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THE QUENCHING OF FLAMES BY FLAME ARRESTERS IN A LARGE-SCALE DUCTING SYSTEM

by

K. N. Palmer and P. S. Tonkin

SUMMARY

The effectiveness of crimped ribbon and other types of flame arrester mounted in a ducting of 30.5 cm cross-section has been compared experimentally and theoretically with that of similar arresters mounted in a narrower tube and investigated previously. The arresters were mounted in a wide duct up to 12 m long and filled with propane/air mixtures, which were ignited either near the open end or near the closed end of the ducting.

The velocities of flames just able to propagate through the arresters did not depend on the diameter of the ducting, but when explosion pressures were substantially above atmospheric the performance of the arresters was substantially reduced.

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INTRODUCTION

The performance of different types of flame arrester in the quenching of flames of a range of combustible gases and vapours has been described earlier[1,2,3]. The arresters were of types having a low resistance to gas flow (e.g. crimped ribbon, perforated sheeting, wire gauze) and with each type it was generally found that the velocity of the flame as it approached the arrester would determine if it would be quenched by the arrester. Each arrester could be assigned a critical velocity of approach of the flame, below which the flame was quenched and above which it propagated through the arrester, and the critical velocity usually depended on the thickness of the arrester and the diameter of the passages through it. Similar results were found for a range of solvent vapours.

In most of this work the arresters were installed in tube systems of diameter 6.4 cm and of length up to 14.3 m. But in industry flammable vapours and gases are mixed with air and can be conveyed in pipes or ducting of up to 1 m or so in diameter, and so the behaviour of flame arresters on this scale is of practical importance. The present investigation was therefore carried out with ducting of larger scale than hitherto, of 30.5 cm square cross-section, to determine whether the effectiveness of the arresters varied with the duct diameter. The arresters were of types that were used in the smaller-scale tests, and they were tested against flames propagating in the stoichiometric propane/air mixture. Some further tests were also carried out with the smaller-scale crimped ribbon arresters; this work is described in the Appendix.

EXPERIMENTAL

Apparatus and materials

Arresters

Two crimped ribbon arresters were used, of nominal crimp heights 0.048 and 0.075 in. Both arresters were constructed of crimped and flat metal ribbons laid alternately in a rigid metal frame (Plate 1); the internal dimensions of the frames were 30.5 x 30.5 cm. The area of crimped ribbon was divided into three rectangular sections by two flat strengthening bars running parallel to sides of the frame. Each bar was 0.8 cm in width and its centre was 10.2 cm from the parallel inner edge of the frame (Plate 2). Further strengthening of the crimped area was provided by two metal rods running in holes drilled through the frame and the crimped ribbon, at right angles to the strengthening bars. The centres of the rods were 10.2 cm from the parallel edges of the frame. The position of the rods may be seen in the left hand arrester in Plate 1.

Details of the dimensions of the crimps and of the thickness of the arresters are given in Table 1. The crimp sizes were determined by dividing the face of the arrester into 9 areas, each of which was then photographed. The sides of the crimp cells were measured on enlarged photographs, with a ruler, to an accuracy of about 5 per cent (Plates 3 and 4), and the area and perimeter of the cells were then calculated. A total of 8 cells was measured on each photograph, and hence a total of 72 determinations was made for each arrester. Values for the mean area of cell and for the mean equivalent hydraulic diameter of cell $\frac{4 \text{ x area of cell}}{\text{perimeter of cell}}$ are included in Table 1. The variation in values was $\pm$ 10 per cent for the smaller crimp and $\pm$ 30 per cent for the larger crimp. In both arresters the thickness of the ribbon was 0.0069 cm. The crimped ribbon arresters were fitted into a flanged support for insertion in the explosion ducting. Details of the support are shown in Plates 1 and 2.

The perforated plate arresters were made of brass sheeting, with circular holes. Details of the arresters are given in Table 2, and the pattern of the spacing of the holes is shown in Fig. 1. The plate arresters were fixed in the explosion ducting by bolting them directly to the flanges.

TABLE 1

Characteristics of the crimped ribbon arresters

Nominal crimp height in	Thickness of arrester (y) cm	Total crimped area cm^2	Fraction of crimped area open to gas flow	Mean area of one cell cm^2	Mean equiv. hydraulic diameter (d) cm
0.048	3.2	879	0.87	1.75×10^{-2}	0.11
0.075	5.1	874	0.92	7.6×10^{-2}	0.18

TABLE 2

Characteristics of the perforated sheeting arresters

Diameter of hole (d) cm	Thickness of arrester (y) cm	a (Fig. 1) cm	b (Fig. 1) cm	Area of hole in unit area of sheeting
0.175	0.073	0.283	0.466	0.37
0.123	0.070	0.198	0.320	0.38
0.100	0.072	0.176	0.291	0.31
0.055	0.046	0.112	0.180	0.24

A series of tests was also carried out with a wire gauze arrester. This was of steel, 28-mesh, and the mesh width was 0.053 cm and the wire diameter was 0.038 cm. It was bolted directly to the flanges of the explosion ducting.

Explosion ducting

Seven duct lengths were used and they were bolted end to end in a horizontal straight line. Each length was made of steel and was 30.5 cm (1 ft) square in cross-section and 1.83 m (6 ft) long; sketches are given in Fig. 2. The ends of the ducting lengths were flanged, and flanges were also fitted longitudinally along the front of the ducting (Fig. 2, top diagram) to which could be bolted flat perspex sheets 0.6 cm (¼ in) in thickness, or steel covers. The front of each ducting length was provided with an opening 1.53 m (5 ft) in length, acting as a window, and in five of the lengths this opening was equidistant from the ends. In the remaining two lengths, between which the arrester was usually mounted, the opening commenced 1.3 cm (0.5 in) from the end flange. This arrangement enabled the behaviour of the flame to be observed nearer to the arrester than would otherwise be possible. In all experiments one end of the ducting system was closed by a steel plate bolted to the end flange, and the other end of the system was completely open. Details of the ducting arrangements are given in Fig. 3.

When ignition was near the open end of the duct, it was sometimes necessary to ensure that the arrester would not be damaged by heat from the exhaust gases of the flame if it propagated through the arrester. To prevent damage, the duct length immediately past the arrester was turned so that the open front faced upwards, and a vent 30.5 cm (1 ft) square was installed as near as possible to the arrester; the remainder of the opening in the ducting was covered by a perspex or steel sheet. The vent was closed by a polythene sheet, about 0.004 cm thick, and this melted if a flame passed through the arrester; the hot exhaust gases were then discharged mainly through the vent instead of through the arrester. With this arrangement, direct vision of the flame propagating through the arrester was no longer possible.

Fittings were attached to the ducting for a spark electrode, a pressure gauge, and an inlet pipe for the gas mixture. The interior of the ducting system was smooth, with the duct lengths carefully aligned, and with no projections (except for the spark electrode). In some experiments with crimped ribbon arresters, with ignition near the closed end of the ducting, a metal strip was mounted horizontally across the centre of the duct; the strip obstructed the flame as it approached the arrester and accelerated the rate of propagation. The width of the strip was either 1.3 or 2.8 cm and the thickness was 0.3 cm.

A further group of tests with the crimped ribbon arresters, which was carried out with an explosion tube 6.4 cm in diameter, is described in the Appendix. In these tests only part of the area of the arresters was exposed to the flame, so that the behaviour of the arresters could be compared directly with that of arresters tested previously in the 6.4 cm diameter tube.

Camera and pressure gauge

The velocity of propagation of flame along the ducting was recorded with a cine camera, which viewed the flame through the perspex windows bolted to the front of the ducting. The film record also showed whether or not the flame passed through the arrester. The camera was electrically driven, and the speed could be adjusted up to about 280 frames/s. The film was of fast panchromatic quality (H.P.3). The velocity of the film through the camera could be measured from the marks made on the film by a neon lamp incorporated in the camera.

Measurements of explosion pressures were made in some tests. The pressures were detected by an electrical capacity cell, and after amplification the signal was fed to a cathode ray oscilloscope. A permanent record was obtained from the oscilloscope by photographing with a rotating drum camera.

Gas mixture

In all experiments a stoichiometric propane/air mixture was used (4 per cent by volume). The propane was specified by the manufacturers as being at least 97 per cent pure and it was mixed with atmospheric air in the explosive mixture. The flow of propane, from a cylinder, and the flow of air, from a blower, were measured with rotameters and were then mixed by passing along a pipe which was about 6.4 cm in diameter and 9 m in length. In this pipe was installed a flame arrester, which prevented any flash-back of flame from the ducting. A gate valve near to the ducting was used to seal off the delivery pipe during the explosion.

Procedure

The arrester was bolted into the ducting system, either directly or in a supporting frame, and the spark electrode used as an igniter was fixed in the required position and connected to a small induction coil. The electrical capacity cell, used in pressure measurement, was also put in position at this stage, if it was required.

