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SOME MEASUREMENTS ON THE VELOCITIES OF DROPS IN WATER SPRAYS

by

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Summary

The velocities of drops in water sprays generated by impinging jet batteries have been measured. The velocities of drops from 0.133 mm to 0.600 mm were substantially independent of the pressure at the jets and rate of flow, and the relation between drop size and velocity may be expressed by a simple equation.

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Fire Research Station,
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SOME MEASUREMENTS ON THE VELOCITIES OF DROPS IN WATER SPRAYS

Introduction

A method for determining the velocities of drops comprising a water spray has been described in a recent note (1). The present note describes the results obtained with sprays projected downwards from batteries of impinging jets as used in the study of the extinction of kerosine fires by water sprays. (2). The influence of the properties of the sprays on the drop velocities obtained is discussed.

Experimental

The water sprays used were projected downwards from two batteries of impinging jets of 3/64 in. bore, arranged symmetrically on either side of the axis of a 30 cm. diameter combustion vessel and 175 cm. above the liquid level in the vessel. The water pressure at the jets could be varied and the rate of flow to the combustion vessel at any selected pressure could be controlled by varying the number of pairs of impinging jets in operation. A full description of the apparatus is given elsewhere (2).

Drop velocities were measured at a point 30 cm. above the liquid level in, and on the axis of, the combustion vessel in sprays produced at nozzle pressures of 5, 10, 30 and 85 Lb/in^2, and at flow rates of 0.4, 0.6, 0.8 and 1.2 $g.cm^{-2}min^{-1}$. Not less than three samples of spray were collected in the drop velocity apparatus, described elsewhere (1), for each of the sixteen sprays. The velocity of the air entrained by each spray was measured at the sampling point (2).

Results

The velocities measured with the apparatus were the "absolute velocities" of the drops, i.e. the velocities relative to the nozzle, which is the velocity of the air stream (entrained air velocity), plus the velocities of the drops relative to the air stream (relative velocity). The entrained air velocity for each spray, and the relative velocities of drops of different mean diameters, corrected for deceleration in the sampling apparatus, (see Appendix) are given in Table 1. At the foot of Table 1, the number of samples, N, and the number of drops, n, in each size group is also given. The drop velocities were obtained from the combined test results for each spray. Two sets of figures are given for the spray at 10 Lb/in^2 and 0.4 $gm.cm^{-2}min^{-1}$, because two series of tests were made under different conditions which resulted in appreciably different entrained air velocities, and the correction applied for deceleration in the sampling apparatus is dependent on the absolute velocity of the drops.

Analysis of Variance. Effect of pressure and flow rate. For a valid analysis of variance, the criteria are that the equivalent samples are drawn from populations of the same variance and the values of the samples are independent of each other. The first condition was approximated to by obtaining the mean velocities for each drop size from the first three spray samples for each level of pressure and flow rate. It was observed, however, that the velocities of drops of different diameters in a spray sample were not independent of each other, i.e., the velocities of drops of different diameters in one sample of a group of three all tended to deviate in the same way from the respective mean velocities for that group, and so a valid analysis of variance for the effect of drop size on velocity could not be made.

Analyses of variance were therefore made on the effect of pressure and flow rate on the absolute and relative velocities of the drops separately for each drop diameter from 0.133 to 0.400 mm., the range for which complete figures were available. The data on which the analyses were made are given in Table 2, and the results of the analyses in Table 3.

The effect of flow rate on absolute velocity was significant to the 5 per cent level for drops of 0.133 and 0.200 mm dia., and that of pressure significant for drops up to 0.333 mm dia. Neither pressure nor flow rate were significant in their effect on relative drop velocity for any drop size analysed.

Effect of pressure and flow-rate drops larger than 0.400 mm diameter. The effect of pressure and flow rate on the velocities of drops greater than 0.400 mm diameter could not be estimated by analyses of variance because the data were incomplete. No regular variation of relative velocity with either rate of flow or pressure was however apparent (Table 1), although the velocity of 0.600 mm drops at 85 Lb/in^2 was appreciably higher than their velocities at lower pressures and so it was assumed that, as far as the present experiments were concerned, the relative velocities of drops greater than 0.400 mm diameter were independent of flow rate and pressure.

