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THE FUNDAMENTAL STUDY OF FLAME ARRESTERS

1. Wire gauze arresters in a short narrow tube.

by

K. N. Palmer

SUMMARY

The performance of wire gauzes as flame arresters for gas explosions in a short tubing system has been studied. The gauzes were mounted inside the tube, which was straight and was held vertically, and flammable mixtures containing propane, ethylene, or Town's gas were passed into the tube and then ignited at the open end. The velocity of the flame that was just quenched by a single gauze was approximately inversely proportional to the width of the mesh of the gauze. Tests were also made with packs of coarse gauzes and combinations of coarse and fine gauzes. Some theoretical considerations are given.

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INTRODUCTION

Flame arresters are devices which are able to prevent or quench the passage of flame; their main use is in industrial plant for preventing the propagation of explosion through combustible gas mixtures in ducts or other systems. A single layer or a pack of wire gauze are common and cheap forms of flame arrester, but they suffer from the disadvantage that gauze is flimsy and so the possibility of accidental damage is a serious risk with this type of arrester. Another common type of arrester, which is more robust, consists of a crimped and a flat metal ribbon wound concentrically to give an array of cells of triangular cross-section. These arresters are more able to withstand flames burning continuously on them than are gauze arresters. Other types of flame arrester include beds of pebbles or Raschig rings, ball bearings, sintered metal discs, and closely spaced metal plates.

Although flame arresters of various types have been used for a considerable time, as in the Davy safety lamp, a recent review(1) showed that often their use is on an empirical basis without any definite knowledge of the capabilities and limitations of the arresters. The early work on arresters was concerned with the quenching of methane/air explosions in coal mining, with particular emphasis on the development of safety lamps and flame-proof apparatus. Statham and Wheeler(2) studied the possibility of using perforated plates and batteries of parallel metal rings (ring reliefs) to prevent explosions propagating out of vented flame-proof apparatus. They showed that with perforations of a given size the resistance of perforated plates to the passage of flame decreased as the area of the plate was increased. With ring reliefs they found that the most important factor for the passage of flame was the width of the gap between consecutive rings. They also recommended that the minimum width of the rings should be 1.5 inches. Minchin(3) studied the passage of coal gas flames through perforated plates and concluded that the efficiency of this type of arrester was reduced if the holes were closely spaced. He suggested that some of the heat loss by a flamelet in a plate perforation was the result of radiation, and he gave a correlation between a factor derived from the radiation received by neighbouring flamelets and the performance of the plate in quenching flames.

Wire gauze arresters are often installed in the vent pipes of petroleum storage tanks and they have also been used to quench flames issuing from vents during oil mist/air explosions in engine crankcases. Lamb(4) and Freeston, Roberts and Thomas(5) showed that packs containing several layers of 20- or 40- mesh gauze were capable of preventing the flames of oil mist explosions in large vessels from passing through vents into the surrounding atmosphere. Mansfield(6) showed in smaller scale Town's gas/air explosions that gauzes wetted with oil could be more effective flame arresters than the same gauzes when dry. The Home Office Miners Lamps Committee(7) considered the passage of methane/air explosions through wire gauze and correlated the distance of travel of the flame to the gauze with the Safety Number (S). S was defined by the relation

$$S = \frac{nd}{a^2}$$ where n = number of apertures, d = diameter of the wire,

and a = area of hole per unit area of gauze. The Committee also investigated

the passage of flame through perforated plates[8]. Later work on methane/air explosions in pipes was carried out by Loison, Chaineaux, and Delclaux[9] using a flame arrester consisting of a pile of plates having their planes parallel to the axis of the pipe. The arrester was attached 10 m. from the closed end of a pipeline 25 cm. in diameter, and a further 18 m. of pipeline were connected to the other side of the arrester and terminated at vents whose diameters ranged from nil to that of the pipe; ignition was at the permanently closed end of the pipeline. Counts were then made of the percentages of trials in which the flame passed the arrester. Maas and Quaden[10] studied the behaviour of crimped ribbon arresters mounted in pipelines up to 25 m. in length and of 5 cm. diameter. The fuels used were coal gas and a methane/hydrogen mixture, with air as supporter, and both quiescent and flowing gas mixtures were tested. Observations were then made of whether or not the explosion passed the arrester; in no case did the arrester fail the first time that it was used although in the presence of flames accompanied by high pressure waves (probably detonations) the arresters failed on the second exposure.

Sintered metal arresters have been described by Egerton, Everett, and Moore[11]; they used hydrogen and methane as fuels, with oxygen as supporter, and the mixtures were initially at sub-atmospheric pressures. The sintered metals were found to be more effective against hydrogen/oxygen than against methane/oxygen flames, and the efficiency of the arrester could not be correlated with its porosity. Perforated plates were much less efficient than the sintered metal discs. The efficiency of the sintered metal arresters was appreciably reduced by combining two so that the rough faces were in contact; the drop in efficiency was believed to be due to the ignition of small pockets of gas trapped between the arresters.

A system of pebble bed arresters and vents suitable for insertion in petroleum pipelines was described by Radier[12], but the extent to which it had been tested was not made clear.

Although experimental information is available on most types of arrester there has been very little fundamental work to relate the performance and properties of the arresters with the properties of the flames, the nature of the explosive gas mixtures, and the dimensions of the systems in which the arresters were installed. Also there is insufficient information to enable safe values of the dimensions of the passages through the arresters to be correlated with such fundamental properties of the gas mixtures as the quenching distances and the laminar burning velocities, about which a considerable amount of information is available[1]. Finally, in a substantial part of the work so far published, the combustible mixture used was methane/air and as explosions in this mixture are comparatively easily quenched, the arresters found to be suitable might be unsafe for explosions in the gases and vapours more commonly used in industry. It has been found with flame-proof equipment that a flange gap safe for methane explosions may not be safe for explosions with faster burning fuels. An investigation of the fundamental aspects of flame arresting has therefore commenced, in order that a better understanding may be obtained of the modes of action of the arresters and their limitations in relation to the systems in which they are installed. This report describes experiments on wire gauze arresters installed in a simple tubing system. Wire gauzes were used because they are a simple form of arrester in common use and with them a wide range of sizes of aperture and of thicknesses could be studied.

EXPERIMENTAL

Materials and apparatus

Gauzes of various meshes and materials were used as the arresters; some characteristics of the gauzes are listed in Table 1. In each case the values for the wire diameter and the mesh width (the width of a hole in the gauze) are the means of three determinations.

TABLE 1

Characteristics of the wire gauzes

Material of gauze	Nominal mesh	Nominal wire gauge S.W.G.	Mesh width (m) cm	Wire diameter (D) cm	Surface area of wire in unit area of gauze (A) cm^2	Proportion of area of gauze blocked by wires
Brass	4	20	0.551	0.0838	0.829	0.246
"	6	20	0.329	0.0940	1.40	0.395
Steel	6	20	0.330	0.0935	-	-
Brass	10	24	0.198	0.0559	1.39	0.392
Steel	10	24	0.199	0.0546	-	-
Brass	18	28	0.106	0.0356	1.58	0.437
Steel	28	28	0.0531	0.0376	-	-
Brass	30	32	0.0572	0.0267	2.00	0.663
"	40	34	0.0404	0.0231	2.29	0.595
Steel	40	34	0.0399	0.0236	-	-
Brass	60	37	0.0248	0.0175	2.60	0.656
Steel	60	37	0.0251	0.0173	-	-
Brass	80	39	0.0192	0.0130	2.54	0.645
Steel	80	39	0.0212	0.0122	-	-
Phosphor bronze	120	43	0.0125	0.0089	2.61	0.659
" "	200	46	0.0065	0.0061	3.04	0.734

The following approximate relations may be derived from the values given in the Table:

$$m = 13.2\ D^{1.5}$$

$$A\ D^{0.35} = 0.535$$

Three fuels were used in the preparation of the explosive gas mixtures: propane, ethylene, and Town's gas. The propane was specified by the manufacturers as being at least 97 per cent pure; the ethylene was specified as being 98.2 per cent pure. The Town's gas was used from the mains supply and samples of the gas were taken from the mains before and after the series of tests. The two samples gave the analyses shown in Table 2. With each of the fuels fast flames were obtained by enriching the fuel/air mixture with oxygen; the oxygen was of normal commercial purity.

TABLE 2

Analysis of the Town's gas samples

Percentage by volume

Constituent	Initial sample	Final sample
CO_2	4.9	4.3
$C_n H_m$	4.2	5.5
O_2	0.3	0.4
CO	20.5	23.7
H_2	46.4	43.8
$C_n H_{2n+2}$	17.5	17.8
N_2 (by difference)	6.2	4.5

The tube in which the explosions were produced was of perspex; the length of the tube was 170 cm., the internal diameter was 6.4 cm., and the wall thickness was 0.6 cm. The tube was cut into two sections, the shorter section being 58.5 cm. in length, and the two sections were held vertically so that they butted endwise on to each other; the arrester was sandwiched tightly between the two sections and was held in position by friction only. In all experiments the gas mixture was ignited at an open end of the tube, with the other end of the tube closed. The apparatus could be adapted to permit experiments with either upward or downward propagation of flame and for the propagation of the flame along either the shorter or the longer section of the tube before reaching the gauze. Measurements of flame velocities near the gauze were made using a rotating drum camera; the speed of the drum was calibrated by means of a signal generator in conjunction with a cathode ray oscilloscope.

Procedure

In each experiment with single gauzes a fresh sample was cut to form a circular disc whose diameter equalled that of the outside of the tube, and after the gauze was washed in carbon tetrachloride it was dried and then sandwiched horizontally between the ends of the two sections of tube. When multiple layers of coarse gauzes were used the gauze circles were bolted together so that the meshes were aligned, the edges of the gauzes were then soldered and the bolts were removed before cleaning and insertion of the gauze assembly in the tube. As packs containing three or more layers of coarse gauze gave no sign of distortion by the flame they were each used for several experiments. Combinations of fine and coarse gauzes were assembled by soldering the circles together at the edges; the building of packs of fine gauzes was not attempted, because of the difficulty in obtaining alignment of the meshes. After the gauze was inserted in the tube the system was made gas-tight by binding the junction with transparent adhesive cellulose tape.

The explosive gas mixture was then metered through the tube, allowing about ten changes of the gas in the tube, and the supply was then cut off. The quiescent gas mixture in the tube was ignited by a small gas flame applied to the open end of the tube, and the movement of the flame near the gauze was recorded by the drum camera. The velocity of the flame was measured at the following positions relative to the gauze:

(i) at about 1.5 cm. from the gauze surface on the approach side (initial velocity).

(ii) at the gauze surface on the approach side (approach velocity) and, if the flame passed the gauze,

(iii) at the gauze surface on the departure side (departure velocity).

(iv) at about 1.5 cm. from the gauze surface on the departure side (final velocity).