The gas mixture was then passed through the ducting system, and during this time the open end of the ducting was covered with a perforated sheet to prevent dilution of the mixture by the atmosphere. After ten changes of the gas in the ducting the supply of mixture was cut off and the gate valve in the supply pipe was closed. In all tests the gas mixture was quiescent at the moment of firing. The cine camera was started and the gas mixture ignited immediately after removing the perforated cover from the open end of the ducting. After the explosion, the ducting system was purged with air.

The film from the cine camera was developed and projected on to a screen; the velocity of the flame as it approached the arrester was calculated from measurements of the movement of the flame on the screen and the velocity of the film in the cine camera.

Results

Gas ignited near open end of ducting

In tests with each type of arrester, the velocities of flames propagating in gas mixtures ignited near the open end of the ducting were slow and did not vary appreciably along the ducting. Although some acoustic vibrations were set up, and caused the flame velocities to vary periodically, the amplitudes of the vibrations were relatively small compared with those obtained in earlier experiments with narrow explosion tubes[1,2] of similar lengths. Consequently the velocity of the flame on arrival at the arrester was greater in the narrow tubes than in the present experiments with wider ducting. Inspection of the photographs obtained with the cine camera showed that the foremost part of the flame was usually near to the top of the ducting, as would be expected from convection, and that the flame front was noticeably wrinkled. In a few cases, however, the foremost part of the flame was at the bottom of the ducting. With either type of flame the rate of advance of the foremost part was taken as the velocity of propagation.

The results obtained with the crimped ribbon arresters are summarised in Table 3. Relatively few experiments were done because, with the arrester of smaller crimp size, the flame velocities were much too low for the flame to be likely to pass through the arrester. With the arrester of larger crimp the flames were able to pass through and a larger number of tests might have caused heat damage to the arrester, even though this would be minimised by the melting of the polythene vent. Although direct observations were not made, the flame did not appear to be appreciably delayed at the surface of the arrester in the two experiments in which it passed through the arrester. This was in contrast to the behaviour observed with a similar arrester in a narrow tube (Appendix) and with the perforated plate arresters. As a result, the velocity of propagation of the flame on arrival at the large-scale crimped ribbon arrester was taken to be the velocity of propagation as it passed through the arrester.

TABLE 3

Results for crimped ribbon arresters, flames ignited near open end of ducting (arrangement (xi), Fig. 3)

Nominal crimp height in	Flame velocity at arrester cm/s	Flame quenched by arrester
0.048	260 400	Yes Yes
0.075	320 370 530	Yes No No

The results obtained in experiments with perforated plate arresters are given in Fig. 4. In almost every case where the flame ultimately propagated through the arrester, the flame was checked on arrival and there was a delay before it propagated through the arrester. Values of the delay are given in Table 4. The cine camera records showed that when the foremost part of the flame arrived at the arrester, usually near to the top of the ducting, the flame was checked but hot gases flowed on through the arrester. The hot gases would of course displace cold gas, which flowed back through the arrester in the lower part of the ducting, so that when the flame in the lower part of the ducting arrived at the arrester it could stabilize on the arrester. Because of the delay, the velocity with which the flame finally propagated through the arrester could differ from that measured on its approach to the arrester and used in Fig. 4. It is possible that stabilization of flame also occurred in experiments when the flame was ultimately quenched, but this could not be decided with the experimental method used.

TABLE 4

Delay of flame at perforated sheeting arresters.
All flames passed through the arresters.

Diameter of aperture in arrester cm							
0.055		0.100		0.123		0.175	
Flame velocity cm/s	Delay m s	Flame velocity cm/s	Delay m s	Flame velocity cm/s	Delay m s	Flame velocity cm/s	Delay m s
525	170	460	170	360	10	260	20
510	200	450	20	350	10	230	0
330	40	310	240	290	220	150	210
290	200	210	150	270	0	130	>1400
260	180	200	70	-	-	110	40
240	170	-	-	-	-	90	0
-	-	-	-	-	-	85	30

In the experiments with a 28-mesh wire gauze arrester, all the flames were quenched by the arrester. The flame velocities ranged between 240 and 525 cm/s, using ducting arrangement ix (Fig. 3).

Gas ignited near closed end of ducting

The crimped ribbon arresters were the only type used in these tests, because perforated sheeting and 28-mesh gauze arresters would not be capable of quenching the fast flames that developed in this ducting arrangement.

The results of tests carried out with no obstructions inside the ducting, apart from the flame arrester, are summarised in Table 5. Values are given of the velocity with which the flame approached the arrester and, where measured, the explosion pressure at this instant. Values of the maximum pressures developed by the explosions are also included; the arrival of the flame at the arrester was taken to be at the instant when there was a discontinuity in the pressure record. The cine camera records showed that the flame propagated at a fairly constant velocity along the ducting, the foremost part of the flame being in the centre of the ducting, and the flame did not stabilize on the arrester. The length of the flame was several duct widths, i.e. a metre or so.

In order to increase the violence of the explosions with the arrester of smaller crimp, a bar of width 1.3 or 2.75 cm was mounted centrally across the ducting at a distance of 1.8 m (6 ft) upstream of the arrester (i.e. 1.8 m from H, Fig. 3). The results of these tests are given in Table 6. In some instances when the arrester failed to quench the explosion there was no record of flame emerging from the arrester, although flame was later seen to be propagating in the duct a metre or so downstream of the arrester. Thus either the flame ceased to emit light on emerging from the arrester, because of cooling by the arrester, or the flame was quenched and then the unburnt gas mixture was reignited by hot combustion products passing through the arrester. A similar effect was found in subsequent experiments with a narrow explosion tube, described in the Appendix.

TABLE 5

Results of tests with crimped ribbon arresters; no obstructions in ducting

Nominal crimp height of arrester in	Ducting arrangement (Fig. 3)	Velocity of flame at arrester cm/s	Flame quenched by arrester	Explosion pressure when flame reached arrester p.s.i.g.	Maximum explosion pressure p.s.i.g.	Position of pressure gauge (Fig. 3)
0.075	xii	8100	No	3.2	3.2	0.9 m from H
0.048	xii	7600	Yes	2.0	3.3	0.9 m from H
		7900	"	2.0	3.3	" " "
		9400	"	-	-	-
	xiii	10200	Yes	3.4	4.1	0.9 m from H
		12500	"	3.4	3.4	0.9 m from L
	xiv	10300	Yes	1.5	3.3	4.6 m from H
		10700	"	-	-	-
	xv	9200	Yes	-	1.8	0.9 m from L
		10400	"	1.6	3.3	6.4 m from H
	xvi	7400	Yes	1.6	2.5	8.2 m from H
		9400	"	-	1.3	0.9 m from L

TABLE 6

Results of tests with arrester of smaller crimp, and with obstructing bar in duct. Ducting arrangement xii (Fig. 3)

Width of obstructing bar cm	Velocity of flame at arrester cm/s	Flame quenched by arrester	Explosion pressure when flame reached arrester p.s.i.g.	Maximum explosion pressure p.s.i.g.	Position of pressure gauge (Fig. 3)	Observations
1.3	7600	Yes	5.6	5.6	0.9 m from H	
	9100	"	6.2	6.2		
	9200	No	5.0	5.0		
	9700	"	5.0	5.0		
	9750	Yes	5.0	5.0		
2.75	11300	No	-	-	-	Perspex windows broken
	13300	"	-	-	-	-
	-	-	9.1	9.1	0.9 m from H	Perspex windows broken

DISCUSSION

Gas ignited near closed end of ducting

Previous results with crimped ribbon and other arresters[1,2,3,5] had shown that the relationship between the dimensions of the arrester and the velocity of the flame that was just quenched by the arrester could be represented by

$$(V + v) = \frac{2.4\pi\, k\, (T_h - T_o)\, ny}{Q/\chi_o} \quad \text{...............(i)}$$

where
- k is Thermal conductivity of flame gases
- n is Number of apertures in unit area of arrester face
- Q is Heat lost by unit area of flame
- T_h is Mean temperature of flame gases in arrester
- T_o is Temperature of the arrester
- V is Flame velocity, relative to the unburnt gas
- v is Gas velocity along the explosion tube
- χ_o is Thickness of flame propagating at standard burning velocity
- y is Thickness of arrester

Equation (i) is not independent of d, the aperture diameter, because n is a function of d.

In the derivation of equation (i) the pressure of the flame gases was assumed to be atmospheric, and this was a reasonable assumption for the cases considered[1,2,3,5], which were explosions in a straight narrow tube without obstructions. However, in the present experiments with ignition at the closed end of the ducting the explosion pressure rose appreciably above atmospheric, and so equation (i) needed to be modified to allow for the effect of increased pressure on the performance of the flame arresters.