Relation between relative drop velocity and drop diameter. Because of the independence of relative velocity on pressure or flow rate, it was thought reasonable to sum the velocities at each pressure and flow rate for each drop size. The first part of Table 4 gives the arithmetic mean of the relative velocities for each sample for each drop size, $\bar{V}$, after applying the correction for deceleration in the sampling apparatus. It has been shown elsewhere (1) that the number of drops captured had a direct bearing on the accuracy of the estimate of drop velocity and thus a more accurate estimate of velocity on summing over different conditions would be obtained by weighting the velocities for each sample for the number of drops captured. This weighted mean velocity V_n is given in the second part of Table 4. The standard deviation for each mean velocity is also given in Table 4, together with the standard error and 95 per cent confidence limits of the weighted mean velocity.

The weighted mean velocity, $\bar{V}_n$, has been plotted against drop diameter in Fig. 1. A regression analysis on these velocities and zero velocity for zero diameter gave the relation below, the first two terms of which were highly significant.

$$V = 402D + 319D^2 + 819D^3$$

where V = relative velocity, cm/sec.
D = drop diameter mm.

Theoretical calculation of relative drop velocity. An estimate may be made of the relative velocities of drops in a spray at a plane below the nozzle by calculating the final velocity of single drops falling an equivalent distance in still air (Appendix). Curves 1, 2, 3 and 4 in Fig. 2 show the relation between velocity in a plane 145 cm. below the point of projection and drop diameter for drops, falling downwards in still air, with initial velocities of 2300, 1400. 800 and 600 cm/sec, the calculated downward velocities of projection from the impinging jet batteries at 85, 30, 10 and 5 Lb/in^2 respectively. From these curves, the mean theoretical velocities, weighted for the number of drops captured at each pressure, were calculated from the experimental data for each drop size and plotted in Fig. 2. The best curve (curve 6) was drawn for these velocities for drops up to 0.600 mm diameter, the largest diameter for which an adequate number of drops were captured at all four pressures. The regression curve from Fig. 1, curve 7, and the 95 per cent confidence limits of the weighted mean velocity (Table 4) for each drop diameter and the curve for the terminal velocity of drops in still air, Curve 5, are included in Fig. 2 for purposes of comparison.

Discussion

When a spray cloud is projected into space, the drops decelerate from their initial velocity, imparting energy to the air through which they pass which appears as an air current associated with the spray cloud. It was found (2) for the system of spray generation used in the present experiments that the velocity of the air current is proportional to the square root of the flow rate and the cube root of the pressure of generation of the spray.

Relative velocity. The calculated relative velocity of drops, curve 6, Fig.2, was less than the directly determined experimental velocity, curve 7; this was probably due to over-estimation of the distance of fall. Since there was an air current accompanying the spray, drops falling 145 cm. in space fell a shorter distance relative to the air current, and therefore would have had a higher velocity than that calculated for 145 cm. fall in still air.

The analysis of variance for relative velocity, Table 3, showed that for drops of up to 0.400 mm. diameter the velocity was not significantly dependent on pressure or rate of flow. Curve 6 shows only a small deviation from terminal velocity for drops of 0.400 mm. diameter due only to the results for drops generated at 85 Lb/in^2 nozzle pressure, smaller sized drops being at their terminal velocity. Since the terminal velocity of drops is independent of the pressure of generation, no significance of the effect of pressure on this group of drops would be expected. It has been shown elsewhere that the mass median drop size of a spray from the system used is proportional to the seventh root of the flow rate (3); the coalescence of drops producing this effect would be expected to reduce the velocity of drops of a given diameter as rate of flow increased. The effect however would be small and the differences in velocity that would be so produced fall within the 95 per cent confidence limits of the measured velocities, and therefore would not be expected to be found significant.

Pressure would however be expected to influence the velocity of drops greater than 0.400 mm dia., the effect increasing as drop size increased. Curves 1, 2, 3 and 4, Fig. 2, show that the calculated velocity of drops of 0.467 to 0.800 mm diameter would not be expected to show differences in velocity between nozzle pressures of 5 and 10 Lb/in^2, their velocities being at, or close to, terminal values. But a significant increase in velocity would be expected to be found between pressures of 10 and 30 Lb/in^2 and 30 and 85 Lb/in^2 the increase between 30 and 85 Lb/in^2 being the greater.

