, calculations were made (see Appendix) to determine whether the trajectory of water drops deflected by a wind could be predicted. This would enable the results to be extended to other heights of curtain and other wind speeds.

The equations of motion were not integrated analytically, partly because of the complications introduced by the downward momentum imparted to the air in the curtain, but approximate solutions were obtained by numerical integration. Fig 6 shows the calculated trajectories and times of flight of 3 sizes of droplet produced by F33/120 nozzles at a pressure of 1.7×10^5 N/m^2 (25 lbf/in^2). The 3 sizes were the measured values of the mass median and lower and upper deciles of the droplet distribution from this nozzle at a pressure of 2×10^5 N/m^2 (29 lbf/in^2)^3. For simplicity it was assumed that the downward air velocity was set by momentum exchange with a spray of the same water flow rate but containing only 0.4 mm (0.016 in) dia droplets. The elutriating effect of the sideways wind is clearly shown in Fig.6.

A comparison is made in Table 3 between calculated and measured horizontal deflections at ground level, for two wind speeds. Bearing in mind the large approximations made in the calculations, the calculated deflections of the mass median droplet agree with the median of the measured water distribution. The positions of the upper and lower deciles of the water distribution are also similar to the deflections calculated for the 0.76 and 0.14 mm (0.03 and 0.006 in) dia droplets (corresponding to the upper and lower deciles of the droplet size distribution), although in view of the finite width of curtain under still air conditions there would be no reason to expect an accurate agreement.

5. GENERAL DISCUSSION

The requirement to use the minimum water is in opposition to the requirement of minimum deflection.

It is clear from the results shown in preceding sections that a water curtain can be deflected by a cross wind. The deflections produced for various water flow rates, nozzle pressures and wind velocities can be obtained from the results and an estimate of the variation of deflection with height can be made from Fig.4.

The point to consider now is, to what extent are these deflections likely to interfere with the proper operation of the curtain in practice? The deflection will depend on the degree of venting of the fire, the area of the flame over which air is entrained, the geometry of the building and the air entry path. If the curtain is deflected too much then it will be more difficult to ensure that a sufficient depth of wetted-down surfaces surrounds the fire. Water carried into the fire is not effectively used, since too little is available for extinction.

We now consider what kind of air speeds might obtain in a fire. For a fully vented fire in a large compartment 5 m (16 ft 5 in) high to which air can freely flow from all sides the mean air velocity across a water curtain immediately surrounding the fire, calculated using the entrainment relation of Thomas[4], will be in the region of 0.3 m/s.

The median deflection 2.7 m (9 ft) below the nozzles (Table 2) will then be not more than about 1/10 of the deflection for a wind speed of 3 m/s, i.e. some 0.2 m (8 in) even for the smallest nozzles and lowest flows. At floor level, 5 m (16 ft 5 in) below the nozzle, extrapolation of Fig 6 suggests that the deflections would be about 3 times as large, i.e. not more than 0.6 m (2 ft). It is not likely that deflections as small as this could affect the wetting down operation of the curtain significantly.

A situation giving higher wind velocities might be with a narrow building having a fully vented fire at one end occupying nearly the whole width of the building and a curtain as wide as the building, with substantial openings to admit air at the other end. If the base of the fire were square the average velocity of cold air approaching the fire could then be about 4 x 0.3 = 1.2 m/s for a building some 5 m (16 ft 5 in) high. Applying the results of Table 2 and Fig.6 leads to a median deflection at floor level of 2.1 m (7 ft) for 3 and 4 mm (0.12 and 0.16 in) dia nozzles, i.e. 50 per cent of the water would be deflected more than 2.1 m (7 ft). The median deflection for 6 mm (0.24 in) and a mixture of 6 and 4 mm (0.24 and 0.16 in) nozzles would be about 0.8 m (3 ft) and larger for tall buildings. Under these circumstances it would be advisable to use the larger nozzles, to reduce the deflection of the curtain, so that the wetted down area was more predictable.

The reduction in the rate of water application per unit floor area caused by the broadening of the wind-deflected distribution, is undesirable and in some circumstances could entirely nullify the effect of a water curtain if this was generated from a low flow of water. As an example some calculations have been made to see whether fire would be expected to spread across a water curtain of the type used for these measurements but 5 m high, with and without a draught of 1.2 m/s impinging on it.

It is assumed that a fire 5 m high and wide and radiating at 8 W/cm^2 has spread up to and into the water curtain (see Fig 4) to a point at which the water application rate is sufficient to halt fire spread. The water distribution has been taken to be that which would be predicted by the previous results at a depth of 5 m below the nozzles, i.e. the angular distribution is assumed not to change substantially with height. The critical water application rate to halt spread may vary according to the type of fuel but for the sake of argument the value of 0.08 l m^{-2}s^{-1} established by O'Dogherty et al[7] for fast spreading fires in wood cribs in a large building, probably representative of a fairly bad fire situation in a low fuel, has been taken.

Then the remaining thickness of the water curtain has been examined to see whether the fire could ignite material beyond the curtain, or just within the far side of the curtain, by radiation and so continue to spread.