The velocity of the flame was calculated from measurements of the slope of the flame front on the photographic record and the speed of rotation of the camera drum. If the propagation of the flame through the tube was sufficiently slow, the flame travelled at a uniform velocity when 1.5 cm. from the gauze and the record given by the drum camera was a straight line, as in Plate 1(a). With faster flames, however, vibrations of up to about 1 cm. amplitude developed and caused the flame to move at a variable velocity; hence the camera record was wavy, as in Plate 1 (b and c). In such cases the maximum value of the flame velocity at or near the point 1.5 cm. from the gauze was taken as the local flame velocity; the photographic record for the maximum value was usually clearly defined and measurement could be made with the minimum of subjective error. When the photographic record was obscure, so that definite measurements were not possible, the record was rejected. In order to be consistent, whenever the flame velocity near the gauze was variable the above method of measurement was used for (i) and (iv) above.

RESULTS

Observation of the flames

The velocity of propagation of the flame in the tube could be altered by changing either the composition of the explosive mixture, or the length of the tube between the igniting flame and the gauze (the run-up length), or the direction of propagation. This behaviour was similar to that described by other workers for flames propagating in tubes without gauzes. A sufficiently wide range of flame velocities was produced by using gas mixtures whose compositions ranged from near-limit fuel/air mixtures to a stoichiometric mixture containing 1 part of fuel (by volume), 9.6 parts of air, and 3 parts of additional oxygen. The flame velocities obtained with a given mixture were not very reproducible; further details of this are given later. If the run-up length of the tube were increased the flame velocities also increased; hence a given flame velocity was obtained with a fuel/air mixture nearer the flammability limits if the run-up were increased.

The photographic records given by the flames were sufficiently clear for accurate measurements of the initial velocities of the flames ((i) above). When the flames were within a few mm. of the gauze the records sometimes became diffuse, so that measurement of the flame velocity was less precise; in consequence although the approach velocity ((ii) above) usually appeared to be less than the initial velocity, no empirical relationship was established between the two quantities. When the flame passed the gauze the record of the departure velocity ((iii) above) was equally uncertain, although the final velocity of the flame ((iv) above) was usually as clearly defined as the initial velocity of the flame. The mean ratios of the initial velocity to the approach, departure, and final velocities for one complete set of results (those represented in Fig. 1) were calculated on a logarithmic basis and are listed in Table 3, irrespective of the gauzes used. In view of the uncertainty sometimes associated with the determination of the approach velocity the value of the initial flame velocity (measured about 1.5 cm. from the gauze) was used as the characteristic velocity of the flame as it neared the gauze.

TABLE 3

Ratios of flame velocities near the gauze

Ratio	Initial velocity / Approach velocity	Initial velocity / Departure velocity	Initial velocity / Final velocity
Mean value	2.35	0.66	1.12
Total number of values	78	19	19
Standard deviation about mean	1.92	2.62	2.03

If the flame did not pass the gauze the damage suffered by the gauze was small, the greatest damage being slight discoloration of the very fine gauzes. If the flame passed through the gauze little damage was caused to gauzes coarser than 18-mesh, but gauzes finer than 60-mesh were usually destroyed. Gauzes of intermediate mesh were often split. The destruction of gauzes was frequently accompanied by the emission of light from the molten metal; this emission was particularly marked with the fine steel gauzes and was often sufficient to affect the photographic record and to interfere seriously with the measurement of flame velocities. The interference could be reduced by introducing a blue light filter into the camera.

Experiments with single gauzes

The arresting of propane flames by brass or phosphor-bronze gauzes was investigated using a run-up length of 58.5 cm., the flame propagating upwards, and the results are given in Fig. 1. The initial flame velocity is plotted against the width of the gauze mesh on logarithmic axes and distinction is made as to whether or not the flame passed the gauze; no account is taken of variation in the composition of the explosive mixture even though both lean and rich mixtures were used to produce slow flames. It was possible to draw a straight line which, with a few exceptions, separated the results of experiments in which the gauze quenched the flame from those results for which the flame passed through the gauze. The line was arranged so that equal numbers of the exceptional results fell on each side of it. The line in Fig. 1 is represented by a broken line in Figs. 2 - 6, in which it is included for comparison. The results of experiments with propane flames under similar conditions with steel gauzes are shown in Fig. 2. Further experiments with propane flames propagating upwards, with brass or phosphor-bronze gauzes, were carried out using a longer run-up length (111.5 cm.) and the results are given in Fig. 3. The behaviour of propane flames propagating downwards was studied using a 58.5 cm. length of tube between the igniting source and the gauze, and the results are shown in Fig. 4.

The results for ethylene and Town's gas flames propagating upwards, and with a run-up length of 58.5 cm., are shown in Figs. 5 and 6 respectively. The gauzes used were brass or phosphor-bronze.

Experiments with combinations of gauzes

The effect of increasing the number of layers of gauze in the arrester was studied with 10-mesh gauzes, with up to 10 layers arranged so that the meshes were accurately aligned. The fuel used was propane and the flames propagated upwards, with either a 58.5 cm. or a 111.5 cm. run-up. The results are given in Fig. 7, where the initial flame velocity is plotted on logarithmic axes against the number of gauzes in the pack. A further set of experiments was carried out with packs of 6-mesh gauze, using ethylene flames propagating upwards, with a run-up length of 58.5 cm. The results are shown in Fig. 8.

In an attempt to devise an arrester with the quenching ability of a fine gauze, but with the mechanical strength of a coarse gauze, experiments were carried out with a 120-mesh gauze soldered to a 6-mesh brass gauze. The combined gauzes were inserted in the tube, with a 58.5 cm. run-up length, and were exposed to propane flames travelling upwards. The results are given in Table 4 for experiments with the finer gauze on the underside (120 + 6), the finer gauze being the first reached by the flame, and with the reverse arrangement of gauzes (6 + 120). Evidence was obtained that with the latter arrangement the centre of the finer gauze was lifted by the slight pressure developed as the flame approached, so that when the flame neared the arrester the two gauzes were no longer in contact over their whole area. With neither arrangement of gauzes was the combined arrester as effective as a single layer of 120-mesh gauze (Fig. 1).

TABLE 4

Experiments with combined 6- and 120-mesh gauzes

(120 + 6) arrangement		(6 + 120) arrangement	
Initial flame velocity cm/s	Behaviour of flame	Initial flame velocity cm/s	Behaviour of flame
1091	Passed	981	Quenched
831	"	820	Passed
800	Quenched	582	Quenched
622	"	438	Passed
555	"	410	Quenched
388	"	405	"
		257	Passed
		220	Quenched

In a further attempt to construct a robust arrangement capable of stopping fast flames packs were made up in which a finer brass or phosphor-bronze gauze was sandwiched between two 6-mesh brass gauzes. Propane flames propagating upwards were again used, with the run-up length of 58.5 cm. The results are shown in Fig. 9, where the initial flame velocity is plotted against the mesh width of the central gauze in the sandwich. In no instance was the combination markedly more effective than the central gauze alone, and with the finer gauzes the effectiveness was considerably reduced.

Variation of initial flame velocity with run-up length and gas composition

Even when the experimental conditions were kept as constant as possible the initial flame velocity of a given gas mixture was found to vary between experiments. Values of the mean initial flame velocities of various propane mixtures have been obtained by considering all the experimental results for this fuel represented in Figs. 1 - 9 and Table 4, irrespective of the arresters tested. These mean values are listed as $\bar{V}$ in Table 5, together with their respective standard deviations σ ; in each case the value is the mean of at least six results.

TABLE 5

Mean initial flame velocities ($\bar{V}$ cm/s) of propane-oxygen-nitrogen mixtures

Mixture composition (Parts by volume)			Run-up 58.5 cm. Upward propagation		Run-up 111.5 cm. Upward propagation		Run-up 58.5 cm. Downward propagation	
Propane	Air	Additional oxygen	$\bar{V}$	σ	$\bar{V}$	σ	$\bar{V}$	σ
3	97	-	98	44	172	141	-	-
3.25	96.75	-	-	-	-	-	161	174
3.5	96.5	-	253	147	2224	2417	111	48
4	96	-	295	346	2190	1227	-	-
1	19.1	1	473	270	-	-	747	450
1	14.3	2	824	415	-	-	-	-
1	9.62	3	1889	1321	-	-	-	-

DISCUSSION

The arresting of flames by single gauzes

With each of the fuels tested, and under each set of experimental conditions, there were critical values of the initial flame velocity below which the flames were arrested, and above which they propagated through the arrester. In each of the sets of results shown in Figs. 1 - 6 a line can be drawn to separate the results of experiments in which the gauze quenched the flame from those results in which the flame was not quenched, apart from a relatively small number of results. It may be seen from Figs. 1 - 6 that the lines connecting the critical flame velocities were approximately straight, and that each set of results may be represented approximately by an equation of the form

$$V = \frac{C}{m^n} \quad \text{.....(1)}$$

where V is the critical value of the initial flame velocity, m is the width of the mesh of the gauze (Table 1), and C and n are constants. Values of the two constants corresponding to the various fuels and experimental conditions are given in Table 6. The relation between the critical velocity of the flame and the width of the mesh of the gauze, equation (1), was only slightly influenced by variation of the composition of the fuel, the material of the gauze, the direction of propagation, and the length of the run-up of the flame. The

effectiveness of gauze arresters under the conditions of test thus appears to depend largely on the velocity of the flame as it nears the gauze, and factors such as the direction of propagation and the length of the run-up from the point of ignition to the gauze appear to be of secondary importance except in so far as they affect the flame velocity.

By making several simplifying assumptions a theoretical treatment of the quenching of a flame by a wire gauze has been derived, the detailed argument is given in Appendix A. It was assumed in this theoretical approach that the quenching of the flame was an effect caused by heat transfer from the flame to the gauze, so that if more than a certain critical amount of heat were removed the flame would be quenched.

TABLE 6

Values of the constants in Equation (1)

Fuel	Material of gauze	Direction of propagation	Run-up length cm.	n	C
Propane	Brass and phosphor-bronze	Upwards	58.5	1.00	30.0
"	Steel	"	58.5	1.22	14.9
"	Brass and phosphor-bronze	"	111.5	1.24	17.5
"	"	Downwards	58.5	1.21	13.2
Ethylene	"	Upwards	58.5	1.27	12.8
Town's gas	"	"	58.5	1.10	23.3

The amount of heat removed from the flame by the gauze was calculated in terms of the velocity, temperature, and the thickness of the flame and the dimensions of the gauze from the convective heat transfer data given in standard textbooks. The amount of heat to be removed from the flame for quenching was taken from published results for propane flames on a flat-flame burner. In the theoretical treatment two cases were considered: firstly, a flat flame approaching the gauze, and secondly the more general case of the approach of a curved flame to the gauze. On substituting numerical values in the equation (A2) the relation given as equation (A3) was obtained for the stoichiometric propane/air flame; this relation is represented by the theoretical line in Fig. 1. This theoretical line lies close to the experimental line, although tending to be a little low, and the discrepancy may be explained, at least in part, as arising from the assumptions made in the theoretical approach. The position of the theoretical line, but not the slope, will depend on the composition of the unburnt mixture; the line would be displaced upwards for slower burning mixtures and downwards for faster burning mixtures. It is unfortunate that information on the effect upon the burning velocity of the removal of measured quantities of heat from a flame is very scanty, and that in consequence calculations along the lines described in Appendix A cannot be made for propane-air-oxygen flames or for ethylene or coal gas flames. However, it appears from Table 6 that ethylene and coal gas flames behaved in practice in a similar manner to propane flames under the conditions of test, and hence their behaviour could probably be explained along similar lines to that of propane flames.