The burning of propane/air flames at ambient pressures within the range 0.5 - 2.0 atm. was investigated by Botha[4], using a water-cooled flat-flame burner. The amount of heat to be extracted from unit volume of propane, measured at N.T.P., that was necessary to reduce the burning velocity of a stoichiometric propane/air mixture to 4 cm/s was approximately constant over the pressure range. A reduction of this amount in the burning velocity was previously assumed sufficient to quench the flame[3]. If the pressure of the unburnt propane/air mixture were raised the heat released on combustion of unit volume of mixture would be raised proportionately, but the volume of flame would stay approximately constant, because the flame temperature and the dissociation of product molecules would change little with pressure over the range in question. Hence the heat to be abstracted from unit volume of flame in order to quench it (Q/χ_o) should be approximately proportional to the pressure, and equation (i) should become

$$(V + v) = \frac{2.4\pi\, k\, (T_h - T_o)\, ny}{Q/\chi_o}\, \frac{P_o}{p} \quad \text{.............(ii)}$$

where
- P_o is Atmospheric pressure
- p is Explosion pressure (absolute) when the flame reaches the arrester

The following values were taken for the properties of the flames[2]:

$$k = 1.7 \times 10^{-4} \text{ cal cm}^{-1}\text{s}^{-1}\,{}^{\circ}\text{K}^{-1}$$

$$(T_h - T_o) = 1710^{\circ}\text{K}$$

$$Q/\chi_o = 2.32 \times 10^{-2} \text{ cal cm}^{-3} \quad \text{at atmospheric pressure}$$

Hence equation (ii) became

$$(V + v) = 93\, ny\, \frac{P_o}{p}$$

The results for the large-scale arrester of nominal crimp height 0.048 in, obtained from Tables 5, 6 and 9 (Appendix), are plotted in Figs 5 and 6. Fig. 5 shows the results for experiments in which the flames were quenched by the arrester, and Fig. 6 shows results when the arrester failed to quench the flame. Both Figs 5 and 6 include results of experiments in which the arrester was either exposed to explosions in the wide ducting or parts of the arrester were exposed in turn to explosions in a narrow tube. Equation (ii) is represented in Figs 5 and 6 by a straight line. In theory, all the points shown in Fig. 5 should lie below the line and in Fig. 6 they should lie above the line. Most of the points do in fact lie on the predicted sides of the lines in Figs 5 and 6, indicating that equation (ii) is in reasonable agreement with the results obtained using wide or narrow ducting.

For the small-scale arrester of the same thickness and nominal crimp height, equation (ii) predicted that the arrester should have failed when the flame velocity exceeded 8600 cm/s, when the explosion pressure was at the experimental value of 7 p.s.i.g. obtained in the L-shaped tube described in the Appendix. The results given in Table 8 showed that flames propagating at velocities of 8500 cm/s and above passed through the arrester, although a few flames with velocities above the predicted value were quenched by the arrester. With the straight tube, described in the Appendix, the same arrester quenched all flames with velocities up to 11200 cm/s, the maximum obtained. The explosion pressure when the flame reached the arrester was approximately atmospheric, and equation (ii) predicts that under these conditions the arrester should quench flames propagating at velocities up to 12700 cm/s. Thus equation (ii) was in reasonable agreement with the results obtained with the small-scale arrester, and there was no evidence that variation of the diameter of the arrester exerted an effect upon the flame-arresting properties of the arrester.

Gas ignited near open end of ducting

With the large-scale arrester of nominal crimp height 0.075 in, mounted in the wide ducting, acoustic vibration of the flame as it propagated along the ducting was practically absent. Hence the flame velocities obtained in the experiments with this arrester in Table 3 were low, and these velocities were effectively the velocities of flames relative to the unburnt mixture. In previous experiments with a small-scale crimped ribbon arrester, of the same thickness and nominal crimp height, in a narrow tube[1], acoustic vibrations were obtained although the amptitude was small compared with the thickness of the arrester. In these experiments only the velocity of the flame relative to the tube was measured, and the flame passed through the arrester at velocities in excess of 3000 cm/s. Further experiments with the same arrester, described in the Appendix of the present report, confirmed that the arrester failed when the velocity of the flame relative to the tube exceeded 3100 cm/s (Table 10) and also showed that when the arrester failed the velocity of the flame relative to the unburnt gas was close to that measured with the large-scale arrester in the wide ducting. With these arresters on the two scales of size it appeared that the velocity of the flame relative to the unburnt gas decided whether the flame would propagate through the arrester, and the behaviour of the two arresters in this respect was similar. Comparable behaviour had been reported previously for ethylene/air flames propagating through a perforated block flame arrester in which the apertures were near to the quenching diameter in size[6]. The flame quenching ability then depended mainly on the aperture diameter of the arrester, increased thickness of the arrester yielded comparatively little benefit, and the value of flame velocity predicted by equation (i) was considerably greater than the measured value. In the present case equation (i) predicted a flame velocity of 5200 cm/s for the small-scale arrester, assuming that the full arrester thickness operated.

The results obtained with perforated plate arresters (Fig. 4 and Table 4) could not be compared directly with previous values in a narrow tube[3] because in most cases where the flame passed through the arresters it had previously stabilized on the arresters. The stabilization appeared to be due to bulk movement of gas through the arresters and would be assisted by the thin structure of the arresters.

CONCLUSIONS

1. The velocities of stoichiometric propane/air flames just able to propagate through crimped ribbon, perforated plate, or wire gauze arresters were apparently unchanged when the diameters of the arrester, and the duct in which it was mounted, were increased from 6.4 to 30.5 cm.

2. Flame propagating from the open end of the wider ducting could stabilize on the arrester for a short time, although no fuel/air mixture was being blown through the arrester. Evidence of stabilization of flame was only obtained with thin arresters.

3. A crimped ribbon arrester, of thickness 3.2 cm and nominal crimp height 0.048 in, was able to quench stoichiometric propane/air flames propagating in a straight smooth duct 30.5 cm in section.

When an obstructing bar of width 1.3 or 2.8 cm was mounted across the ducting, the explosion pressure and the flame speed both increased, and some flames passed through the arrester.

4. The behaviour of the crimped ribbon arrester was related theoretically to that of a similar arrester in a narrow L-shaped tube and to other arresters and fuels in straight, narrow, tube systems. When explosion pressures were substantially above atmospheric, the performance of the arrester in quenching flames was correspondingly reduced.

5. The extent to which the flame speeds and the explosion pressures of propane/air mixtures are increased by increasing the tortuosity of the tube system containing the mixtures was considerable, but the ultimate extent was not investigated. Whether flames that are accelerated in this manner would continue to propagate at high velocity in a subsequent straight length of tube is unknown. If not, a determination of the distance covered before the velocity reverts to the usual range for straight tubes would be of considerable practical value.

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APPENDIX

Further tests in a narrow explosion tube

The results obtained with the crimped ribbon arresters in large-scale ducting (Tables 3, 5 and 6) were not in agreement with the results previously obtained with arresters of nominally the same sized crimps in a smaller diameter tube[1]. Some further tests were therefore carried out in which small-scale arresters, and parts of the large-scale arresters, were exposed to flames propagating in a narrower tube whose internal diameter was 6.4 cm. The purpose of the experiments was to re-examine the behaviour of the smaller arresters in the light of the experience with the larger arresters, with which flame luminosity sometimes vanished temporarily on emerging from the arrester or marked acoustic vibrations did not develop. Also, the behaviour of the large-scale arresters in large and small-scale ducting could be compared directly.

Gas ignited near closed end of tube

Two tube arrangements were used. The first was a straight tube, with a run-up length of 158 cm, which has already been described in detail (ref 1, Fig. 1, arrangement xii). In the second arrangement, which was L-shaped and is shown in Plate 5, the arrester was mounted in a tube connected to the bar of a tee-piece, the other end of the bar was blanked off, and the igniter was in a tube connected to the stem of the tee-piece. The distance between the arrester and the tee was 67 cm, between the tee and the igniter was 17 to 33 cm, and between the arrester and the open end of the tube was 102 cm. When used, a capacity cell for the measurement of the explosion pressure was mounted in the blanked end of the tee. The dimensions of the small-scale arrester are given in Table 7. The experimental procedure was the same as that described earlier[1], with the exception that the drum camera was sited about 2 metres away from the tube, thus extending the field of view of the camera. A second drum camera was stationed about 70 cm from the arrester, between the arrester and the open end of the tube, to confirm whether or not the flame had passed through the arrester.

TABLE 7

Dimensions of the small-scale crimped ribbon arresters[1]

Nominal crimp height in.	Thickness of arrester cm.	Total crimped area cm^2	Fraction of crimped area open to gas flow	Mean area of one cell cm^2	Mean equiv. hydraulic diameter (d) cm
0.048	3.2	24.4	0.85	2.0×10^{-2}	0.16
0.075	5.1	24.6	0.91	8.3×10^{-2}	0.25

The results obtained with the small-scale arrester, of thickness 3.2 cm, using the straight tube, showed that the flames were all quenched by the arrester. The flame velocities ranged from 5600 to 11200 cm/s and the explosion pressures, when the flame reached the arrester, were approximately atmospheric. The pressures were measured near to the closed end of the tube.