An estimate has been made of the range of 95 per cent confidence limits for deviations in drop velocity at a given pressure for drops of 0.467 to 0.800 mm. dia. from the data in Table 1; this is presented in Table 5, together with the relevant expected range of velocity between pressures of 5 and 85Lb/in^2 (curves 1 and 4, Fig. 2). The data indicate that while no differences between drop velocities at 85 Lb/in^2 and lower pressures would be expected to be significant for drops of from 0.667 to 0.800 mm. dia., the velocities at 85 Lb/in^2 for drops of 0.467 to 0.600 mm. dia. would be expected to be found significantly greater than their respective velocities at lower pressures. However, such a significant effect was found for 0.600 mm dia. drops only at 85 Lb/in^2. This may have been due to several factors, the most likely of which were the small size of the sample, errors in the apparatus, and the effect of turbulence in the spray cloud.

A detailed examination of the results for the 0.467 and 0.533 mm diameter drops showed that the low drop velocities at nozzle pressures of 85 Lb/in^2 were caused by the capture of abnormally high numbers of slow moving drops in one sample, and by the capture of a single drop of abnormally low velocity on another. The former anomalous result may be attributed to turbulence in the spray cloud, and the latter to the capture of a drop falling from the sampling apparatus on to the sample slide. The collection of a larger number of samples, and hence, a larger number of drops, would be expected to reduce deviations due to such causes.

It was observed during these experiments that back-spray from the impinging jets collected on the jet batteries and fell as large drops into the downward projected spray. The trend observed for the relative velocities of spray drops of 0.667 to 0.800 mm. to show a decreasing rate of increase with drop diameter, Fig. 1, may therefore have been due to drips of water from the impinging jet batteries. Further break-up of these drops would be expected to occur, but the size of the resultant drops would still be large, and their velocities low. The presence of such large drops in the spray captured in a sample would therefore lower the average velocity of their drop size.

Absolute velocity. The absolute velocity of the drops would be expected to increase as either pressure or flow rate increased, because of the dependence of the velocity of the air current, and also, of the relative velocity of the drops of diameters of 0.400 mm or more on pressure and flow rate. The analyses of variance showed such dependence to be significant for pressure up to diameter 0.333, and for flow rate for the first two diameters, 0.133, and 0.200 mm only. The mean square column in Table 3 shows that the bulk of the residual variance was associated with the relative drop velocity. This residual variance increased with increasing drop diameter and decreasing number of drops in samples, resulting in a reduction in significance as drop diameter increased, although a dependence of absolute drop velocity on pressure may have existed.

Conclusions. The measurement of drop velocities in a spray by the method described in this note has shown that, for the apparatus and sprays used, the velocities relative to the air current of drops up to 0.600 mm. diameter were substantially independent of the pressure at the jets and of the flow rate at the sampling point, although an increase of velocity as pressure increased from 10 to 85 Lb/in^2 would be expected. The velocities of drops up to 0.600 mm diameter may be calculated from the equation

$$V = 402D + 319D^2 + 819D^3$$

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References.

(1) F. R. Note No. 175, 1955. D. J. Rasbash and G.W.V. Stark.
(2) F. R. Note No. 58, 1953. D. J. Rasbash and Z. W. Rogowski.
(3) F. R. Note No. 181, 1955. D. J. Rasbash.

Appendix

The deceleration of a falling drop

The range of drop diameters investigated is covered by the intermediate law for deceleration in still air (1) from which is obtained

Now $$F = \frac{18{\cdot}5\eta^{0{\cdot}6}\ \rho_g\ V^2\ \pi\ D^2}{8(D\ V\ \rho_g)^{0{\cdot}6}}$$

Mass x acceleration = force due to gravity - frictional force and therefore

$$\frac{\pi\ D^3.\ (\rho_s-\rho_g)}{6}\, a = \frac{\pi\ D^3\ (\rho_s-\rho_g)}{6}\, g - \frac{18{\cdot}5\ \pi\ D^2\eta^{0{\cdot}6}\ \rho_g\ V^2}{8\ (D\ V\ \rho_g)^{0{\cdot}6}}$$