From the theoretical argument it may be seen that for the type of combustion considered the form of the relation between the critical flame velocity for quenching and the mesh width should be independent of the length of the run-up and of the direction of propagation. In addition, as the gauzes are

unlikely to attain high temperatures if the flame is quenched (see below), the efficiencies of brass, steel, and phosphor-bronze gauzes of the same dimensions should be the same, under the conditions of test. In the main, these deductions are in accordance with the experimental results. A further deduction is that the relation between the flame velocity and the mesh width should be independent of the diameter of the tube; this effect will be tested in future experiments.

Temperature rise of the gauze in flame quenching

The increase in the temperature of the gauze due to contact with the flame front may be easily calculated if the flame thickness is known. The value of the flame thickness could not be determined by direct photography of the flame passing along the tube, but some information is available from the results of experiments on burner flames. Thus Friedman[17] used a fine wire thermocouple probe and showed that the thickness of the region in which most of the heat was released in a 3.2 per cent propane/air flat flame was about 0.2 cm., whereas the luminous zone was only about 0.03 cm. in thickness. Other workers, using a Bunsen-type burner[18], found the thickness of the luminous zone to be less, at about 0.02 cm., and the total thickness of the flame to be about 0.1 cm. The actual value of the thickness of the flame in a tube is thus uncertain, although of the order of a millimetre, but a value of 0.2 cm. has been taken so that if in error it would probably be too large; this error would then lead to an over-estimation of the temperature attained by the gauze. Specimen temperature rises have been calculated in Appendix B for a fine and for a coarse gauze, assuming a flat flame to be propagating through a 4 per cent propane/air mixture. Such a flat flame propagates at 41 cm./s., which is the standard burning velocity for the unburnt mixture[14], so that when the flame is curved and moving more rapidly, the temperature rises would be proportionately greater. As the 200- and 6-mesh gauzes will just quench flames moving at velocities of 4700 and 91 cm./s. respectively (Fig. 1), the expected temperature rises of the gauzes would be 158°C and 0.43°C respectively. As both these temperatures are well below the melting points of the metals (about 1000°C and 940°C respectively) damage to the gauze by quenched flames would not be expected. There would, however, be considerably more heat available in the exhaust gases behind the flame front, so that if the flame passed the finer gauzes they could be heated sufficiently to melt.

Estimates of the flame thickness could of course be obtained from direct measurement of the temperature changes of gauzes by reversing the calculation in Appendix B. A value of flame thickness obtained by this method might be more satisfactory than one obtained from a burner since it is not known whether all the reaction zone, or only part, must be cooled in order to quench the flame. Further experimental work is necessary on this point.

The arresting of flames by gauze packs

The results given in Figs. 7 and 8 for multiple layers of coarse gauzes showed that the benefit obtained by increasing the number of layers tailed off fairly quickly, so that comparatively little was obtained by increasing the number of gauzes of the same mesh above five. This behaviour can be explained, in a qualitative manner, as resulting from the fact that when the thickness of the pack is equal to the thickness of the flame the rate of extraction of heat from the flame will be a maximum and will not be increased by any further increase in the length of channel through the pack. A theoretical treatment of the problem is complicated because the gauze packs have front and rear surfaces capable of abstracting heat from the flame, in addition to the passages running through the pack which are also capable of abstracting heat. These passages are not smooth-walled but consist of intermittent curved surfaces separated by gaps. However, by making the considerable assumption that a pack of N layers of gauze is equivalent to a single layer of gauze, plus an array of tubes of length (N - 1) x the thickness of a single gauze and with continuous smooth walls, a theoretical treatment has been derived and is given in Appendix C.

The equation (C6) from the Appendix is represented by a broken line in Fig. 7, and lies well below the experimental line. The position, but not the shape, of the calculated line is governed largely by the critical flame velocity for one layer of gauze, the calculated value for which was too small by a factor of about two. The calculation indicated that no further genefit would be obtained by increasing the number of gauzes beyond about eight; this is in fair agreement with the experiments. The value of the limiting initial flame velocity of the calculated line was derived from the experimental results, and so cannot be used to test the theory. It is probable that the assumptions made in the theoretical treatment preclude good agreement with the experimental results, but the same theoretical approach should hold for crimped ribbon flame arresters and experimental investigations are planned. These arresters consist of an array of smooth-walled tubes, with comparatively little front face and back face areas, and are thus closer to the array model taken in Appendix C.

Combinations of coarse and fine gauzes

The main feature of the results of these experiments was that a combination of fine and coarse gauzes was less effective in flame quenching than the fine gauzes alone. This behaviour may be explained on the basis that flame cannot pass through the area of the fine gauze that is covered by the wires of the coarse gauze. Thus some of the surface area of the wire in the fine gauze is lost for quenching, being to some extent replaced by the smaller surface area of the wire in the coarse gauze; the efficiency of the combination as an arrester ought to be less than that of the fine gauze, in proportion to the loss of surface area of wire. When a fine gauze is sandwiched between two coarse gauzes the contribution to the surface area of the coarse gauzes may not be complete since some may be lost in contact with the fine gauze, and thus the total effective surface area of the arrester would probably lie between that of one coarse and one fine gauze and two coarse and one fine gauze. The total effective gauze areas for various combinations are calculated in Appendix D, and critical initial flame velocities for quenching are derived.

The calculated velocity for a single 6- and 120-mesh combination (820 cm./s.) is in excellent agreement with the experimental results with the (120 + 6) arrangement (Table 4), but with the alternative arrangement (6 + 120) the experimental results were too scattered for comparison. From the theoretical viewpoint both arrangements should be equally effective in arresting flames. When a gauze is sandwiched between two coarser gauzes the predicted behaviour of the combination was in reasonable agreement with the experimental results (Fig.9) if it were assumed that the faces of the coarse gauze in contact with the fine gauze made a negligible contribution to the quenching of the flame. The central flat portion of the curves in Fig. 9 arises because with the 60- and 120-mesh gauzes the surface areas of wire in unit area of gauze are approximately equal (Table 1).

Further considerations

From both the experimental results and the theoretical viewpoint it is clear that the performance of the wire gauze arresters depended to a considerable extent upon the velocity of the flame as it neared the arrester. It is therefore important to be able to relate the flame velocities which develop in a system to the composition of the combustible mixture and the dimensions of the system; the results given in Table 5 show, however, that under uniform conditions considerable variations of flame velocity can occur. At present there are insufficient results available to lead to any empirical relations, and further experimental work is required. Attention has also been drawn to the lack of information on the effect of the removal of measured amounts of heat upon the burning velocity of common combustible gases; such information would be useful in predicting the behaviour of other combustibles and might make detailed experimental testing unnecessary.

The theoretical approach made in the present paper can be extended to predict the behaviour of arresters under conditions where the unburnt mixture is in motion, such as occur when ignition is made at the closed end of a tube whose other end is open or when the fuel is in an actual flow system; however, experimental investigation is obviously necessary. As wire gauzes are mechanically weak, and are unsuitable for general use as flame arresters, some of the more robust types of arrester also need investigation in order to discover their capabilities and limitations; arresters of great strength and thermal capacity would be needed where the hot gas formed during an explosion is exhausted through the arrester. In the experiments described in the present paper a substantial part of the hot products of explosion escaped without passing through the arrester, and the rigour of the conditions was therefore not a maximum.

Although some progress may be claimed in the elucidation of the fundamental factors governing the behaviour of flame arresters much information remains to be gathered.

CONCLUSIONS

1. With wire gauze mounted in a short vertical tube there was a critical velocity of approach of a flame below which the flame was quenched and above which the flame passed through the arrester. In each case the flame was initiated at the open end of the tube.

2. With single layers of gauze this critical velocity was approximately inversely proportional to the width of the mesh of the gauze, over a wide range of mesh sizes. The relation between the critical velocity and the mesh width was similar for propane, ethylene, and Town's gas flames and was very little affected by change in the direction of propagation and length of the run-up of the flame to the gauze. Both brass and steel gauzes gave similar results.

3. If coarse gauzes were built into packs the critical flame velocity for quenching increased slightly, but the effect did not increase indefinitely as packs containing more than about five layers of gauze did not show further increase in effectiveness.

4. Combinations of coarse gauzes and a fine gauze were less effective than the fine gauze alone.

5. A simple theory based on the assumption that the quenching of the flame results from the abstraction of heat by the wire of the gauze was shown to be in broad agreement with the experimental results for propane flames. Insufficient fundamental information was available to test the theory on the results for ethylene and Town's gas flames.

ACKOWLEDGMENTS

Miss J. S. Hall, Mr. P. S. Tonkin, and Miss S.E. Townshend assisted in the experimental work.

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NOTATION

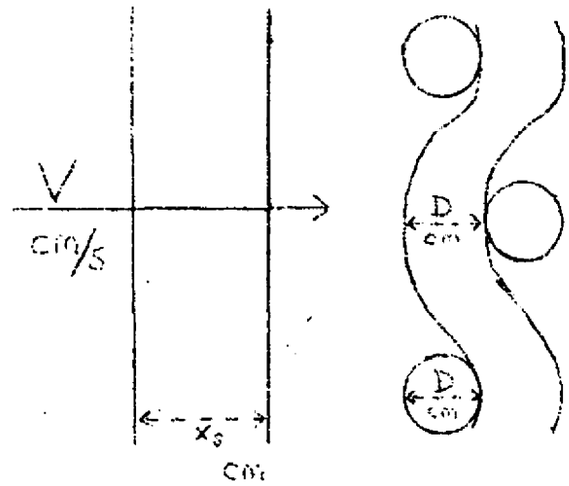
Symbol	Definition	Units
a	Number of meshes in unit area of gauze	-
A	Surface area of wire in unit area of gauze	cm^2
C	Constant	cm^2/s (approx.)
D	Diameter of wire	cm.
h	Heat transfer coefficient	$cal/cm^2/^oK/s$
k	Thermal conductivity of flame gases at film temperature	$cal/cm/^oK/s$
m	Width of mesh in the gauze	cm.
n	Constant	-
N	Number of layers of gauze in a pack	-
Nu	Nusselt number	-
q	Total amount of heat absorbed from the flame by unit area of gauze	cal.
Q	Total amount of heat lost by unit area of flame	cal.
Re	Reynolds number	-
S	Standard burning velocity	cm/s
T_g	Temperature of the gauze	^oK
T_h	Mean bulk temperature of flame gases through the gauze	^oK
V	Initial flame velocity	cm/s
x	Mean thickness of flame travelling at velocity V	cm.
x_s	Thickness of flame travelling at burning velocity S	cm.
y	Thickness of a gauze pack	cm.
z	Constant	-

APPENDIX A

The quenching of flame by a single gauze

Case 1

A flat flame propagating through a stationary unburnt gas mixture towards the gauze. In this treatment it is assumed that the direction of propagation of flame relative to the vertical is immaterial. It should be made clear that although the flame propagates with a velocity of V cm/s the burning gas is not moving at this velocity; the exhaust gases will, however, be in motion and the thrust developed may cause a slight compressive motion of the unburnt gas. This forward velocity has been neglected in the following discussion.