With the same small-scale arrester in the L-shaped explosion tube, the explosions were more violent and the arrester was not able to quench all the explosions. When the arrester failed, the flame re-appeared 30-50 cm downstream of the arrester. Over this distance the flame was either propagating without emitting light, or was extinguished and the hot products re-ignited the unburnt gas; similar behaviour had been observed with a large-scale arrester in the wide ducting. A summary of the results is given in Table 8; the explosion pressures when the flame reached the arrester were about 7 p.s.i.g.

TABLE 8

Tests with small-scale arrester in L-shaped tube
(nominal crimp height 0.048 in.)

Velocities of flames quenched by arrester cm/s	8200, 8500, 8600, 8700, 9300, 9400
Velocities of flames that passed through arrester cm/s	8500, 8800, 9600, 9700, 10800, 11200

Three portions of the large-scale arrester (nominal crimp height 0.048 in, Table 1) were also exposed to flames propagating in the L-shaped tube. One portion was selected for test from each of the three sections of the arrester (Plate 1). In some cases the explosions propagated through the arrester, again without the emission of light on leaving the arrester. A summary of the results is given below.

TABLE 9

Tests with three portions of the large-scale arrester exposed in turn to explosions in L-shaped tube (nominal crimp height 0.048 in).

	Velocities of flames quenched by arrester cm/s	Velocities of flames that passed through arrester cm/s
First portion	9100, 9600, 10300, 11200, 11800, 11900	10400, 10600, 10700, 10900, 11000, 11300
Second portion	9900, 10000, 10300, 10500	11300
Third portion	9700, 9800, 9900, 10400, 10600, 10700	10300, 10400, 10500, 10700, 11000, 11300

Gas ignited near open end of tube

The tubes used were straight and had run-up lengths of 158 or 312 cm; they have already been described in detail (ref 1, Fig. 1, arrangements vi and vii). The experimental procedure was the same as that described earlier[1], with the exception that the drum camera was situated about 2 metres away from the tube. From the camera record it was possible to measure both the velocity of the flame relative to the tube and, from the vibratory motion of the flame, the velocity of the flame relative to the unburnt gas. The dimensions of the small-scale arrester are given in Table 7.

A short series of tests was carried out with the small-scale arrester of nominal crimp height 0.075 in, in which the velocities of the flame relative to the unburnt gas and to the tube were measured. The results are summarised in Table 10. In the more extensive investigation reported previously(1) only the flame velocity relative to the tube had been measured. In experiments in which the flame propagated through the arrester, it was delayed on arrival at the arrester for 12-14 m s.

TABLE 10

Results of tests with small-scale arrester
(nominal crimp height 0.075 in)

Velocity of flame relative to tube cm/s	Velocity of flame relative to unburnt gas cm/s	Flame quenched by arrester.
2900	340	Yes
3000	350	Yes
3100	350	Yes
3100	350	No
3300	370	Yes
5900	400	No

Further tests were carried out in which three portions of the large-scale arrester (nominal crimp height 0.075 in, Table 1) were exposed to flames in the smaller diameter tube. The maximum velocity of the flame relative to the tube was only 1500 cm/s, which gave a maximum velocity of flame relative to the unburnt gas of 180 cm/s, and in all the tests the flame was quenched by the arrester. The low maximum velocities were attributed to the relatively mild acoustic vibrations that developed during the explosions, possibly due to damping of the vibrations by the crimped metal which was more resilient than in the small-scale arrester.

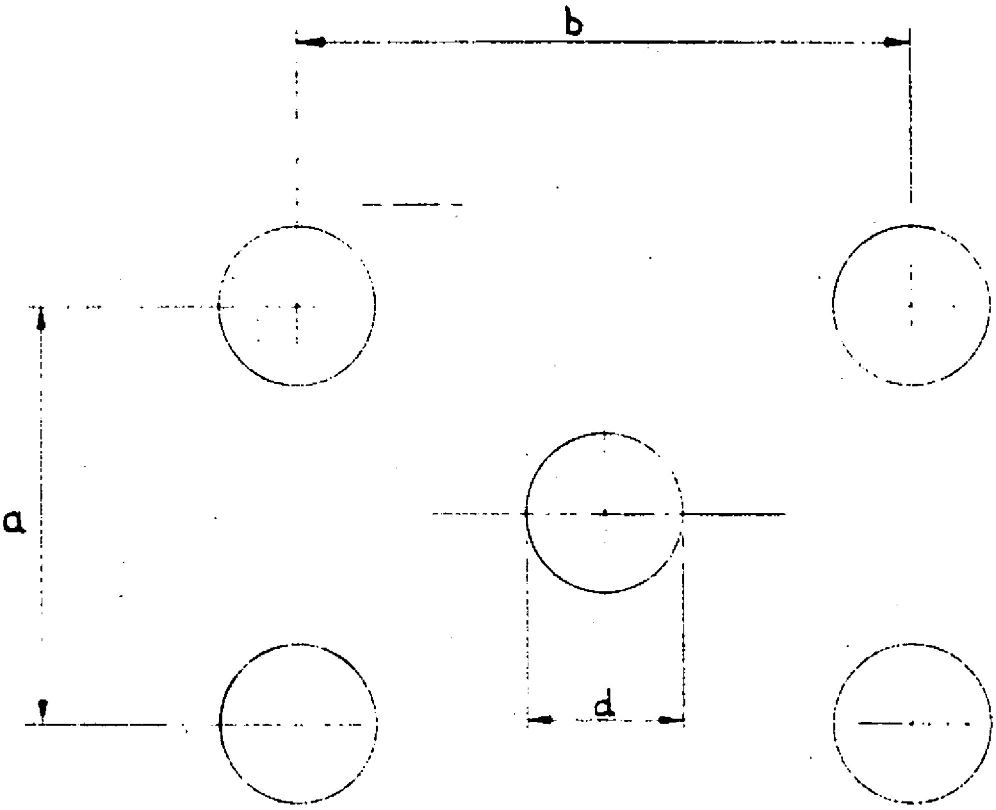

FIG. I. THE ARRANGEMENT OF THE HOLES IN THE PERFORATED SHEETING ARRESTERS (SEE TABLE 2)