Putting $\rho_s - \rho_g = \rho_s$ and inserting appropriate values for η, ρ_s and ρ_g

$$a = g - 0.00539\,\frac{V^{1{\cdot}4}}{D^{1{\cdot}6}}$$

From this equation the decrease in velocity of a drop falling a given distance may be found for different initial velocities, the assumption being made that no evaporation occurs, and the drop size remains constant. In Fig.2 curves 1, 2, 3 and 4 are the relations between drop diameter and final velocity for drops falling 145 cm. in still air with initial downward velocities equal to the calculated downward velocities of spray from the impinging jet batteries operating at 85, 30, 10 and 5 Lb/in^2 respectively. In Fig. 3 a family of curves has been plotted of the reduction in velocity, ΔV, in falling the mean distance, 1.5 cm., in the sampling apparatus, against the velocity after falling that distance, (the measured velocity V). In applying this correction to the measured velocities, it is thus assumed that the drops of a given diameter are uniformly distributed in space.

(1) Perry. Chemical Engineers' Handbook. McGraw Hill Book Co., London.

Symbols

a = acceleration, LT^{-2}
C = drag coefficient, dimensionless
D = Drop diameter, L
F = frictional force, MLT^{-2}
g = acceleration due to gravity, LT^{-2}
$\underline{V}$ = relative drop velocity, LT^{-1}
$\bar{V}$ = mean relative drop velocity, LT^{-1}
$\bar{V}_n$ = mean relative drop velocity weighted for number of drops captured, LT^{-1}
n = number of drops,
N = number of samples,
η = viscosity, $ML^{-1}T^{-1}$
ρ_g = density of air ML^{-3}
ρ_s = density of drop. ML^{-3}

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TABLE I

THE RELATIVE VELOCITY OF DROPS CORRECTED FOR DECELERATION IN SAMPLING APPARATUS

Pressure Lb/in^2	Flow Rate $g\ cm^{-2}\ min^{-1}$	DROP DIAMETER - mm																						Entrained Air Velocity cm/s
		0·133		0·200		0·267		0·333		0·400		0·467		0·533		0·600		0·667		0·733		0·800		
		Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	Velocity cm/s	No. of Drops	
5	0·4	82	552	118	256	166	183	222	140	380	65	354	34	444	36	633	11	366	11	656	6	647	5	52
	0·6	-70	304	185	50	135	39	285	17	378	17													70
	0·8	82	212	189	81	147	73	254	50	329	21	394	16	420	12	576	15	1261	2	551	2	1258	1	99
	1·2	44	603	200	227	142	172	168	74	230	28	161	37	250	19	263	6	357	4	143	2	1200	1	157
10	0·4	143	291	155	125	177	66	235	40	264	32	129	8	813	8	628	7	1285	3					75
	0·4	-23	857	68	215	115	152	173	105	234	62	258	23	294	15	323	10	657	7	1291	8			67
	0·6	-91	546	156	116	446	67	389	28	415	14													94
	0·8	136	531	143	190	140	98	91	49	398	31	317	10	329	7	137	8	451	2	217	2	216	1	143
	1·2	159	625	175	224	190	191	303	93	338	32	296	21	375	11	590	12	1221	6	1219	1	1218	1	200
30	0·4	98	3618	131	1359	178	641	250	247	348	82	179	33	820	10	700	5	772	10	603	9	699	4	139
	0·6	62	1943	93	889	138	617	233	268	421	90	457	34	586	31	489	19							180
	0·8	92	1480	219	448	260	204	285	59	398	30													174
	1·2	20	4070	137	982	176	488	259	277	346	104	380	58	456	29	695	5	572	6	1097	1	1096	1	261
85	0·4	148	247	178	103	218	80	247	39	370	26	539	11	1178	2	1175	4							186
	0·6	33	2185	112	568	147	234	247	89	240	22	151	3	31	2									273
	0·8	87	4625	69	2130	73	675	133	298	130	125	356	27	164	8	1134	2							227
	1·2	9	7449	37	2031	69	1111	134	335	240	161	159	56	328	24	650	5	117	1					301
N Σn		97 30138		97 9994		97 5091		97 2208		95 942		82 371		71 214		50 109		35 52		17 31		9 14		

TABLE 2

The Absolute and Relative Velocities of Drops in a Spray
(Velocities corrected for deceleration in apparatus)