Now, consider a zone of the flame of thickness x_s within which most of the heat of combustion is liberated, and from which a critical amount of heat must be removed in order to quench the flame; the quantity x_s will be named the flame thickness. As the combustible mixture is pre-mixed the thickness of the flame will be governed by the velocity of the chemical reactions in the flame.

Then, as the flame passes the gauze, the amount of heat absorbed from the flame by unit area of the gauze in unit time $= hA(T_h - T_g)$ cal.

The flame is in contact with the gauze for time $= \frac{x_s}{V}$ s. approx.

Thus, the total amount of heat absorbed from the flame by unit area of gauze

$$= q \text{ cal.} = hA(T_h - T_g)\frac{x_s}{V} \text{ cal.}$$

A value for h may be derived from the Nusselt number which, for laminar flow, is related to the Reynolds number as follows(13):

$$Nu = \frac{hD}{k} = 0.32 + 0.43\ Re^{0.52}$$

For very low values of Re, this approximates to

$$\frac{hD}{k} = 0.32$$

$$\text{Hence } q = \frac{0.32k}{D} A.(T_h - T_g)\frac{x_s}{V}$$

$$= \frac{0.32 \times 0.535k}{D^{1.35}}(T_h - T_g)\frac{x_s}{V} \qquad \text{from Table 1}$$

$$= \frac{0.32 \times 0.535 \times (13.2)^{0.9}}{m^{0.9}} k.\ (T_h - T_g)\frac{x_s}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(A1)$$

Now, as the flame is flat the total amount of heat absorbed by unit area of gauze is equal to the total amount of heat lost by unit area of flame, assuming no side losses. Also, the flame propagates at the standard burning velocity S cm./s.

i.e. $q = Q$ and $V = S$

$$\text{i.e. } Q = \frac{1.746}{m^{0.9}} k\ (T_h - T_g)\frac{x_s}{S}$$

Case 2

A curved flame propagating through a stationary unburnt gas mixture towards the gauze.

As the velocity of the flame is proportional to its surface area the flame travels more quickly than before. In the present case each sq. cm. of gauze is opposed, on the average, by V/S sq. cm. of flame

i.e. $q.\frac{S}{V} = Q.$

E.g. (A1) therefore becomes $Q = \frac{1.746}{m^{0.9}} k. (T_h - T_g) \frac{xS}{V^2}$

Now the thickness of the flame, x, is governed by the velocity of the chemical reactions in the flame. Therefore if the flame is propagating at a velocity V, greater than its standard burning velocity S, and if the duration of the chemical reactions in the flame remains constant, the thickness of the flame will be increased by a factor V/S.

i.e. $x = x_s \frac{V}{S}$

Then $Q = \frac{1.746\ k}{m^{0.9}} (T_h - T_g) \frac{x_s}{V}$ .....(A2)

Calculation

In equation (A2) both Q and T_h, and probably x_s, depend upon the composition of the unburnt mixture. In order to simplify calculations based on equation (A2) the composition of the unburnt mixture was assumed to be constant (at a value of 4 per cent propane in air) and the flame velocity was assumed to have been varied by changing the area of the flame. (This method of altering the flame velocity would of course be difficult to achieve in a controlled manner in practice). If it is further assumed that, for quenching, the burning velocity must be reduced to that at the lower flammability limit (2.4 per cent propane/air) then Botha and Spalding[14] showed in their experiments with a flat flame burner that a total of 5.0 cal./cc. propane must be removed from the flame.

The following information is available on adiabatic flame temperatures[15] and other thermal properties[16]:

Flame temperature of 4 per cent propane/air : 2260° K)
" " " 2.4 " " " " : 1750° K) T_h = 2000° K approx.

T_g = 290° K.

Mean film temperature $= \frac{2000 + 290}{2} = 1145°$ K.

k, for nitrogen (the major constituent of the flame), at 1145° K

$= 2.90 \times 5.8 \times 10^{-5}$ c.g.s. units.

Also, as 1 cc. flame was originally $\frac{25}{26} \times \frac{290}{2260}$ cc. unburnt mixture.

The volume propane burnt per cc. of flame $= \frac{25}{26} \times \frac{290}{2260} \times 0.04$ cc. at 290° K.

Thus, for quenching, it is necessary to remove from each cc. of flame

$\frac{25}{26} \times \frac{290}{2260} \times 0.04 \times 5$ cal.[14]

$= 2.468 \times 10^{-2}$ cal.

Now, from equation (A2), for the flame to be just quenched,

$$\frac{Q}{x_s} = \text{total amount of heat lost by unit volume of flame}$$

$$= \frac{1.746k}{m^{0.9}} \frac{(T_h - T_g)}{V}$$

i.e. $$2.468 \times 10^{-2} = \frac{1.746 \times 2.90 \times 5.8 \times 10^{-5} \times 1710}{m^{0.9} \quad V}$$

or $$V = \frac{20.34}{m^{0.9}} \quad \text{.....(A3)}$$

This relation is represented by a broken line in Fig. 1.

APPENDIX B

The temperature rise of the gauze due to passage of a flame moving at the standard burning velocity

Case 1 : Phosphor-bronze gauze, nominally 200-mesh

The gauze contained $\frac{1}{0.0065 + 0.0061}$ wires/cm. (Table 1)

or $\frac{2}{0.0126}$ wires/cm^2.

i.e. mass of wire per cm^2 of gauze $= \frac{2}{0.0126} \times \pi \times 0.00305^2 \times 8.8$ g.

i.e. thermal capacity per cm^2 of gauze $= \frac{2}{0.0126} \times \pi \times 0.00305^2 \times 8.8 \times 0.088$ g.

Now for a flat flame unit area of gauze removes heat from unit area of flame, and so for quenching a 4 per cent propane/air flame each cm^2 of gauze must absorb $2.468 \times 10^{-2}\ x_s$ cal. (from Appendix A)

Then, taking $x_s = 0.2$ cm. (see Discussion)

Temperature rise of gauze $= \frac{0.2 \times 2.468 \times 10^{-2} \times 0.0126}{2\pi \times 0.00305^2 \times 8.8 \times 0.088}$ °C

$= 1.37°$ C

Case 2 : Brass gauze, nominally 6-mesh

This gauze contained $\frac{2}{0.423}$ wires/cm^2 (Table 1)

i.e. mass of wire per cm^2 of gauze $= \frac{2}{0.423} \times \pi \times 0.047^2 \times 8.4$ g.

i.e. thermal capacity per cm^2 of gauze $= \frac{2}{0.423} \times \pi \times 0.047^2 \times 8.4 \times 0.092$ g.

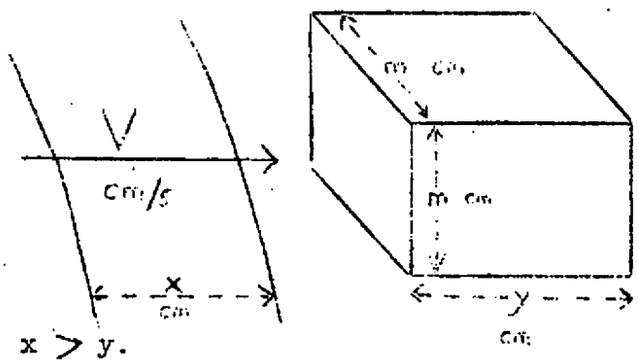
i.e. temperature rise of gauze $= \frac{0.2 \times 2.468 \times 10^{-2} \times 0.423}{2\pi \times 0.047^2 \times 8.4 \times 0.092}$ °C

$= 0.195°$ C

APPENDIX C

The quenching of flame by packs of coarse gauze

The following treatment is proposed as being applicable to a curved flame propagating through a stationary unburnt gas mixture towards the gauze pack. Consider first the gauze pack to be an array of tubes and neglect the heat absorbed by the front and back faces of the pack. Let each tube be of hydraulic diameter m cm. (mesh width) and of length y cm.; let there be a tubes per cm^2 of gauze pack.



Case 1 : $x > y$.

Using the same notation as in Appendix A

The amount of heat absorbed from the flame by unit area of the pack in unit time

$$= h\,A\,(T_h - T_g) = h.a.\,4my\,(T_h - T_g) \text{ cal.}$$

The flame is in contact with the pack for time $= \frac{x}{V}$ s. approx.

i.e. $q = h.a.\,4my\,(T_h - T_g)\,\frac{x}{V}$ cal.

$$Q = q.\frac{S}{V} = 4\,a\,h\,m\,y\,(T_h - T_g)\,\frac{x\,S}{V^2} \text{ cal.}$$

Thus $\frac{Q}{x_s} = 4\,a\,h\,m\,y\,(T_h - T_g)\,\frac{x}{x_s}.\frac{S}{V^2}$ cal.

The next step is to obtain a value for the heat transfer coefficient, h. There is little information available on the transfer of heat from a gas at a high temperature to a cold-walled tube, at very low values of Re. In addition, in the present case, end effects are uncertain. It seems probable, however, that a relation of the form $Nu = z$ where z is a constant, would hold approximately[19]. Then $h\,m = k\,z$.

i.e. $\frac{Q}{x_s} = 4\,a\,k\,y\,z\,(T_h - T_g)\,\frac{x}{x_s}.\frac{S}{V^2}$

Now as $\frac{x}{x_s} = \frac{V}{S}$

$$\frac{Q}{x_s} = 4a\,k\,yz\,\frac{(T_h - T_g)}{V} \quad \text{.....(C1)}$$

Case 2 : $x = y$

This is the limiting case because if $x < y$ only a length x of the tubes will be used at any given instant for heat transfer.

From equation (C1)

$$\frac{Q}{x_s} = 4a\,kz\,(T_h - T_g)\,\frac{x}{V} = 4\,a\,k\,z\,(T_h - T_g)\,\frac{x_s}{S} \quad \text{.....(C2)}$$

In the derivation of equations (C1) and (C2) the absorption of heat by the front and back faces of the pack was neglected. Allowance may be made for this absorption by assuming that a pack of N gauzes is equivalent to a single gauze plus an array of tubes of thickness that of (N - 1) gauzes. This assumption has been made in the following calculation.

Calculation

Consider a pack of 10-mesh gauze quenching a 4 per cent propane/air flame. Let the pack contain N layers of gauze, and let it be assumed that the assembly is equivalent to:

1 layer of 10-mesh gauze, abstracting heat $\frac{Q_1}{x_s}$ cal.

plus an array of tubes, with walls of length 2 (N - 1)D cm., abstracting heat $\frac{Q_2}{x_s}$ cal.

Then $\frac{Q_1}{x_s} + \frac{Q_2}{x_s} = \frac{Q}{x_s} = 2.468 \times 10^{-2}$ cal. (from Appendix A).