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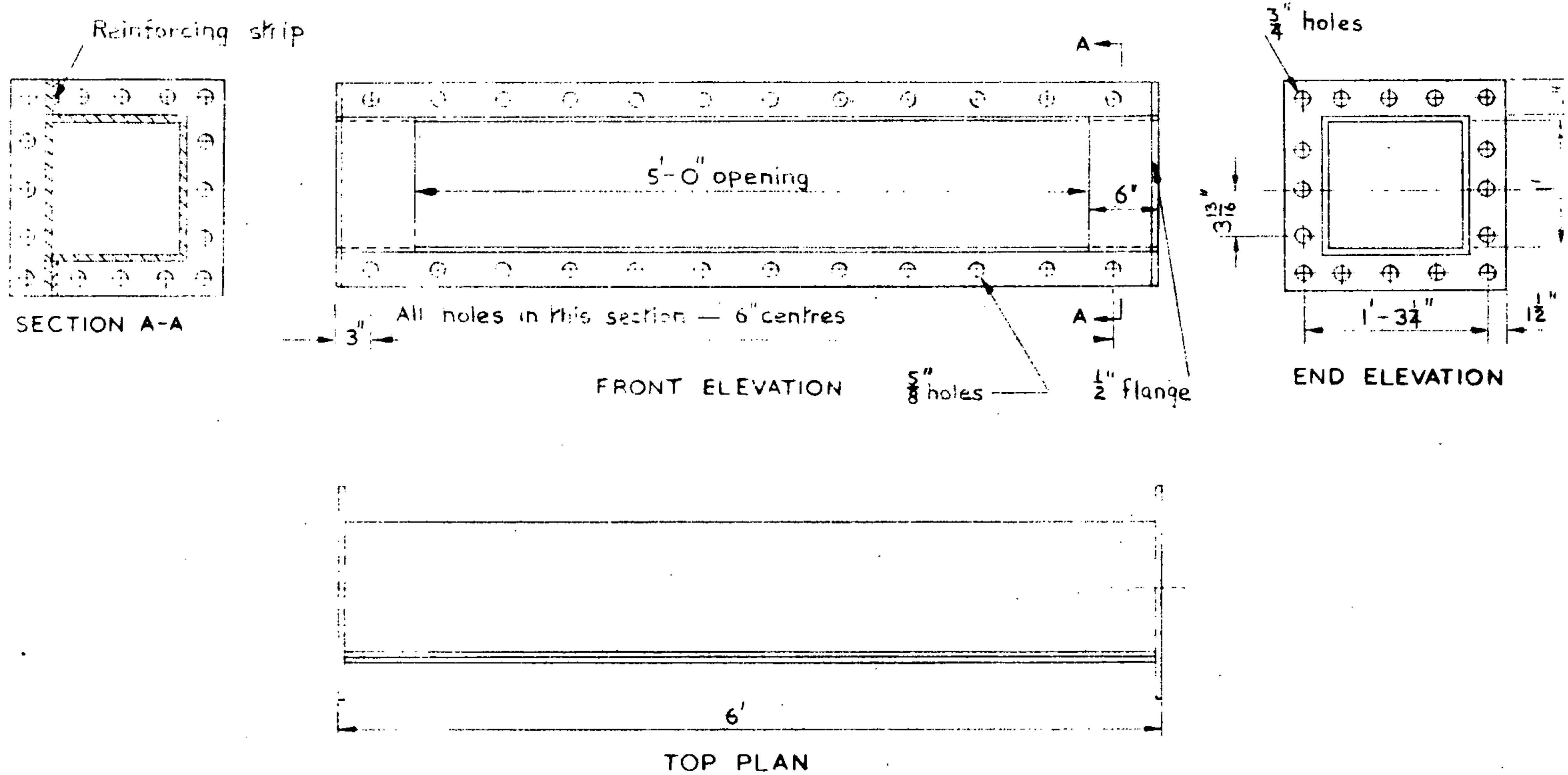
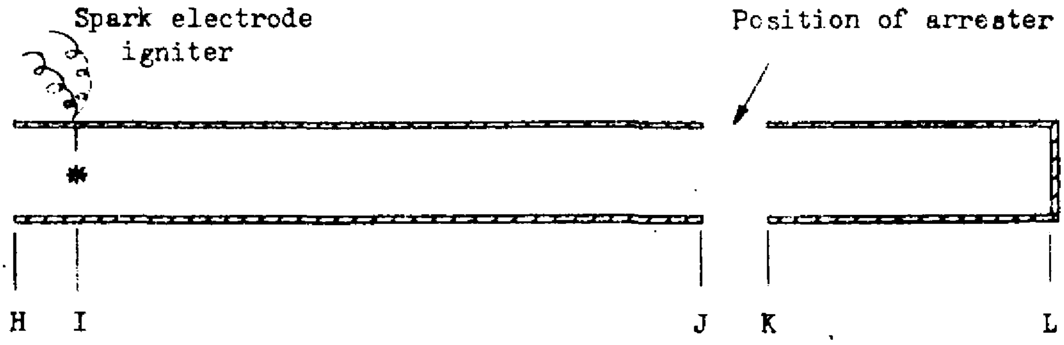
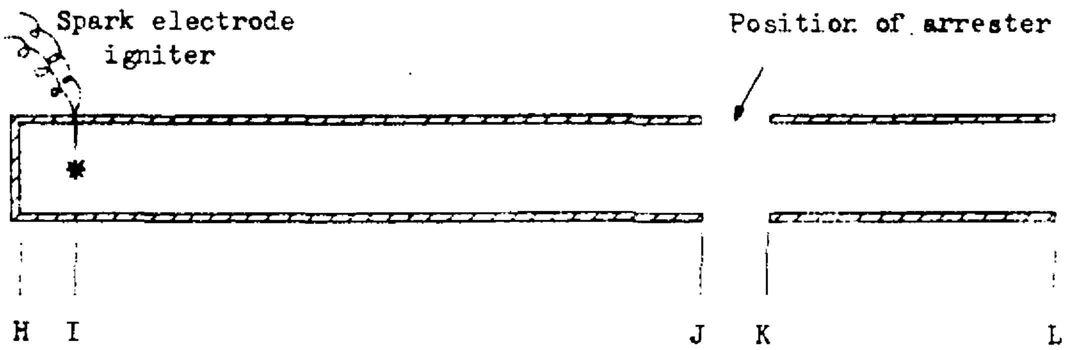


FIG. 2 DIMENSIONS OF EXPLOSION DUCTING



Igniter near open end of ducting



Igniter near closed end of ducting

Not to scale.

Table 11

Dimensions of ducting systems

	Arrangement	HI m	HI ft	IJ m	IJ ft	KL m	KL ft
Igniter near open end of ducting	i	1.7	5.5	0.2	0.5	3.7	12
	ii	1.5	5.0	0.3	1.0	3.7	12
	iii	1.1	3.5	0.8	2.5	3.7	12
	iv	0.5	1.5	1.4	4.5	3.7	12
	v	1.4	4.5	2.3	7.5	3.7	12
	vi	0.5	1.5	3.2	10.5	3.7	12
	vii	1.4	4.5	4.1	13.5	3.7	12
	viii	1.4	4.5	6.0	19.5	3.7	12
	ix	1.4	4.5	7.8	25.5	1.8	6
	x	0.6	2.0	8.5	28	3.7	12
	xi	1.4	4.5	9.6	31.5	1.8	6
Igniter near closed end of ducting	xii	0.5	1.5	3.2	10.5	1.8	6
	xiii	0.5	1.5	5.0	16.5	1.8	6
	xiv	0.5	1.5	6.9	22.5	1.8	6
	xv	0.5	1.5	8.7	28.5	1.8	6
	xvi	0.5	1.5	10.5	34.5	1.8	6

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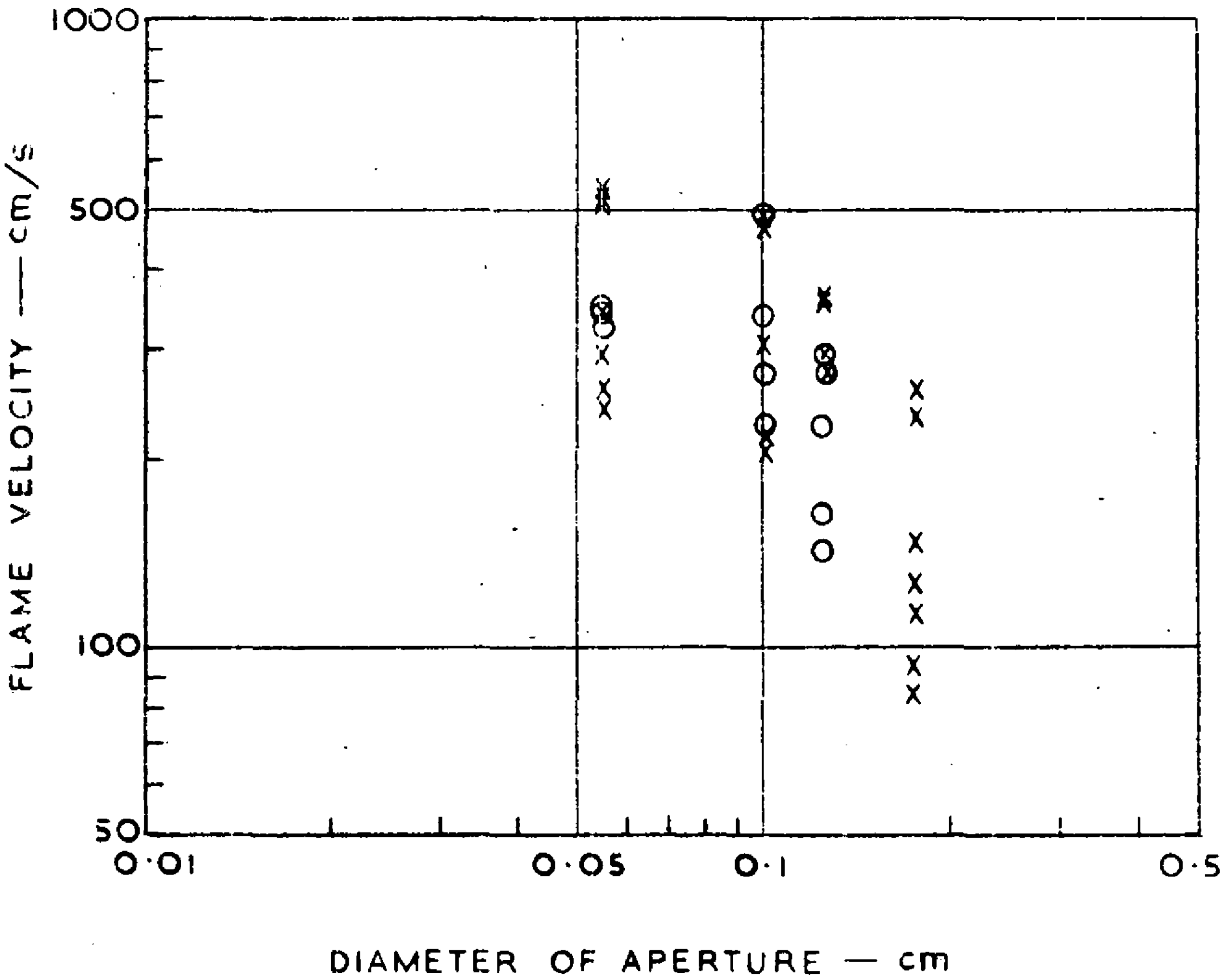
FIG.3. DETAILS OF THE EXPLOSION DUCTING ARRANGEMENTS