Mean of velocities from three samples

Pressure (lb/in^{-2})	Rate of Flow $g.cm^{-2}min^{-1}$	Absolute Velocity, (cm/s)					Relative Velocity (cm/s)				
		Mean Drop Diameter (mm)					Mean drop diameter (mm)				
		0.133	0.200	0.267	0.333	0.400	0.133	0.200	0.267	0.333	0.400
5	0.4	111	191	295	398	609	59	139	243	346	557
	0.6	20	311	287	347	487	-50	241	217	277	417
	0.8	175	278	252	390	489	76	179	153	291	390
	1.2	216	276	311	350	408	59	119	154	193	251
10	0.4	162	181	260	360	335	87	106	185	285	260
	0.6	17	218	372	538	560	-77	124	278	444	466
	0.8	279	268	268	281	565	136	125	125	138	422
	1.2	380	386	389	483	585	180	186	189	283	385
30	0.4	260	341	358	419	466	121	202	219	280	327
	0.6	236	316	333	408	664	56	136	153	228	484
	0.8	271	395	447	494	594	97	221	273	320	420
	1.2	263	483	521	567	843	2	222	260	306	582
85	0.4	331	300	405	586	696	145	114	219	400	510
	0.6	303	388	435	592	517	30	115	162	319	244
	0.8	340	330	416	498	546	113	103	189	271	319
	1.2	298	414	464	569	693	-3	113	163	268	392

TABLE 3.

The effect of rate of flow and nozzle pressure on velocity of drops in a spray
(Velocity corrected for deceleration in apparatus)

ANALYSIS OF VARIANCE

Drop diameter mm	Source of variance	Absolute Velocity					Relative Velocity				
		Sum of squares	Degrees of freedom	Mean square	Variance ratio	Significance per cent	Sum of squares	Degrees of freedom	Mean square	Variance ratio	Significance per cent
0.133	Pressure	75263	3	25088	4.8	4	4668	3	1556	0.4	>20
	Rate of flow	49646	3	16549	31.4	< 1	35103	3	11701	3.0	10
	Residual	47407	9	5267			35319	9	3924		
	Total	172316	15				75090	15			
0.200	Pressure	47338	3	15779	7.6	1	16461	3	5487	3.1	10
	Rate of flow	37734	3	12578	6.1	1	1589	3	530	0.3	>20
	Residual	18625	9	2069			15784	9	1754		
	Total	103697	15				33834	15			
0.267	Pressure	58871	3	19624	8.7	1	4262	3	1421	0.5	>20
	Rate of flow	19388	3	6463	2.9	10	2282	3	761	0.3	>20
	Residual	20458	9	2262			26387	9	2932		
	Total	98717	15				32931	15			
0.333	Pressure	80610	3	26870	4.7	4	3292	3	1097	0.2	>20
	Rate of flow	13581	3	4527	0.8	> 20	16536	3	5512	0.8	>20
	Residual	51291	9	5699			58662	9	6518		
	Total	145482	15				78490	15			
0.400	Pressure	62139	3	20713	1.3	20	17035	3	5678	0.4	>20
	Rate of flow	25351	3	8450	0.6	>20	1342	3	447	0.1	>20
	Residual	138199	9	15355			142455	9	15828		
	Total	225689	15				160832	15			

TABLE 4

The Means and Standard Deviations of Calculated Relative Velocities

	Mean Drop Diameter mm										
	0.133	0.200	0.267	0.333	0.400	0.467	0.533	0.600	0.667	0.733	0.800
Mean Velocity, $\bar{V}$ cm/sec.	59.5	139.1	171,9	229.9	321.1	295.0	463.3	614.8	705.9	722.1	904.8
Standard Deviation, cm/sec.	73.4	51.1	84.3	72.8	83.0	127.1	300.3	296.4	419.3	439.1	364.6
Weighted Mean Velocity, $\bar{V}_w$ cm/sec.	49.2	101.7	137.3	208.8	297.8	293.9	445.0	545.6	704.5	768.7	787.1
Standard Deviation, cm/sec.	48.6	50.8	63.0	61.6	91.8	114.0	165.3	217.4	319.9	378.7	294.7
Standard Error, cm/sec.	4.9	5.2	6.4	6.3	9.4	12.6	16.5	30.7	54.1	92.0	98.2
95 per cent confidence limits of mean cm/sec.	9.8	10.3	12.7	12.5	18.7	25.2	33.0	61.7	109.8	194.0	227.0

Table 5

Within pressure variation of weighted mean drop velocity V_n

Estimated Standard errors and confidence limits for drops greater than 0.400 mm dia.