Now from Appendix A

$$\frac{Q_1}{x_s} = \frac{1.746\ k}{m^{0.9}} \frac{(T_h - T_g)}{V} = \frac{1.746 \times 2.90 \times 5.8 \times 10^{-5} \times 1710}{(0.198)^{0.9}\ V}$$

$$= \frac{2.157}{V} \quad \text{.....(C3)}$$

Also $\frac{Q_2}{x_s} = 4a\,k\,yz\,\frac{(T_h - T_g)}{V}$ from Equation (C1)

$$= 4\ k\ .\ (T_h - T\ ).\ \frac{x_s}{S}\ .\ \frac{yS}{x_s V}$$

i.e. $$\frac{Q}{x_s} = 2.468 \times 10^{-2} = \frac{2.157}{V} + \left[4\,akz\,(T_h - T_g)\,\frac{x_s}{S}\right]\frac{yS}{x_s V} \quad \text{.....(C4)}$$

Direct evaluation of equation (C4) cannot be made as the value of the constant z is not known. However, if use is made of the experimental limiting flame velocity for quenching (Fig. 7), z may be eliminated. From Fig. 7 we have:

Critical flame velocity for quenching with 1 layer of gauze = 175 cm/s.

" " " " " " many layers " " = 325 cm/s.

and from equation (C4), the calculated critical flame velocity for quenching with 1 layer of gauze (i.e. y = 0 cm.) is $\frac{2.157}{2.468 \times 10^{-2}} = 87.4$ cm/s.

Thus, in proportion, the calculated critical flame velocity for quenching with many layers of gauze should be: $87.4 \times \frac{325}{175} = 162.4$ cm/s.

Equation (C4) then becomes, at the limiting case when y = x

$$2.468 \times 10^{-2} = \frac{2.157}{162.4} + 4\,a\,k\,z\,(T_h - T_g)\,\frac{x_s}{S}$$

$$4\,a\,k\,z\,(T_h - T_g)\,\frac{x_s}{S} = 1.140 \times 10^{-2} \quad \text{.....(C5)}$$

Equation (C4) therefore becomes

$$2.468 \times 10^{-2} = \frac{2.157}{V} + 1.140 \times 10^{-2}\,\frac{y\,S}{x_s V}$$

Now $y = 2(N - 1) \times 0.0559$ cm. (Table 1)

$S = 41$ cm./s. (ref. 14)

$x_s = 0.2$ cm. (assumed in Appendix B and Discussion)

i.e. $V = 76.8 + 10.6\,N$ .....(C6)

This equation is plotted as a broken line in Fig. 7.

From equation (C4) at the limiting case when $y = x$

$$\frac{y\,S}{x_s V} = 1$$

i.e. $$N - 1 = \frac{0.2 \times 162.4}{2 \times 0.0559 \times 41} = 7.09$$

or $N = 8.1$

Thus the limiting quenching velocity should be reached when about eight gauzes are used.

From Equation (C5), z may be calculated:

$$z = \frac{1.140 \times 10^{-2} \times 41}{4 \times 15.5 \times 2.9 \times 5.8 \times 10^{-5} \times 1710 \times 0.2}$$

$$= 0.131$$

APPENDIX D

The quenching of flame by combinations of fine and coarse gauze

Case 1 : a 6- and 120-mesh gauze combination

From Table 1 we have:

Surface area of wire in unit area of 6-mesh brass gauze = 1.40 cm^2

" " " " " " " " 120-mesh phosphor-bronze gauze = 2.61 cm^2

Proportion of the area of the 6-mesh gauze blocked by wires = 0.395

Then the total available surface area of wire in unit area of combination

$$= 0.395 \times 1.40 + 0.605 \times 2.61 \text{ cm}^2$$

$$= 2.132 \text{ cm}^2.$$

This area corresponds to a wire diameter = 0.0195 cm.) from gauze
which " " " mesh width = 0.0365 cm.) characteristics, Table 1.

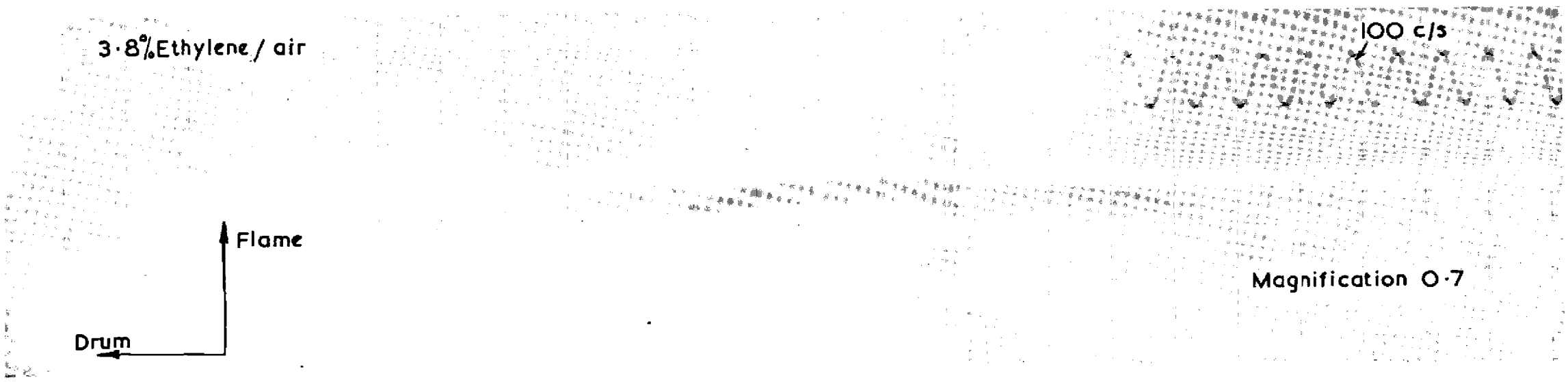
A gauze of this mesh width would be expected, from Fig. 1, to quench flames of velocities up to 820 cm./s. Experimental values for the (6 + 120) and (120 + 6) combinations are given in Table 4.

Case 2 : a fine gauze sandwiched between two 6-mesh gauzes.

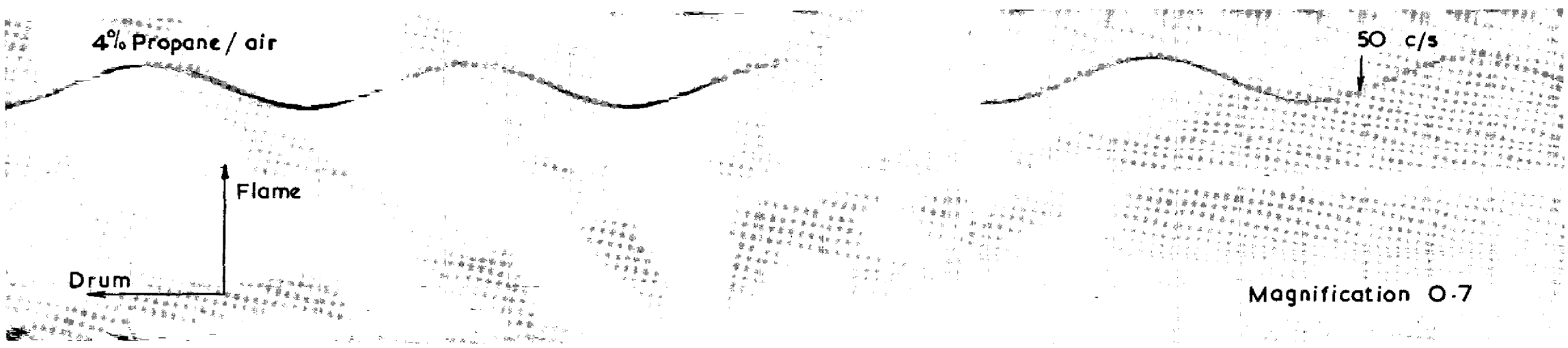
Consider a 6 + 10 + 6-mesh arrangement.

Then the total available surface area of wire in unit area of the combination should lie between: $0.395 \times 1.40 + 0.605 \times 1.39 = 1.394 \text{ cm}^2$

and: $2 \times 0.395 \times 1.40 + 0.605 \times 1.39 = 1.947 \text{ cm}^2$ (see Discussion). These areas correspond to wire diameters of 0.065 and 0.0245 cm. respectively and to mesh widths of 0.225 and 0.053 cm. respectively. Gauzes of these mesh widths would be expected, from Fig. 1, to quench flames of velocities up to 135 and 570 cm./s. respectively. Similar calculations may be made for other gauzes sandwiched between two 6-mesh gauzes; the values found are plotted alongside the experimental results in Fig. 9.