Table 4 shows that at the lowest water flows the maximum rate of water application is reduced to below 0.08 l m^{-2}s^{-1} by the effect of a draught of 1.2 m/s so that the fire could not be prevented from spreading even though in the absence of a draught the curtain had formed a sufficient barrier to fire. At the higher water flows the fire is halted at the point corresponding to 0.08 l m^{-2}s^{-1} and the question then arises of whether further spread by radiation ignition of material on the far side of the curtain could occur. A fire 5 m high and wide radiating at 8 W/cm^2 would produce an intensity of 3 W/cm^2 (the minimum intensity for the spontaneous ignition of wood) on a vertical surface at floor level at 1.5 m so that so long as the curtain can wet down fuel sufficiently over at least this distance no ignition can occur. In the examples taken the remaining width of curtain is always sufficient to prevent ignition provided the main fire is halted.

Thus Table 4 suggests that a minimum water flow of about 0.6 $l\ m^{-1}s^{-1}$, about 2.2 gal $ft^{-1}min^{-1}$, would be required in order to prevent fire spread. This would probably necessitate using nozzles larger than 4 mm in diameter.

In other cases, particularly with a thin curtain and a hot fire, it might be necessary to consider whether the curtain was thick enough. Ignition could occur even within the curtain if the water application rate* were insufficient.

Deflection of the curtain might be particularly undesirable in situations with high piled stock since surfaces facing the fire might then not receive sufficient water to prevent ignition.

6. CONCLUSIONS

(1) The extent of the deflection of water curtains by cross winds can be estimated from the results and relations presented in this note.

(2) To a first approximation the deflection is proportional to wind velocity.

(3) The water distribution of the curtain is broadened when it is deflected, by the elutriating (particle sizing) action of the wind, and this reduces the rate of water falling on unit area of fuel.

(4) For a given water pressure, decreasing the nozzle diameter and hence the water flow rate gave larger deflections because of the decrease in jet momentum.

(5) For a given nozzle size the effect of water pressure on the spray deflection is very small presumably because changes in jet momentum with pressure are accompanied by changes in droplet size.

(6) Drop trajectories calculated from a simplified theory give deflections comparable with those measured, so that the experimental data can be extended to other heights of curtains. The deflection increases with increasing height of nozzle above ground.

(7) The deflection of a water curtain surrounding a well vented fire supplied from all sides with air within a large building would be too small to significantly affect the wetting down action of the curtain.

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*Theoretical water requirement to prevent ignition is $(I - 3)/260\ l\ m^{-2}s^{-1}$ where I is the incident radiant intensity in W/cm^2

(8) Restrictions placed on the air flowing to a well vented fire could lead in extreme cases to deflections which would seriously reduce the wetting down action of the curtain unless high water flow rates were used.

(9) With draughts of up to 1.2 m/s a water flow of 0.5 $l\ m^{-1} s^{-1}$ can give a sufficient width of wetted fuel 5 m below the nozzles to prevent fire spread either directly or by ignition by radiation of fuel on the far side of the curtain.

7. ACKNOWLEDGMENTS

The authors would like to thank the Lechler Apparatebau Company for supplying information on the droplet size distribution of their nozzles.

8. REFERENCES

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APPENDIX

Trajectory of a drop in a water curtain exposed to wind

We assume that the spray consists of drops all sperical and of diameter 'd' projected downwards uniformly within a wedge-shaped spray of semi-angle $\tan^{-1}\frac{1}{4}$ (measured value) with an initial vertical component of velocity of v_o. There is no interference between the drops. A horizontal wind of velocity V is maintained at right angles to the line of the curtain. Consider a drop projected vertically. Let the downward component of air velocity at a depth below the nozzle be v_a ; this is assumed constant over the cross section of the spray. Let the downward component of the velocity of a drop relative to that of the air be v at a time t after leaving the nozzle.

We assume that vertical and horizontal motions can be treated separately.

Vertical motion

The treatment of the vertical motion is similar to that of Schreiner[5] except that the allowance for momentum imparted to the air has been made in more detail, and a more accurate value for the drag coefficient has been used.

Resolving vertical forces gives

$$Mg - D = M\frac{d(v + v_a)}{dt} \qquad (1)$$

where M is the mass of the drop

g is the acceleration due to gravity

D is the drag force on the drop

$$\text{Now } D = \frac{f_c d^2 \rho_a v^2 \pi}{8} \qquad (2)$$

where f_c is the drag coefficient

and ρ_a is the density of air

For the Reynolds numbers (Re) applicable to the present situation we can take the relation between f_c and Re to be[6]

$$f_c = 15\,\text{Re}^{-0.5} \qquad (3)$$

Substituting from (2) and (3) in (1) gives

$$Mg - \frac{15\pi d v}{8}(d \rho_a \eta v)^{\frac{1}{2}} = \frac{Md(v + v_a)}{dt} \qquad (4)$$

where η is the coefficient of viscosity.

Since momentum is conserved we have

$$Q_w \; v_o \;=\; Q_w \; (v_a + v\,) + Q_a \; v_a \qquad (5)$$

where Q_w is the water flow rate per unit length of curtain

v_o is the velocity of the drop at the nozzle

Q_a is the downward mass flow rate of air per unit length of curtain, within the curtain, through a horizontal cross section at a distance h below the nozzles.