	Mean Drop Diameter, mm					
	0.467	0.533	0.600	0.667	0.733	0.800
Standard error of within pressure variation (cm/sec)	25	39	61	94	159	171
Range of 95 per cent Confidence Limits (cm/sec)	106	166	264	412	854	1466
Maximum Expected Range of Velocity (cm/sec.) (Curves 1 and 4, Fig. 6.)	310	520	735	310	390	445

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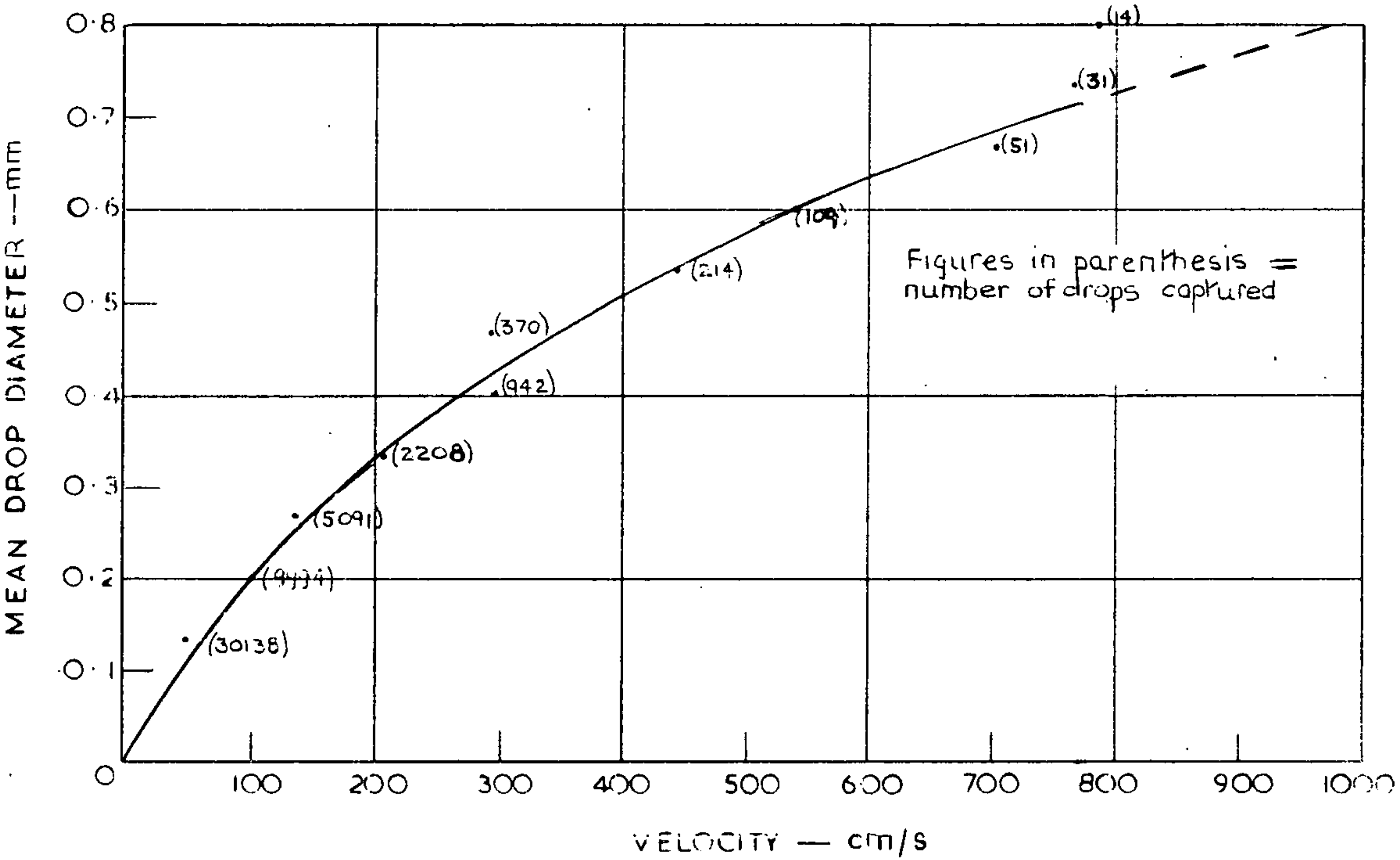