(a) LAMINAR



(b) SLIGHTLY VIBRATORY

(c) MARKEDLY VIBRATORY

PLATE.I. PHOTOGRAPHIC RECORD OF FLAMES

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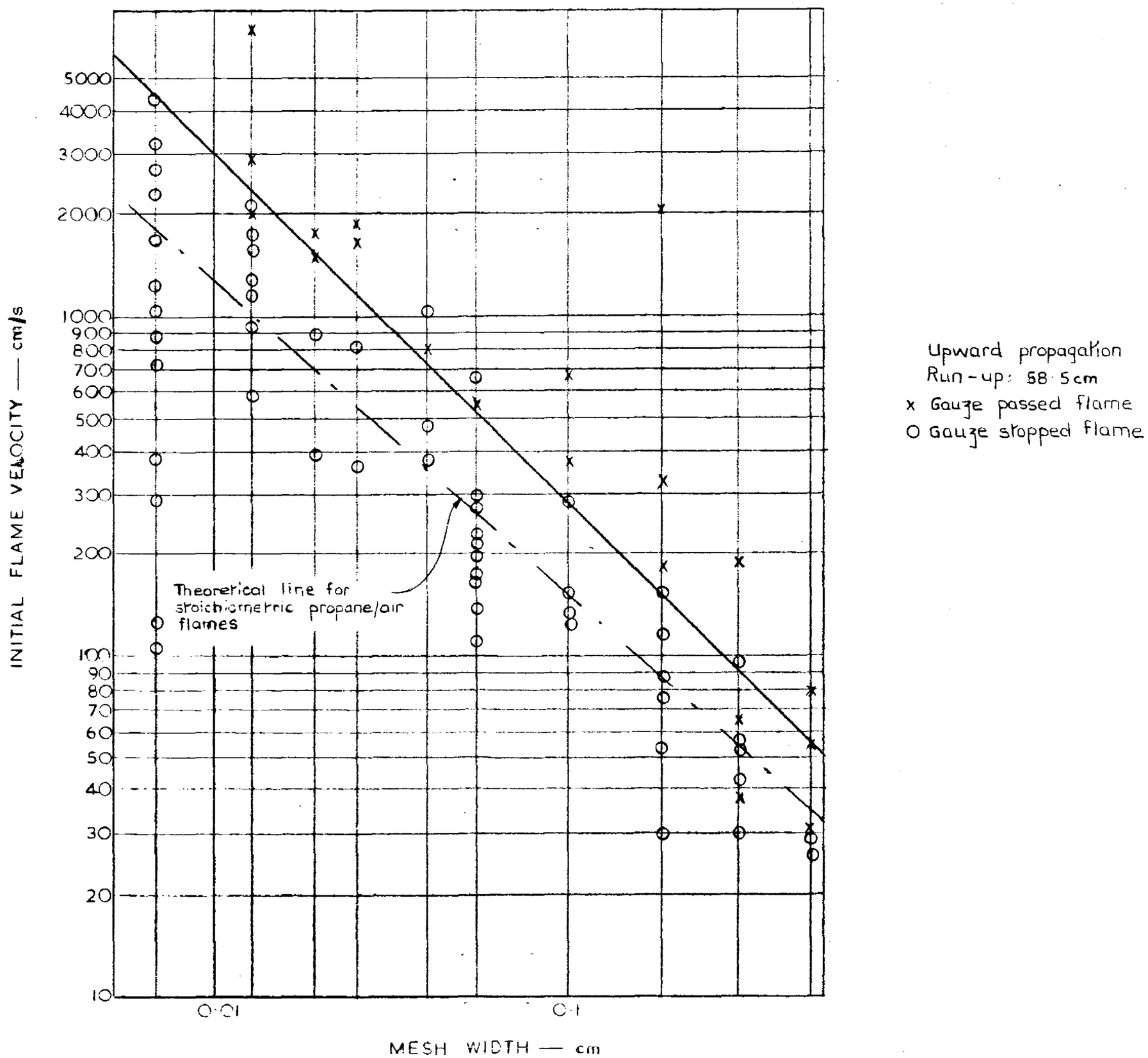
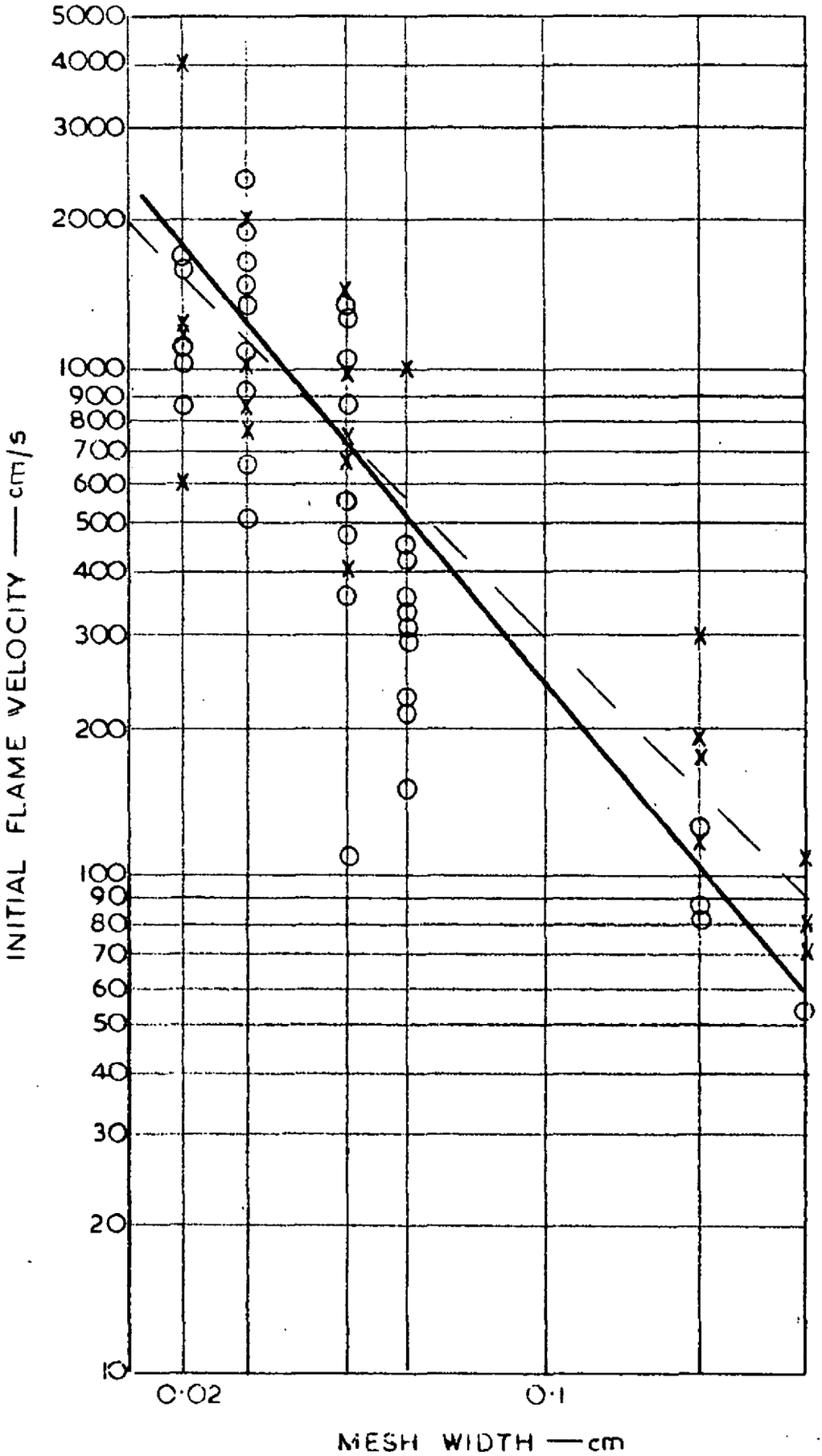