We assume vertical movement is confined to the region of the curtain, i.e. a wedge of semi-angle $\tan^{-1}\frac{1}{4}$ so that

$$Q_a = \frac{h v_a \rho_a}{2} \qquad (6)$$

has been obtained approximately for one nozzle and flow rate by first assuming that the air has no vertical motion and integrating (4) numerically with $v_a = 0$ to give drop velocity as a function of time, and secondly assuming that over short enough time intervals the air velocity v_a can be regarded as constant and equal to that given by equation (5) substituting for Q_a from equation (6).

A check can easily be made on the maximum value of v_a Equations 4, 5 and 6 can be rearranged to give

$$Mg \;-\; Av^{3/2} = M\,(v + v_a)\;\frac{d}{dh}\,(v \;+\; v_a) \qquad (7)$$

where $A = \dfrac{15\,\pi\, d^{3/2}\,(\rho_a \eta)^{\frac{1}{2}}}{8}$

and h = height

and $$\frac{2Qw}{\rho_a}\,(v_o - v_a - v) \;=\; hv_a^{\,2} \qquad (8)$$

Substituting v from (8) into (7) gives

$$\frac{Mg \;-\; A\left(v_o - v_a - \dfrac{hv_a^{\,2}\,\rho_a}{2Qw}\right)^{3/2}}{\dfrac{\rho_a M}{2Qw}\;\left(\dfrac{\rho_a h v_a^{\,2}}{2Qw} \;-\; v_o\right)} = v_a^{\,2} - 2\,hv_a\,\frac{dv_a}{dh} \qquad (9)$$

According to the approximate method v_a has a maximum value of about 2.5 m/s at a time of about 0.03s (Fig.5). Interpolation of the curve for d = 0.4 mm in Fig.4 gives h = 0.35 m for t = 0.03s and inserting h = 0.35 m and $\dfrac{d\,v_a}{d\,h} = 0$ in equation (9) gives by successive approximation $v_a = 2.54$ m/s, in good agreement with the value obtained by the approximate method.

The velocities obtained for a nozzle 3 mm (0.12 in) in diameter operated at a pressure of 17 x 10^4 N/m^2 (25 lbf/in^2) to give a flow rate of 3.2 g/s per cm length of curtain are shown in Fig.5. The droplet size distribution was assumed to be the same as that for a nozzle pressure of 2 atmospheres, close to the pressure actually used in some of these experiments, since this was known[2]. The mass median drop diameter, i.e. the diameter below which half of the mass of the spray was present, was about 0.4 mm.

Numerical integration of the curve for $v + v_a$ in Fig 5 then gives depth as a function of time.

Horizontal motion

For the horizontal movement of the drop we have:-

$$\frac{f_c \; d^2 \; \rho \; \pi \; (V-u)^2}{8} = M \frac{du}{dt}$$

where u is the horizontal velocity of the drop.

Substituting for f_c and integrating gives

$$s = Vt - A \left(\frac{tV}{tV^2 + A} \right) \qquad (10)$$

where s = the horizontal distance from nozzle travelled in time t

and $A = \dfrac{16M}{15 \pi d^{3/2} \rho_a^{\frac{1}{2}} \eta^{\frac{1}{2}}}$

Combination of vertical and horizontal distances travelled in various times leads to the trajectory shown in Fig.6. In order to gain some idea of the elutriating action of the wind the trajectories of particles of diameter 0.14 mm and 0.76 mm have been obtained in a similar manner and are also shown in Fig.6. These correspond roughly to the upper and lower deciles of the droplet distribution from nozzle F33, i.e. about 10 per cent of the mass of water is contained in drops of 0.14 mm (0.006 in) dia or smaller and 10 per cent in drops of 0.76 mm (0.03 in) dia or larger. It has been assumed in these further calculations that the air velocity was determined by momentum exchange with particles of diameter 0.4 mm.

Table 1

Nozzles, water pressures and wind speeds used in tests

Nozzle reference number	Orifice diameter	Water pressure at nozzle		Water flow rate per nozzle		Wind speed	
	mm	$N/m^2 \times 10^4$	lbf/in^2	g/s	gal/min	m/s	ft/s
F33/120	3	7	10	62	0.82	0 3.0 7.6	0 10 25
		17	25	98	1.3	0 3.0 7.6	0 10 25
F34/120	4	7	10	98	1.3	0 3.0 7.6	0 10 25
		17	25	158	2.18	0 3.0 7.6	0 10 25
Alternate F34/120 and F36/120	5 (Average)	7	10	170	2.24	0 3.0 7.6	0 10 25
		17	25	258	3.4	0 3.0 7.6	0 10 25
F36/120	6	7	10	258	3.4	0 3.0 7.6	0 10 25
		17	25	390	5.15	0 3.0 7.6	0 10 25

Table 2

Deflections produced for various nozzles,
water pressures and wind velocities

Nozzle diameter mm	Nozzle pressure		Deflection of peak of distribution for wind velocities of:				Deflection of median of distribution for wind velocities of:			
			3.0 m/s (10 ft/s)		7.6 m/s (25 ft/s)		3.0 m/s (10 ft/s)		7.6 m/s (25 ft/s)	
	N/m^2 x 10^4	lbf/in^2	m	ft	m	ft	m	ft	m	ft
3	7	10	1.5	5	2.6	8.5	1.8	6	3.7	12
	17	25	1.2	4	2.4	8	1.7	5.5	4.6	15
4	7	10	1.2	4	2.3	7.5	2.1	7	3.4	11
	17	25	1.2	4	2.1	7	1.5	5	4.0	13
4 and 6 alternately	7	10	0.8	2.5	2.1	7	0.6	2	2.4	8
	17	25	0.9	3	2.1	7	0.8	2.5	2.3	7.5
6	7	10	0.9	3	2.0	6.5	0.8	2.5	2.1	7
	17	25	0.9	3	1.8	6	0.6	2	2.1	7