FIG 1 THE RELATIVE VELOCITY OF DROPS IN IMPINGING JET SPRAYS.
MEASURED 145cm BELOW THE JET BATTERIES.
REGRESSION CURVE & EXPERIMENTAL POINTS (WEIGHTED MEAN VELOCITY)

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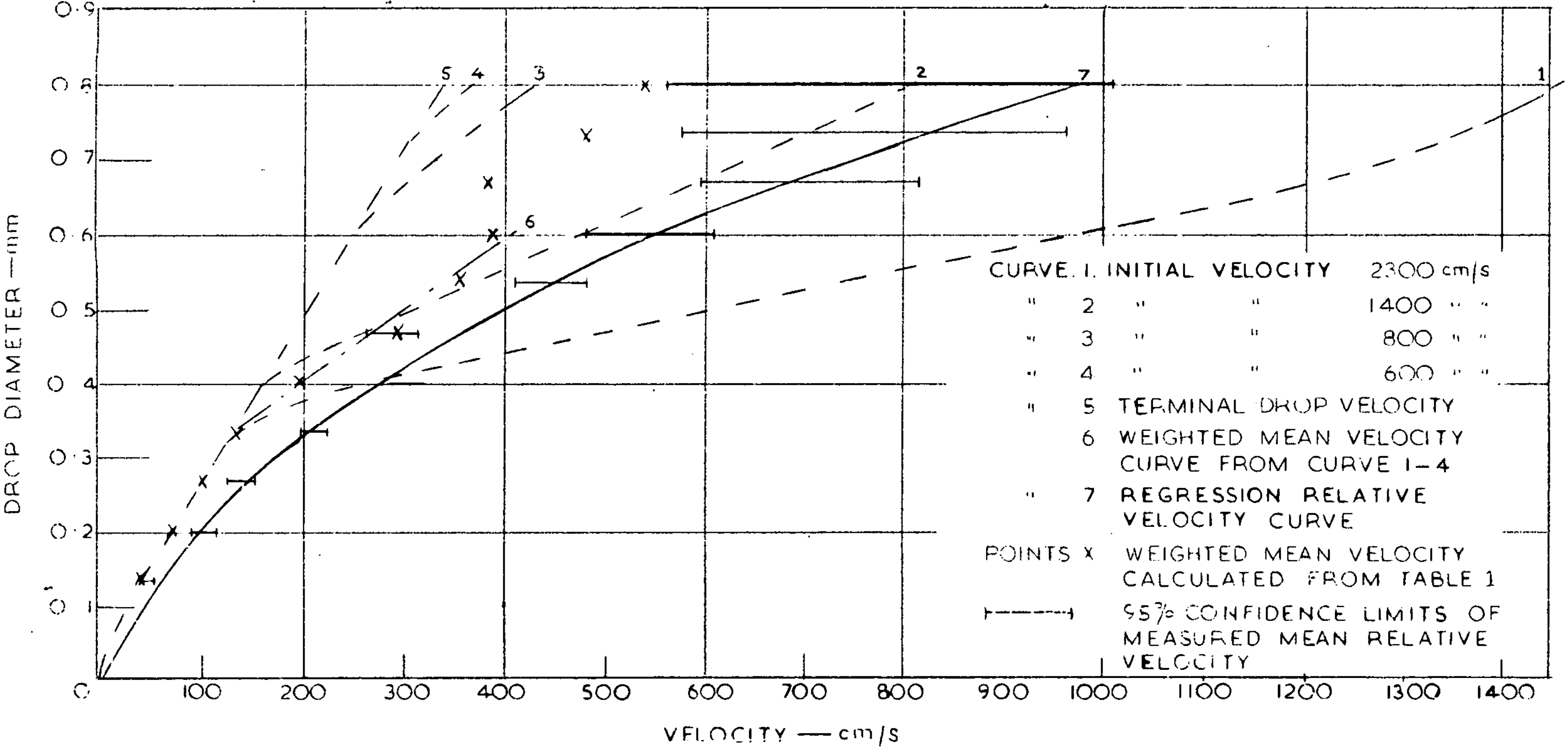