FIG 1. THE ARRESTING OF PROPANE FLAMES BY SINGLE LAYERS OF BRASS AND PHOSPHOR-BRONZE GAUZE

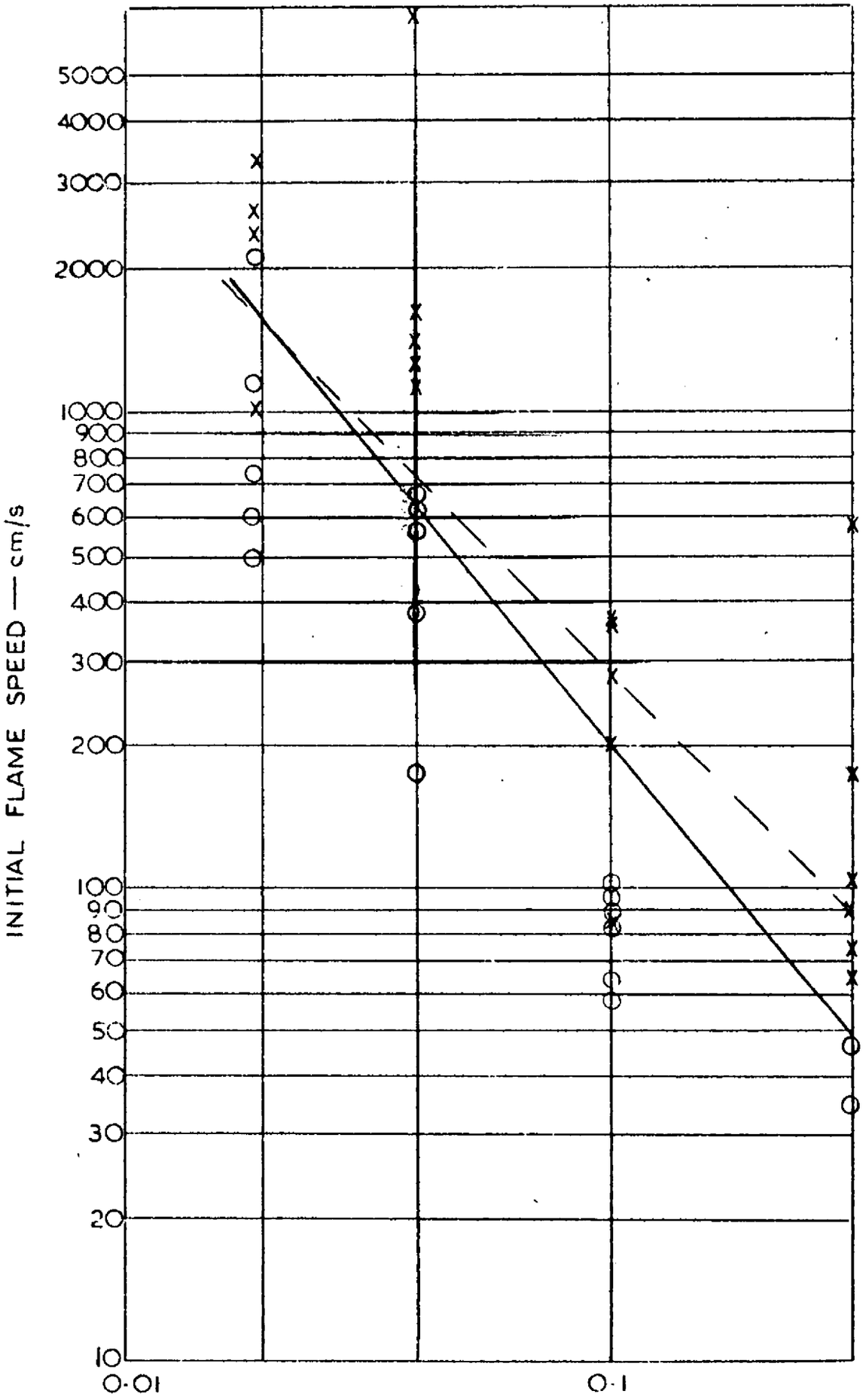
FR 304 3/251



Upward propagation
Run up: 58·5cm
x Gauze passed flame
O Gauze stopped flame

FIG.2. THE ARRESTING OF PROPANE FLAMES BY SINGLE LAYERS OF STEEL GAUZE

F.R. 309 1/2665



Downward propagation
Run up: 58·5 cm
X Gauze passed flame
O Gauze stopped flame

FIG. 4. THE ARRESTING OF PROPANE FLAMES BY SINGLE LAYERS OF BRASS AND PHOSPHOR-BRONZE GAUZE

F.R.309 1/2666

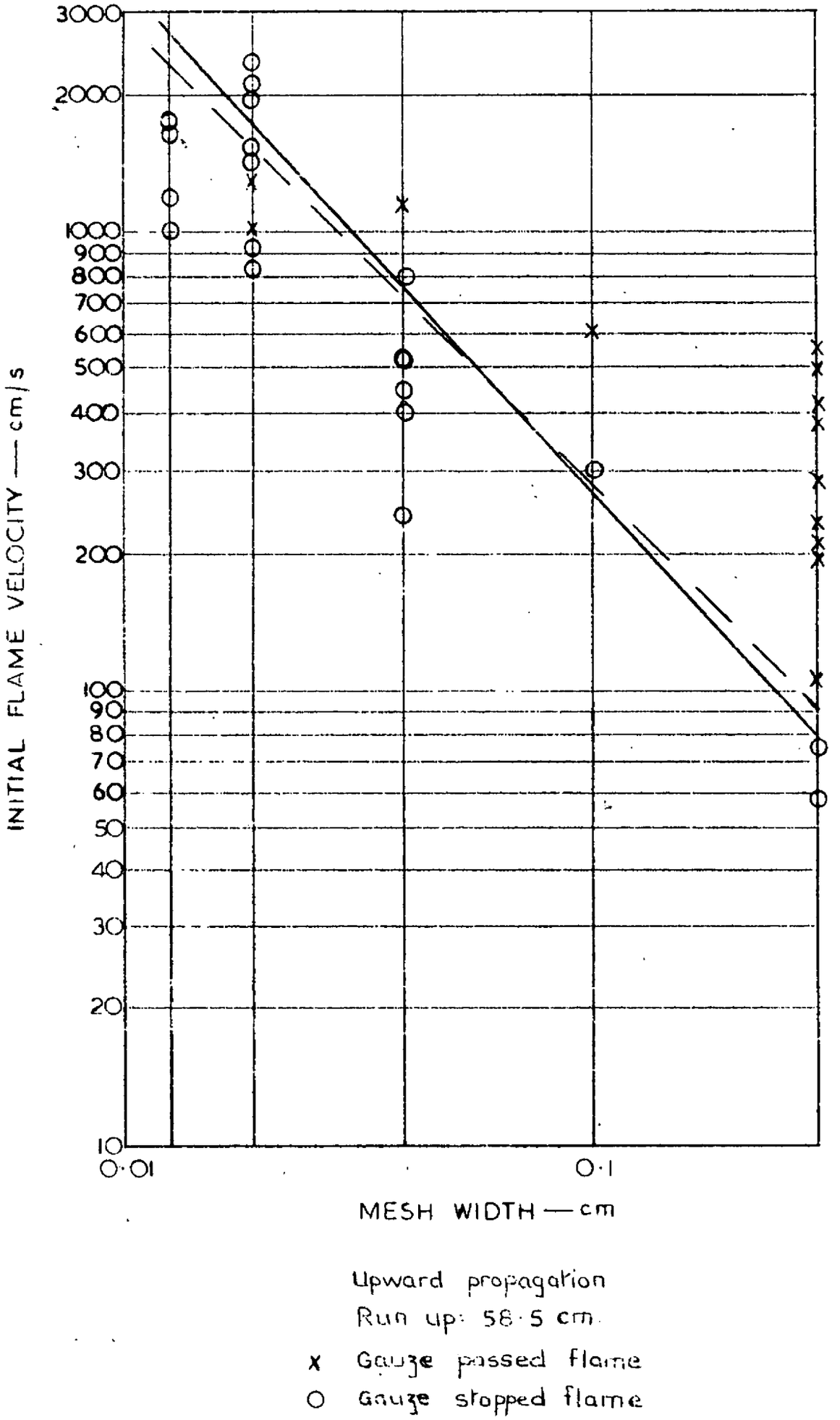


FIG. 6. THE ARRESTING OF TOWN'S GAS FLAMES BY SINGLE LAYERS OF BRASS AND PHOSPHOR-BRONZE GAUZE

FR 309 1/2667

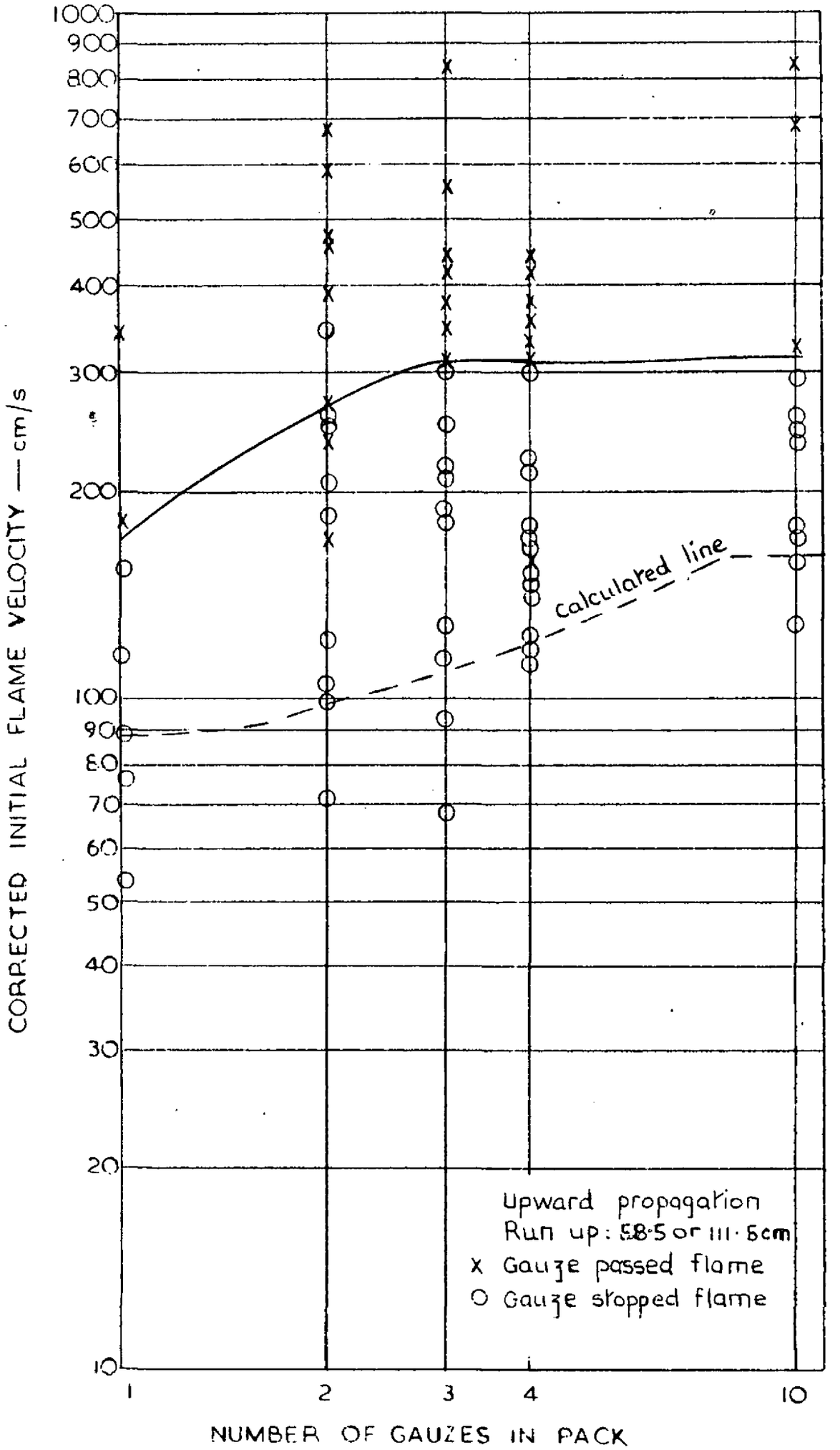