Ignition near open end of tube
Tube arrangements (Fig 3) i – viii, x

o Arrester quenched flame
x Arrester did not quench flame

FIG.4. THE QUENCHING OF FLAMES BY PERFORATED PLATE ARRESTERS

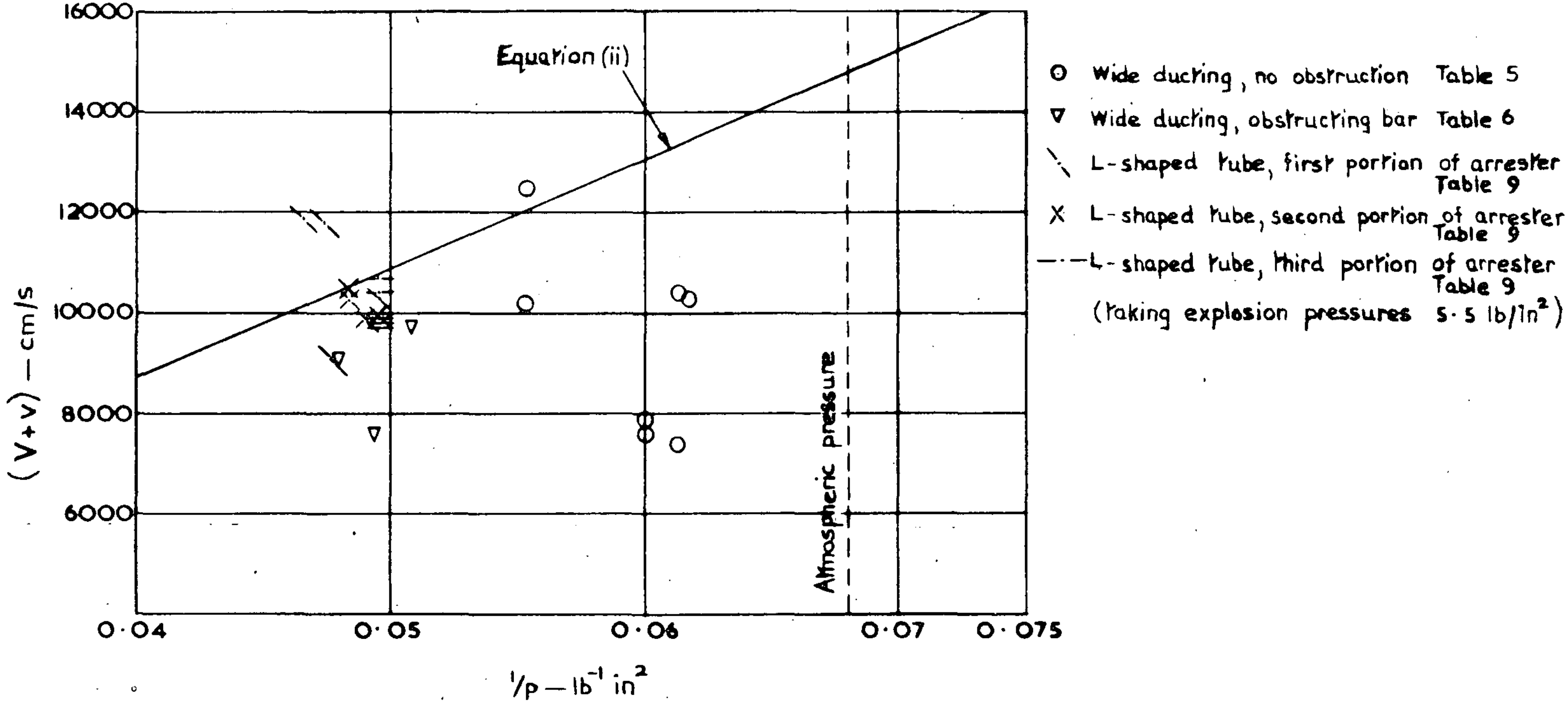


FIG. 5. RESULTS FOR ARRESTER OF NOMINAL CRIMP HEIGHT 0·048 in. (TABLE 1) ALL FLAMES QUENCHED

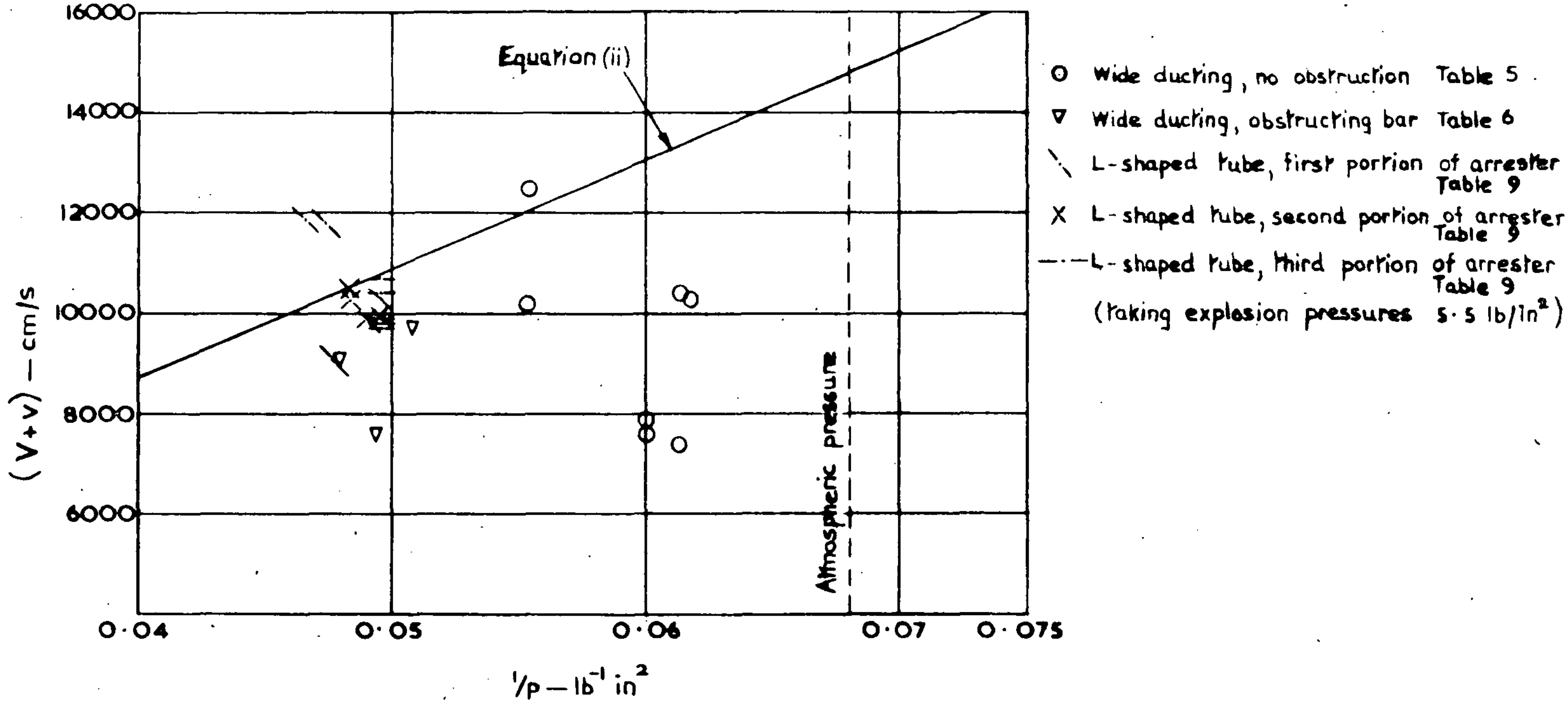