Table 3

Horizontal distances travelled for vertical
fall of 2.7 m

Wind velocity m/s	Drop size (Diam) mm	Calculated distance m	Characteristic point in water distribution	Measured distance m
3.0	0.14	3.05	Lower decile	4.0
	0.40	1.40	Median	1.7
	0.76	0.41	Upper decile	0.6
7.5	0.14	7.80	Lower decile	>6
	0.40	3.80	Median	4.6
	0.76	1.30	Upper decile	2.0

Table 4. Fire spread and depth of "protected" area 5 m below nozzles

Nozzle diameter	Water pressure at nozzle		Water flow rate		No wind		1.2 m/s wind	
mm	N/m^2 x 10^4	lbf/in^2	l m^{-1} s^{-1}	gal ft^{-1} min^{-1}	Fire can spread across curtain?	Depth of "protected" area + (m)	Fire can spread across curtain?	Depth of "protected" area + (m)
3	7	10	0.20	0.8	No	2.5	Yes	0
	17	25	0.32	1.3	No	3	Yes	0
4	7	10	0.32	1.3	No	3	Yes	0
	17	25	0.52	2.2	No	3	No	2.5
4 & 6	7	10	0.56	2.2	No	3	No	3.5
	17	25	0.85	3.4	No	3	No	4
6	7	10	0.85	3.4	No	3	No	4
	17	25	1.28	5.1	No	3	No	4.5

+ Overall depth of wetted area (Fig. 4)