FIG. 7. THE ARRESTING OF PROPANE FLAMES BY PACKS OF 10-MESH BRASS GAUZE

F.R.309. 1/2668

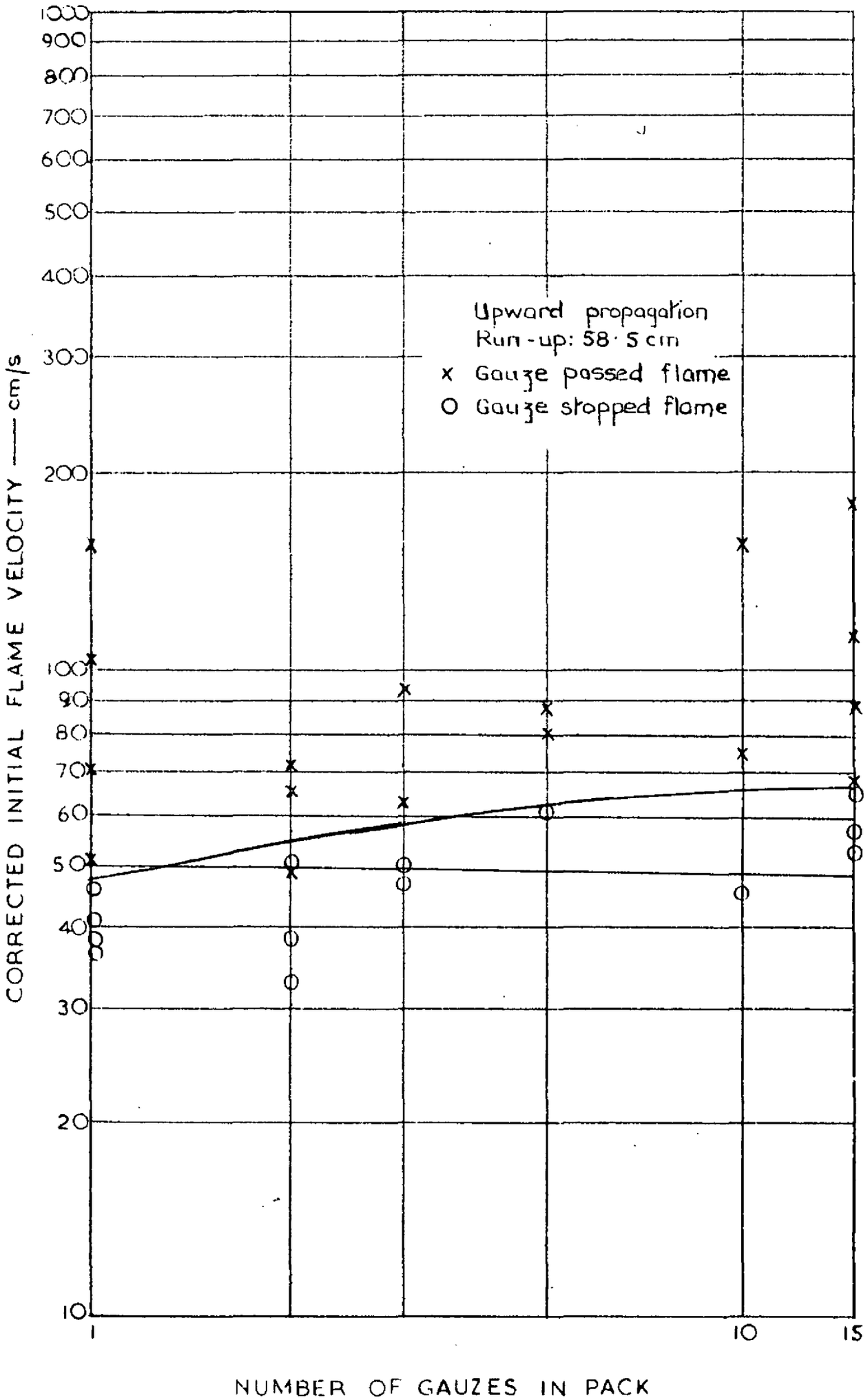


FIG. 8. THE ARRESTING OF ETHYLENE FLAMES BY PACKS OF 6-MESH BRASS GAUZE

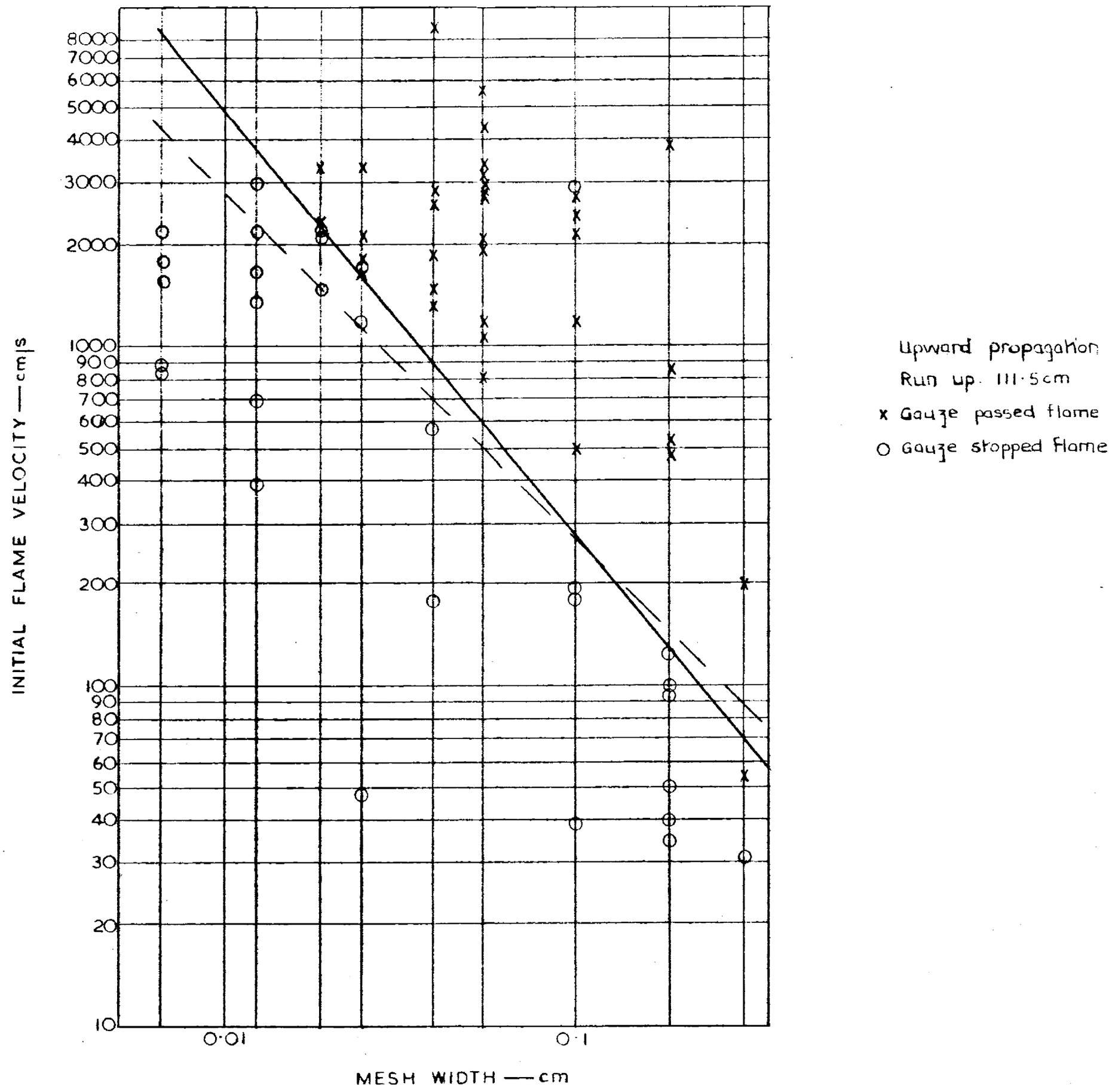


FIG. 3. THE ARRESTING OF PROPANE FLAMES BY SINGLE LAYERS OF BRASS AND PHOSPHOR – BRONZE GAUZE

F.R. 309. 2/252

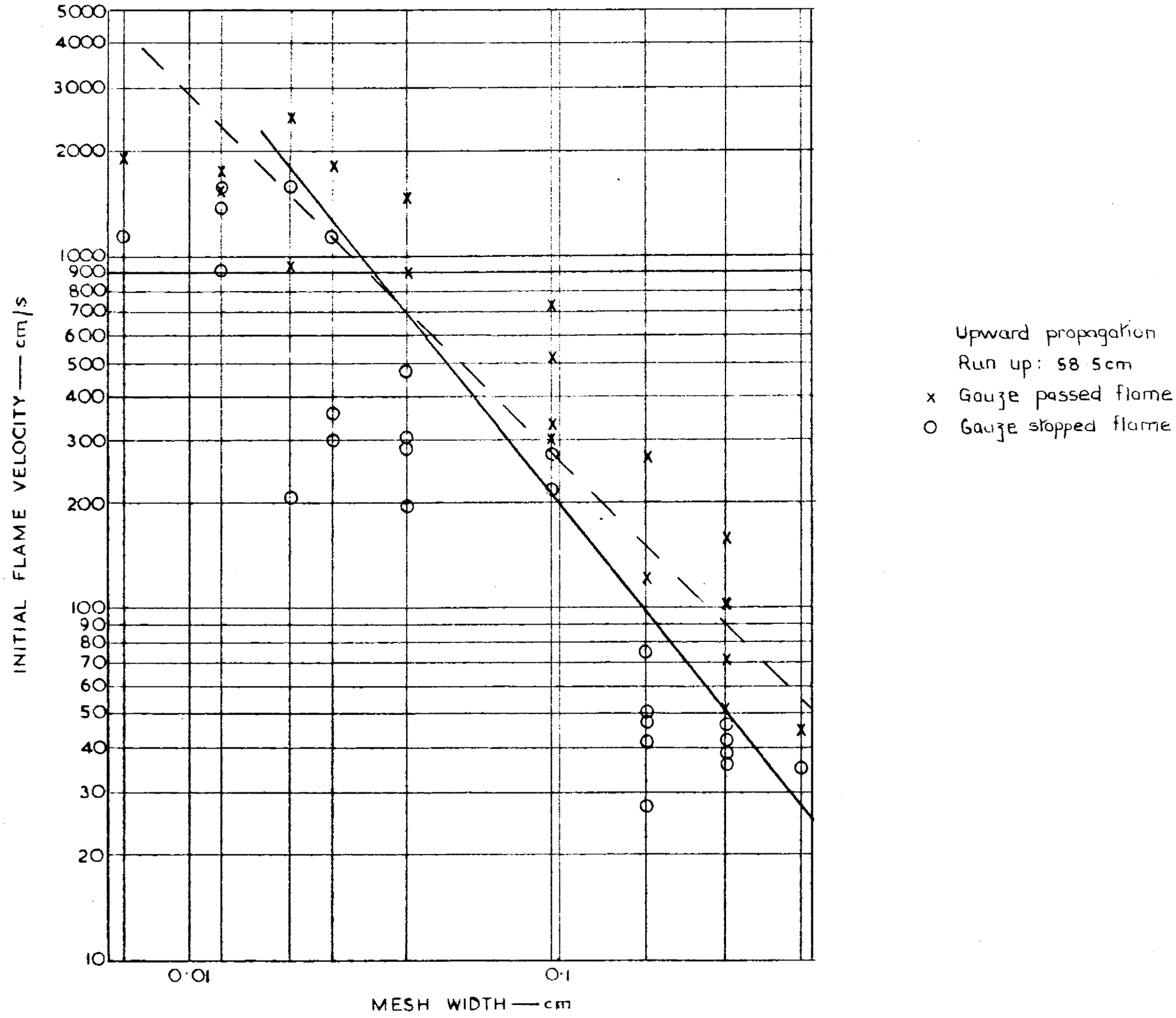


FIG. 5. THE ARRESTING OF ETHYLENE FLAMES BY SINGLE LAYERS OF BRASS AND PHOSPHOR-BRONZE GAUZE

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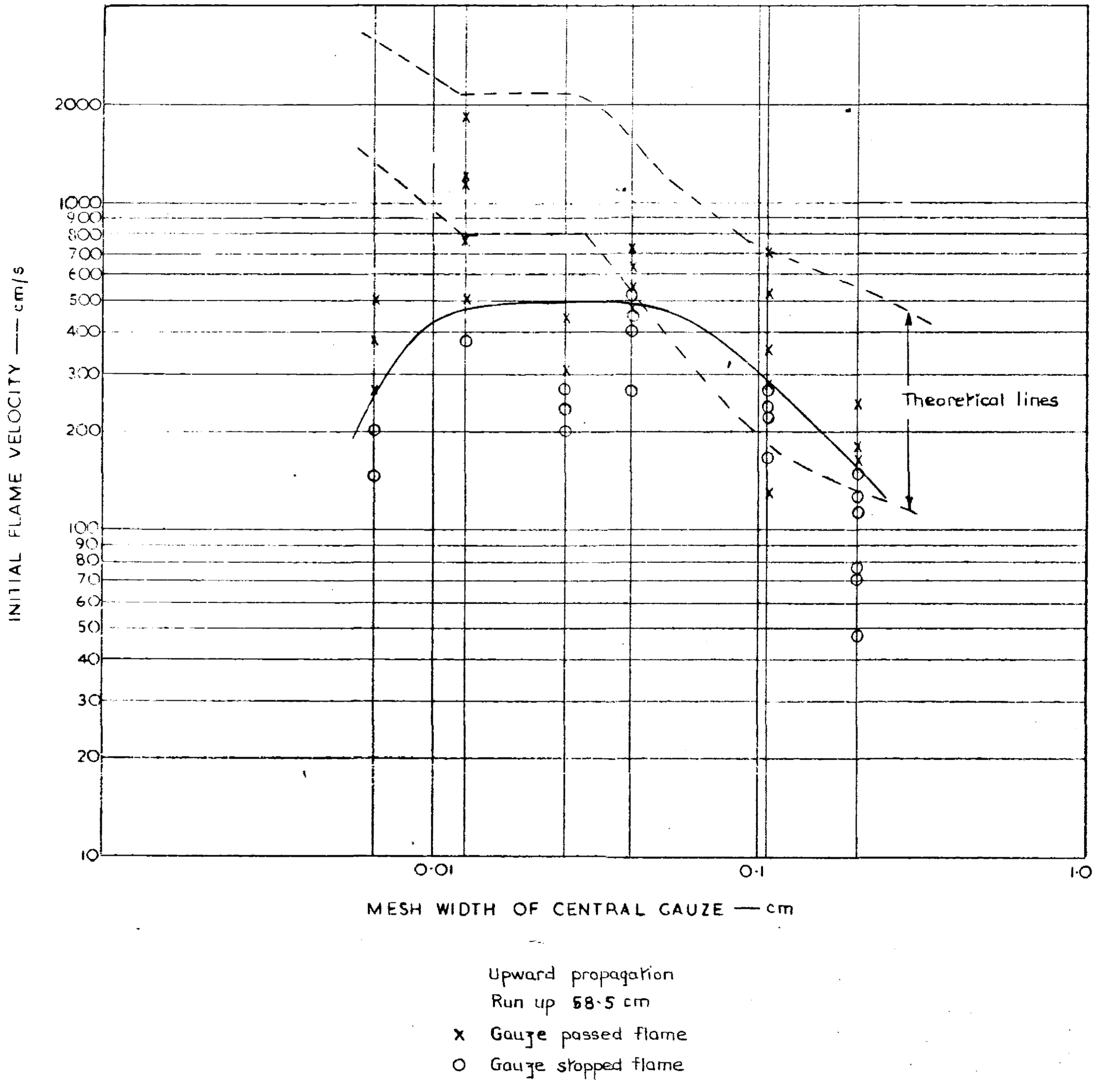

FIG. 9. THE ARRESTING OF PROPANE FLAMES BY SINGLE GAUZES SANDWICHED BETWEEN TWO 6-MESH BRASS GAUZES