FIG.5. RESULTS FOR ARRESTER OF NOMINAL CRIMP HEIGHT 0·048 in. (TABLE 1) ALL FLAMES QUENCHED

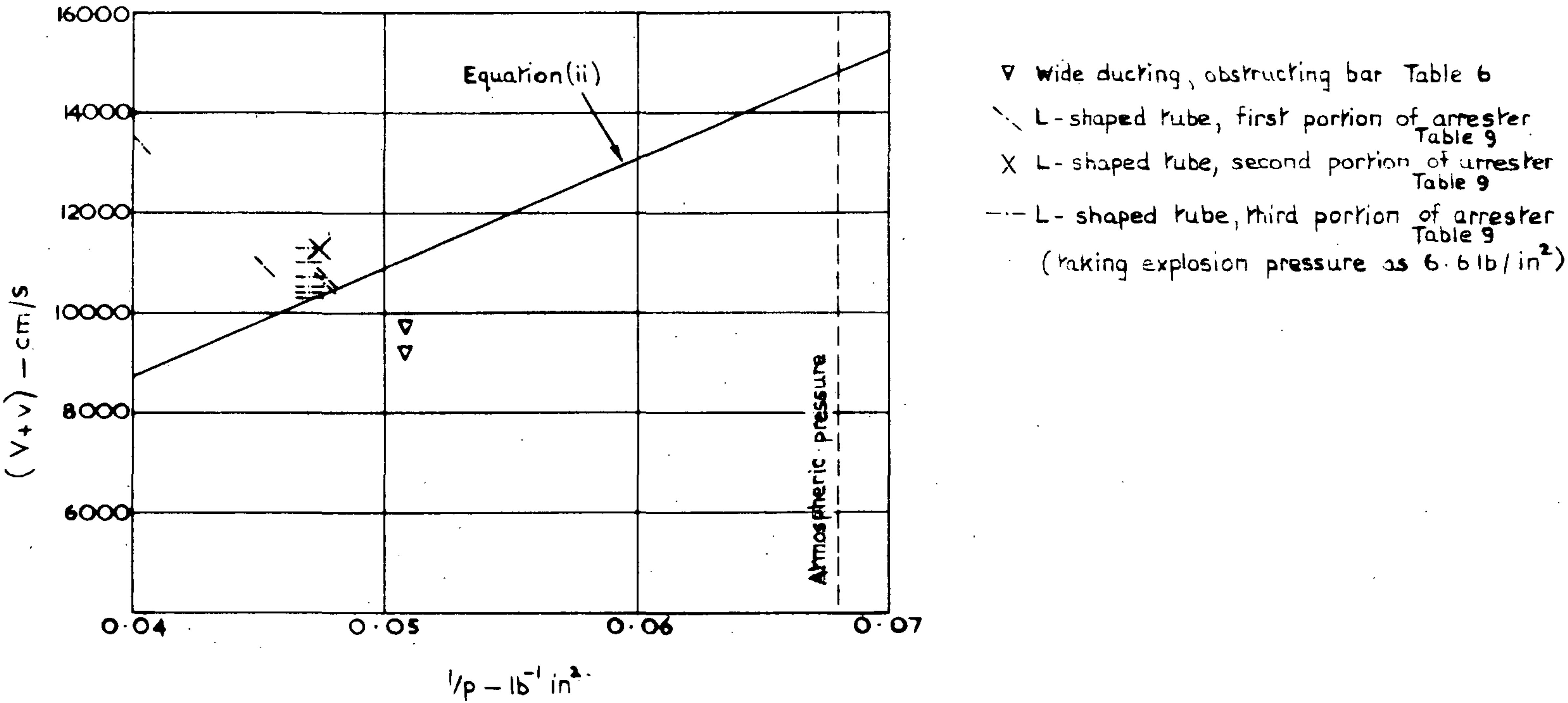


FIG.6. RESULTS FOR ARRESTER OF NOMINAL CRIMP HEIGHT 0·48 in (TABLE.1.) ALL FLAMES PROPAGATED THROUGH ARRESTER

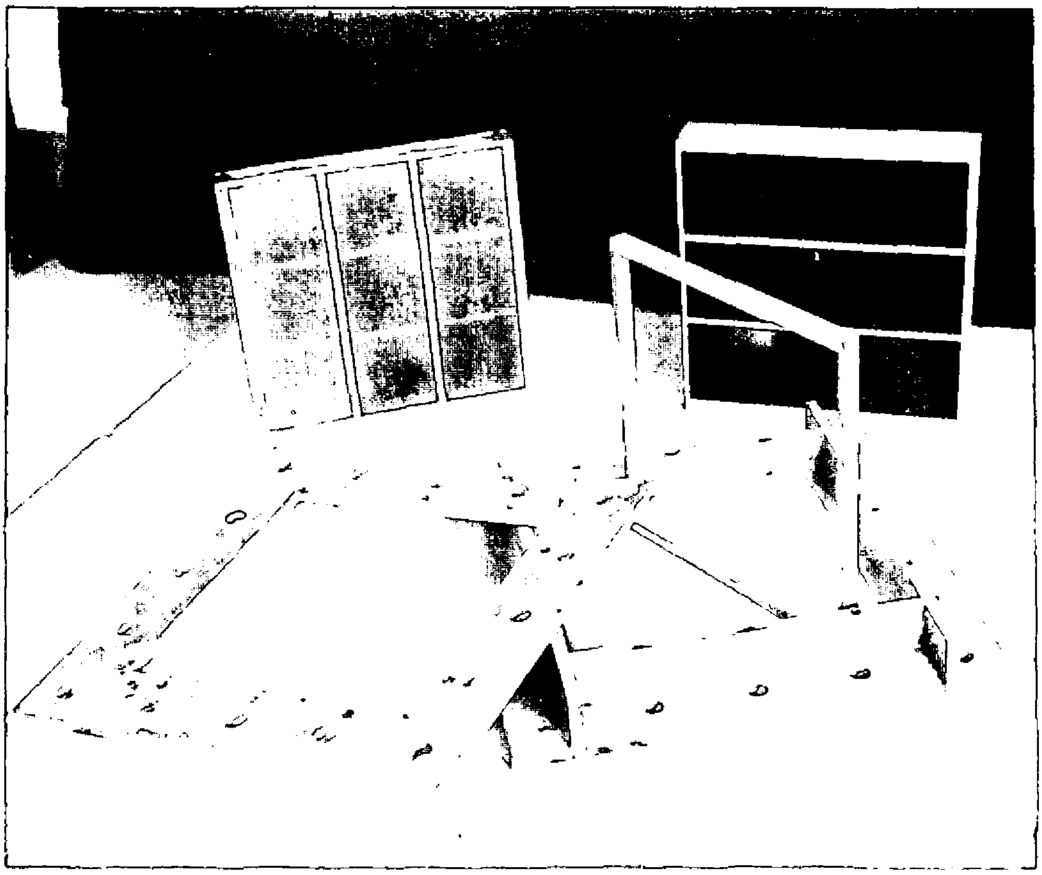


PLATE 1
Flame arresters and flanged support

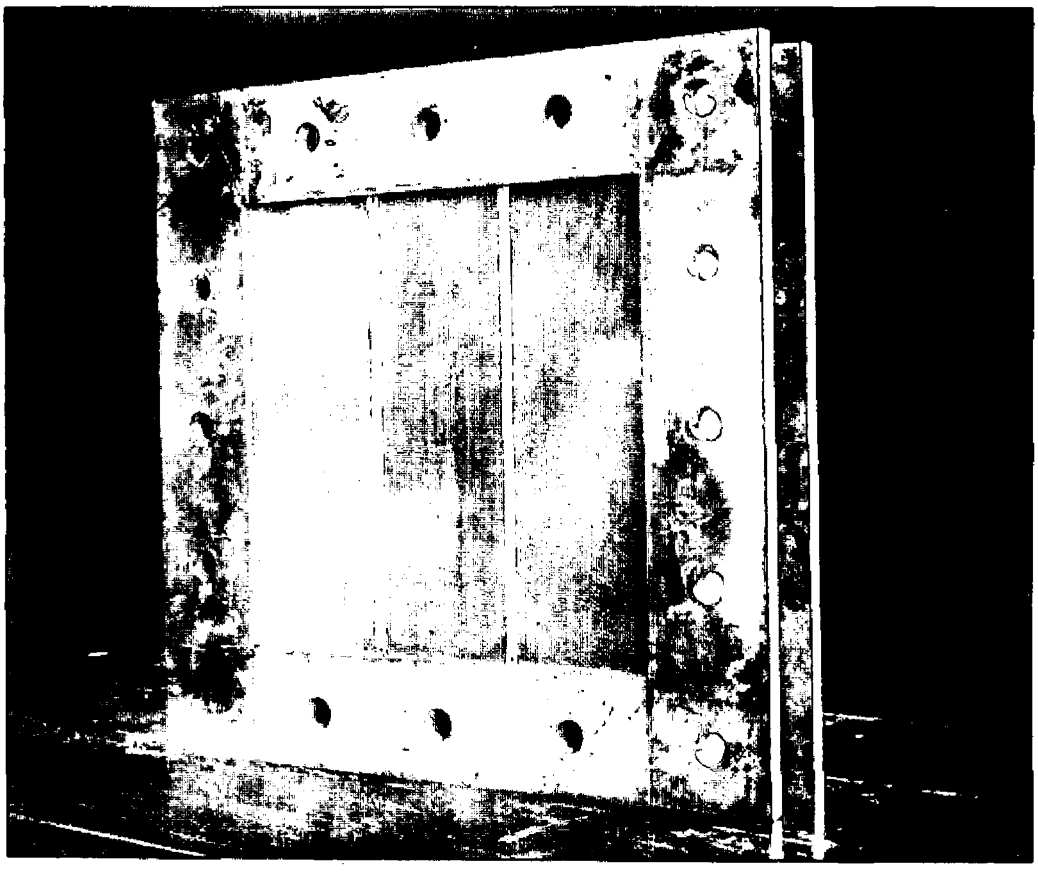


PLATE 2
Flame arrester mounted in support