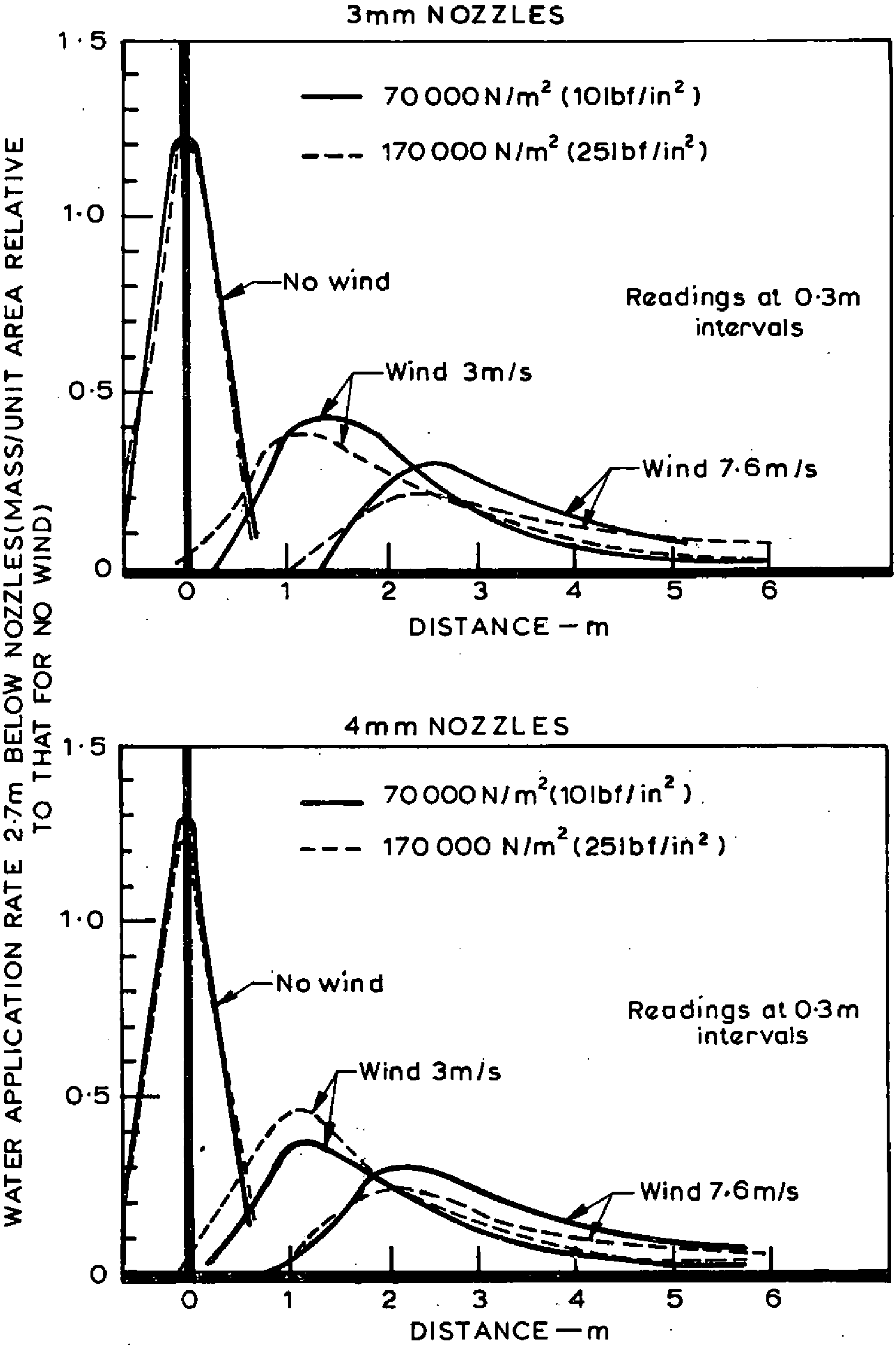

FIG.1. EFFECT OF WIND ON CURTAIN PRODUCED BY 3 and 4mm dia. NOZZLES

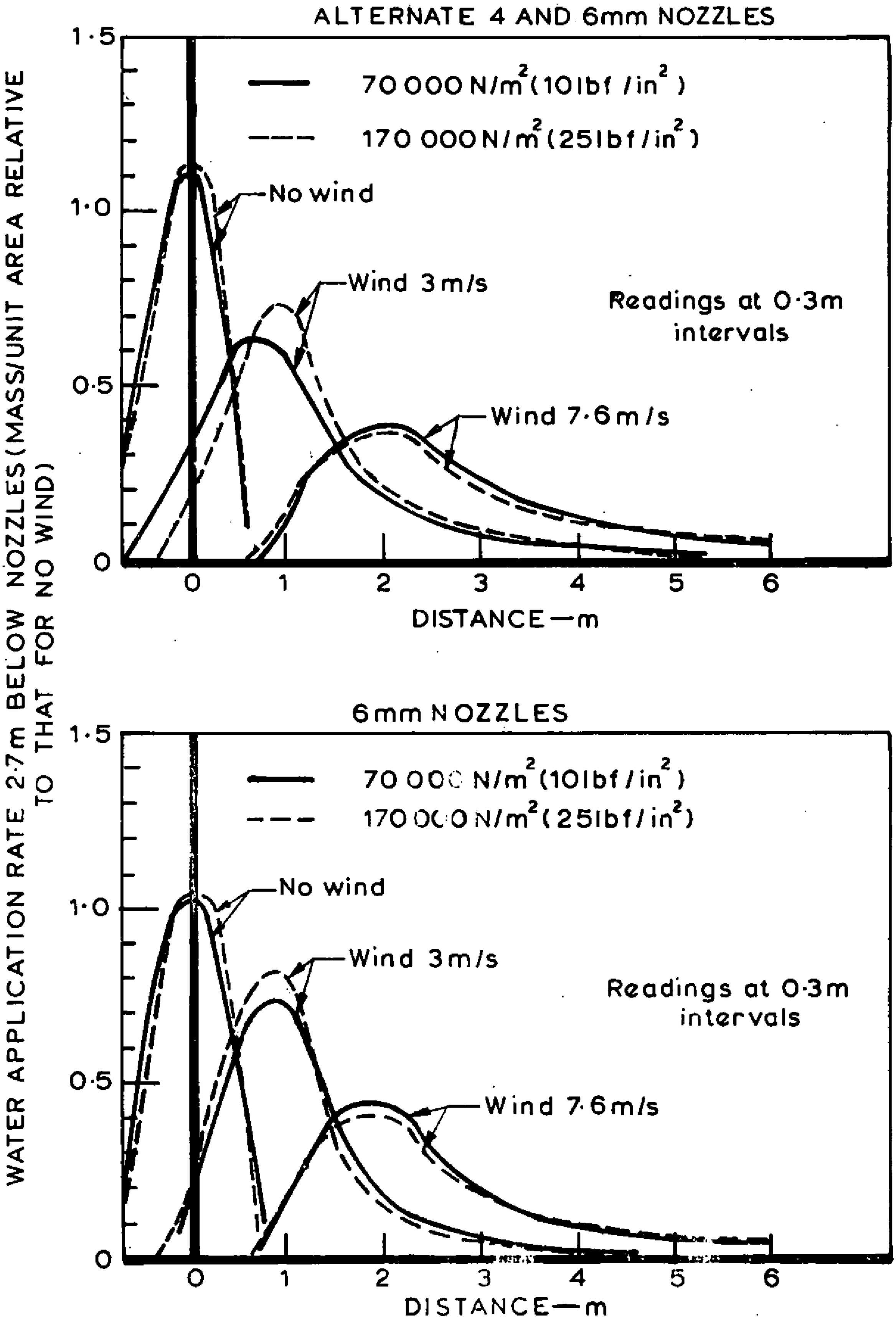