FIG. 2. VELOCITY OF DROPS AFTER FALLING 145 cm. IN STILL AIR

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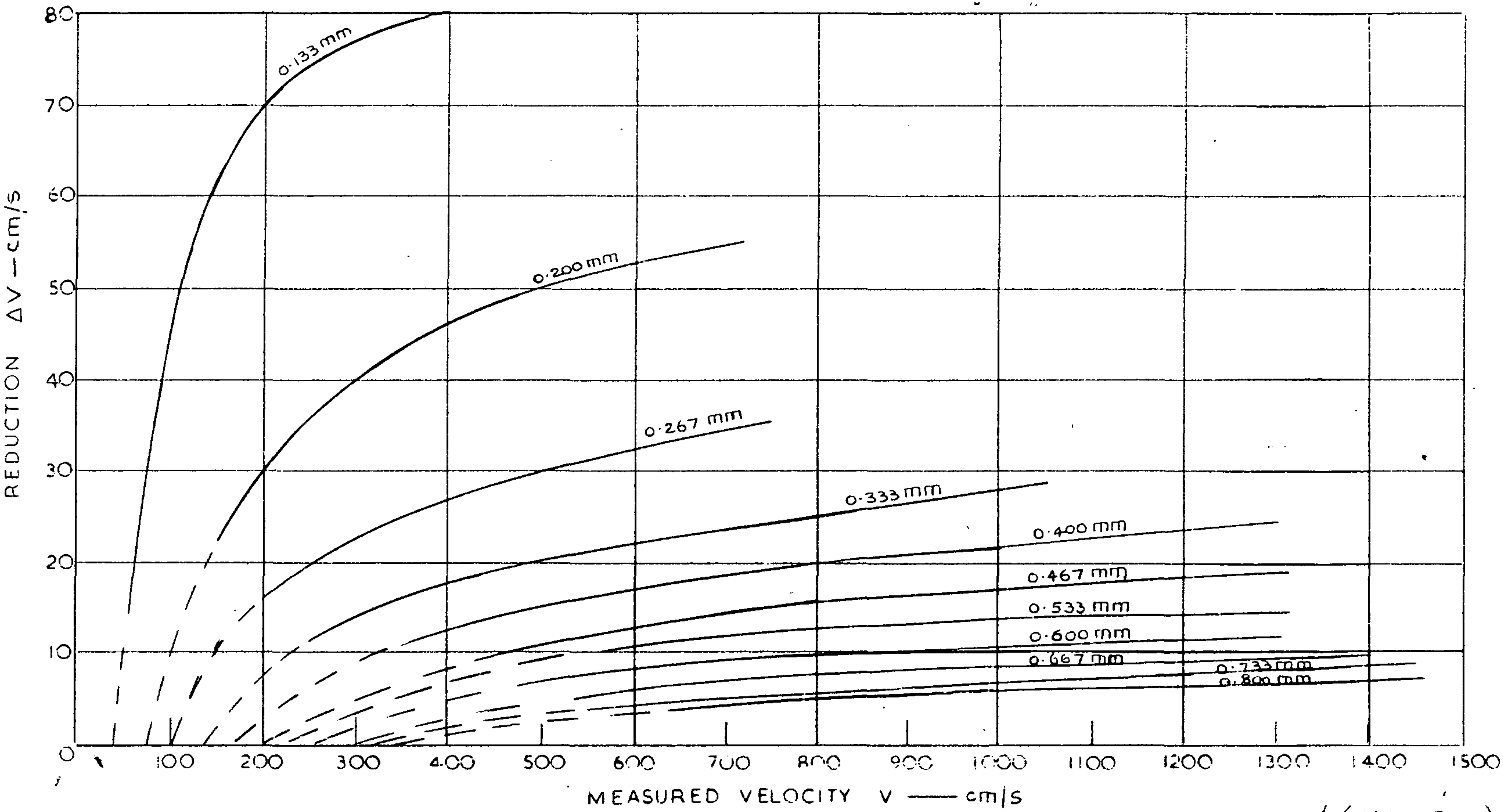

FIG.3. THE LOSS IN VELOCITY OF DROPS IN SAMPLING APPARATUS (MEAN FALL 1·5 cm)