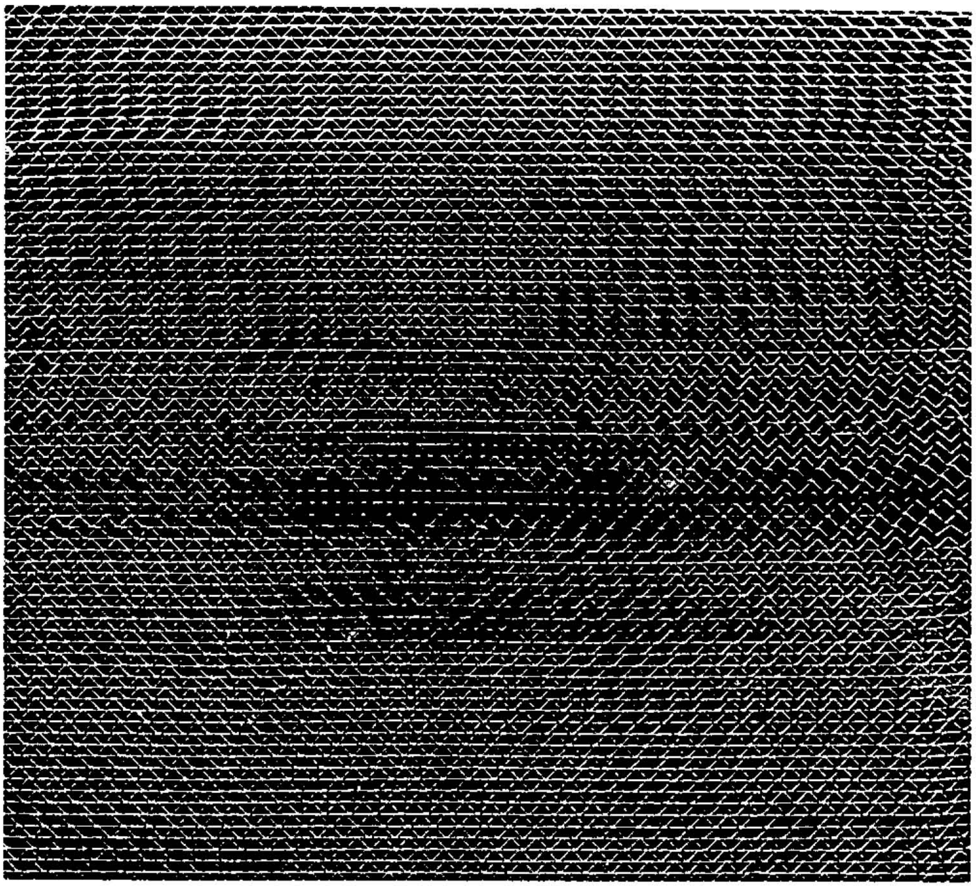


PLATE 3
Portion of crimped ribbon arrester, nominal crimp height 0.048 in.
Enlarged photograph

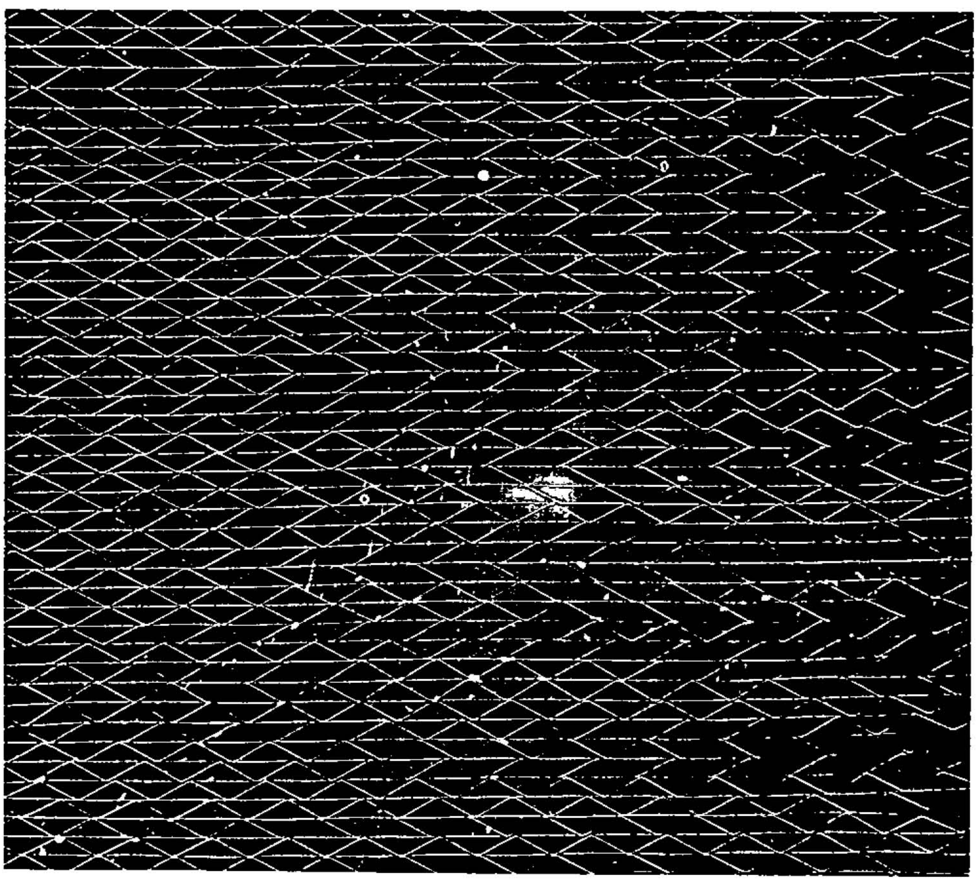


PLATE 4
Portion of crimped ribbon arrester, nominal crimp height 0.075 in.
Enlarged photograph

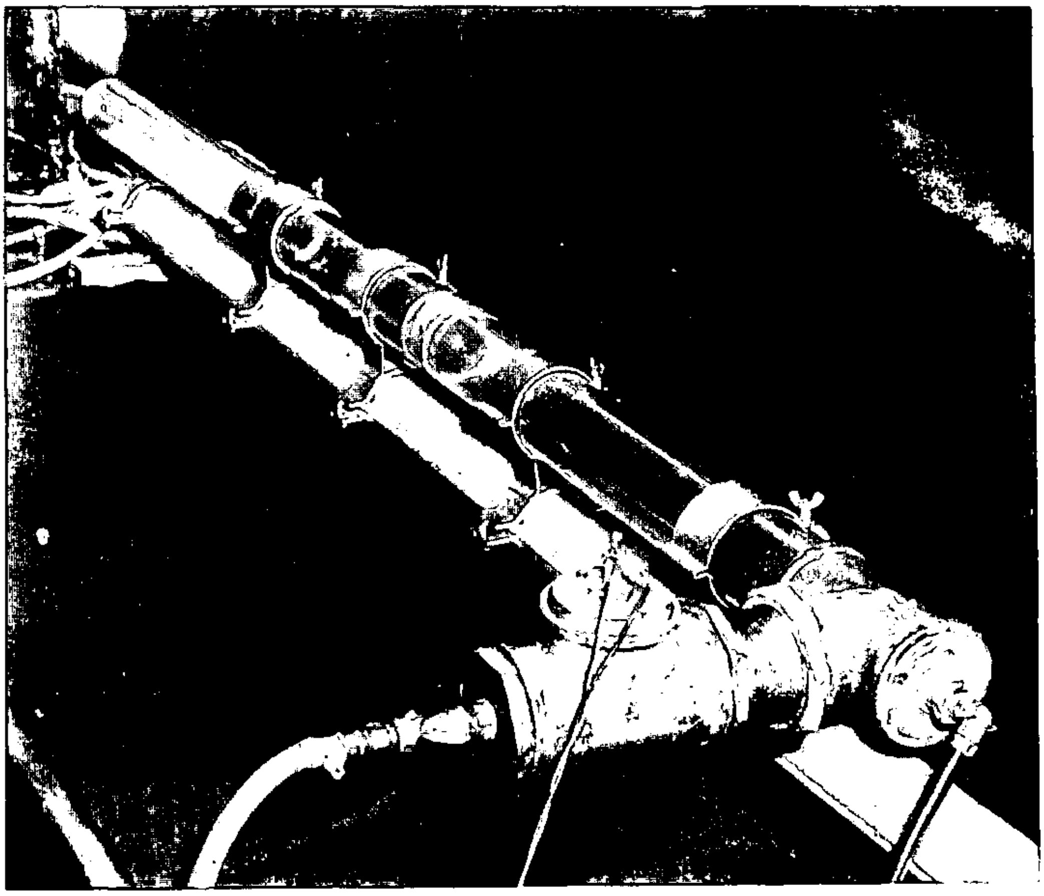


PLATE 5
L-shaped explosion tube, showing igniter near closed end