FIG. 2 EFFECT OF WIND ON CURTAIN PRODUCED BY ALTERNATE 4 AND 6mm dia. NOZZLES AND 6mm dia. NOZZLES

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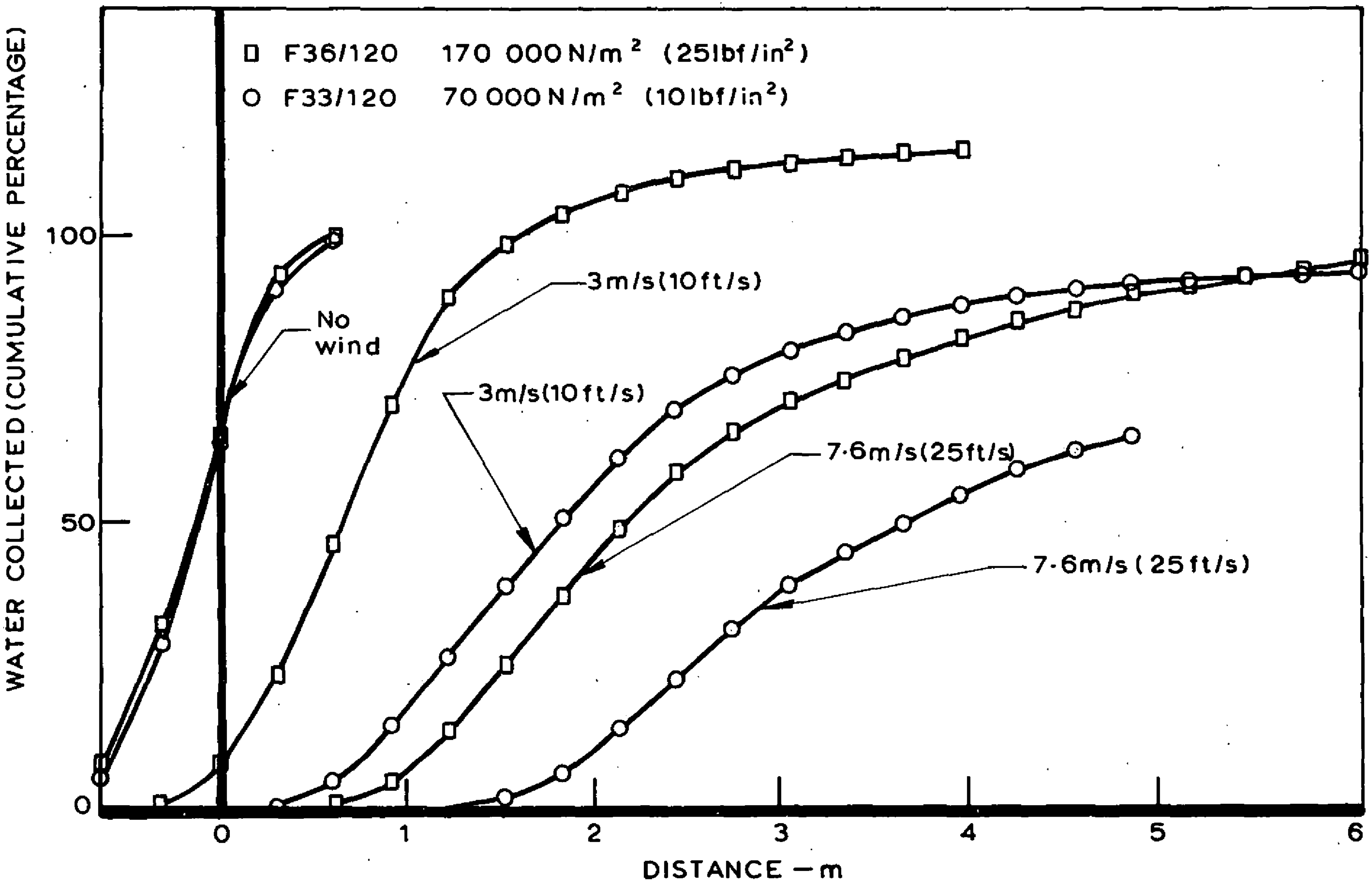


FIG.3 CUMULATIVE DISTRIBUTIONS FOR 2 NOZZLES

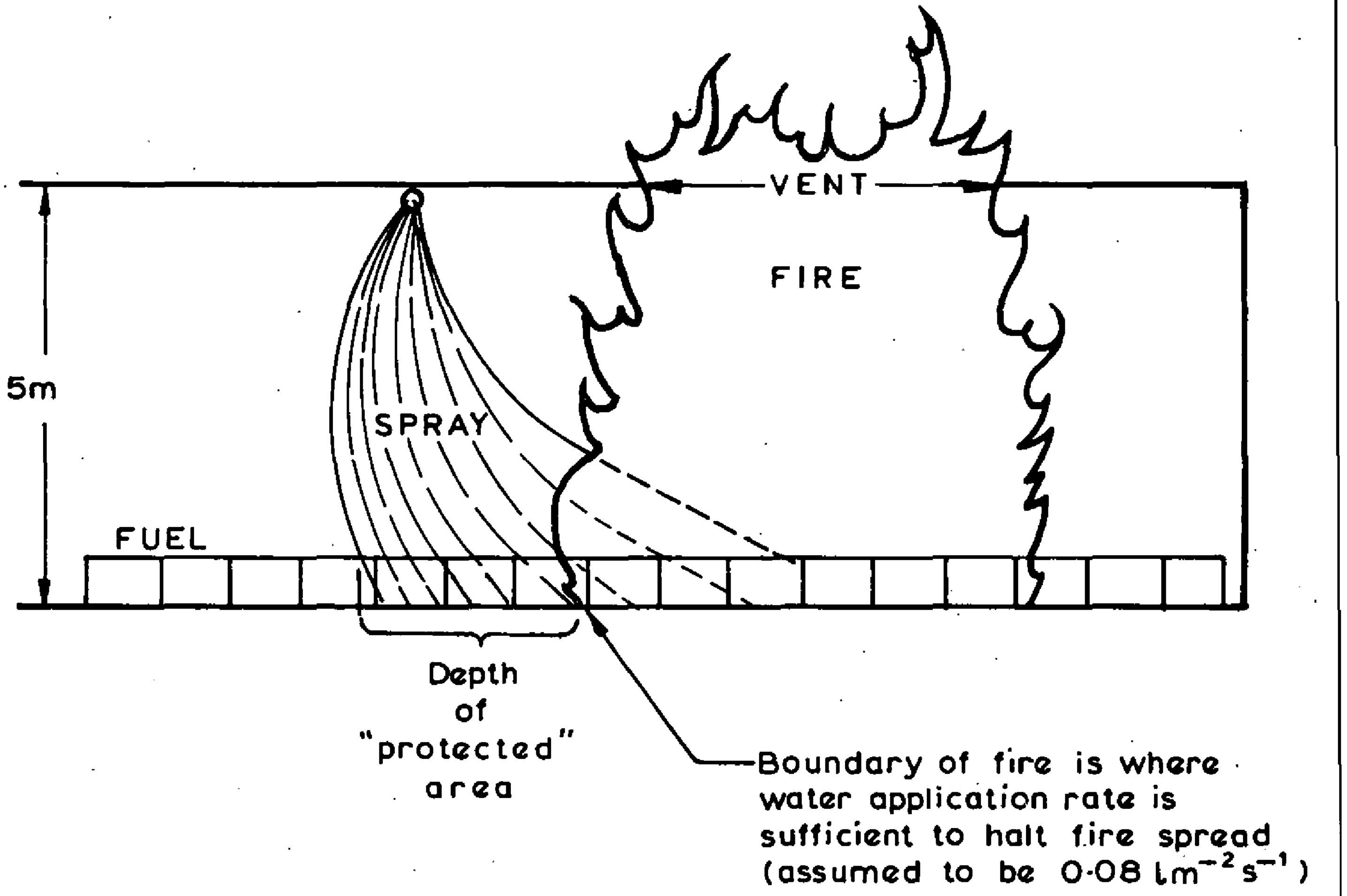


FIG. 4 DEFLECTION OF WATER CURTAIN BY WIND IN THE EXAMPLE DISCUSSED IN SECTION 5

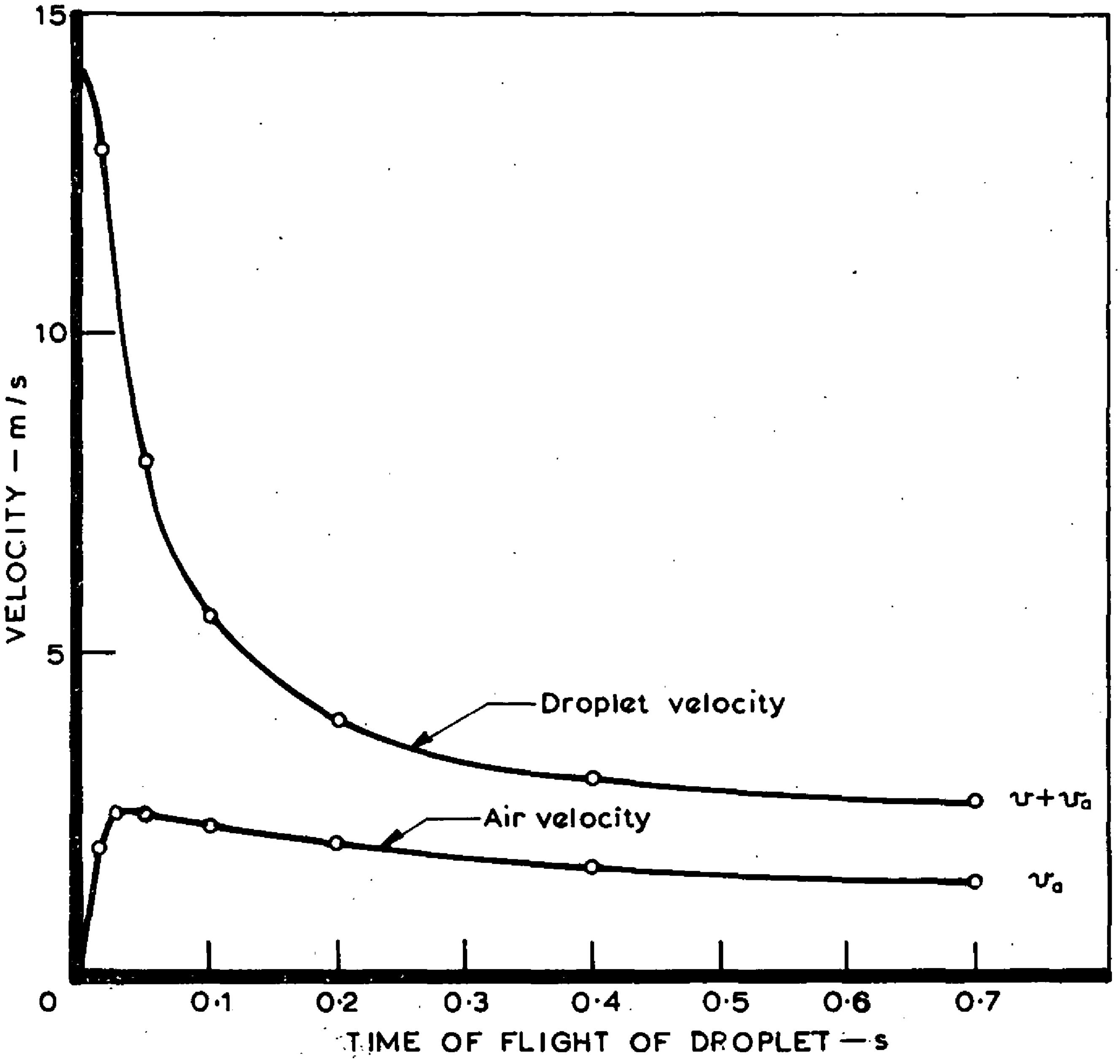
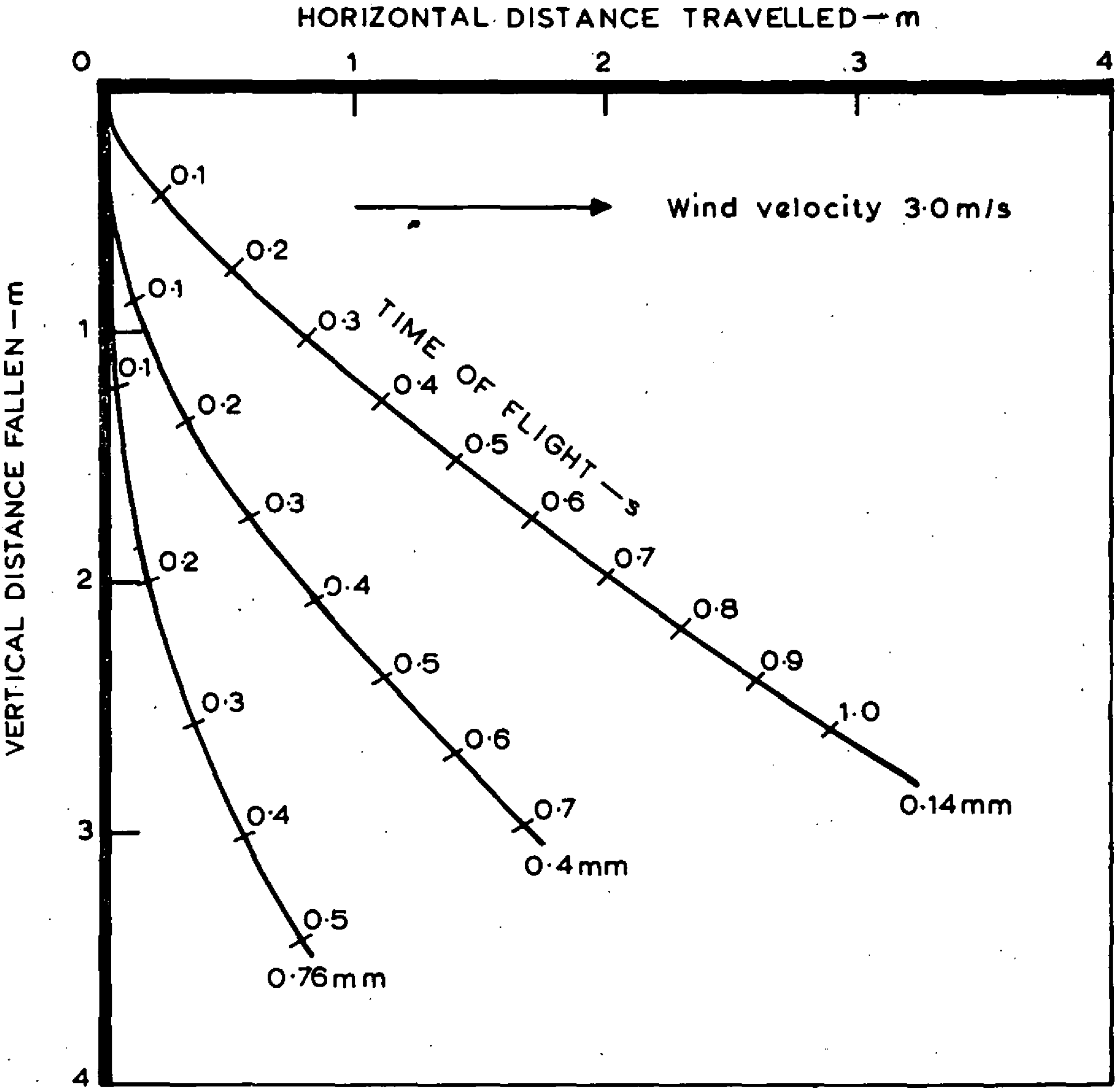


FIG.5 DOWNWARD VELOCITY COMPONENT OF 0.4mm dia. DROP AND OF AIR



Nozzles : F33/120

Nozzle pressure : 170 000 N/m^2 (25 lbf/in^2)

Nozzle diameter : 3 mm (1/8")

Flow rate : 0·32 L m^{-1} s^{-1} (1·3 gal ft^{-1} min^{-1}

FIG.6 TRAJECTORIES OF 3 SIZES OF DROPLETS IN A WIND OF 3·0 m/s