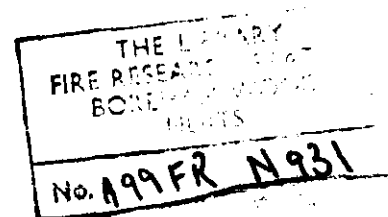


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Fire Research Note

No.931



PERFORMANCE OF METAL FOAM AS A FLAME
ARRESTER WHEN FITTED TO GAS EXPLOSION
RELIEF VENTS

by

Z. W. ROGOWSKI and S. A. AMES

April 1972

FIRE
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PERFORMANCE OF METAL FOAM AS A FLAME
ARRESTER WHEN FITTED TO GAS EXPLOSION RELIEF VENTS

by

Z. W. Rogowski and S.A.Ames

SUMMARY

A new metallic foam known commercially as 'Retimet' was examined for the purpose of protecting industrial equipment for use in flammable atmospheres.

The metal foam functioned as a flame arrester when mounted on the casing of such equipment and relieved pressure resulting from ignition of flammable gas within the equipment but prevented the emergence of flames to the outer atmosphere.

Cubical enclosures up to 28 litres (1 ft^3) in volume have been tested with propane/air and ethylene/air mixtures using two different porosity grades of the metal foam. The pressure developed inside the enclosure was found to be dependent upon the vent area and the porosity of the metal foam. A limiting vent area was found below which damage to the arrester would occur and the outer atmosphere would be ignited. The mechanism of the explosion transmission through the arrester was established.

KEY WORDS: Explosion, Flame arrester, Electrical equipment, Foam, Metallic

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PERFORMANCE OF METAL FOAM AS A FLAME
 ARRESTER WHEN FITTED TO GAS EXPLOSION RELIEF VENTS

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INTRODUCTION

The use of flame arresters to protect industrial equipment has been previously examined and shown to be feasible^{1,2}. The introduction of a new metal foam 'Retimet' led to an investigation into its performance in quenching fast moving flames in pipes. This report describes an examination of the use of metal foam flame arresters to protect industrial equipment for use in areas where flammable gases or vapours may occur. This application requires some specific aspects of performance which may be unimportant in other uses. Thus the arrester matrix must be able to absorb a substantial quantity of heat, without sustaining any thermal damage and at the same time the pressure drop across the arrester must not be too large.

EQUIPMENT AND MATERIALS

Explosion Vessels

Three cubical explosion vessels were used, having capacities of 2.8 litres ($\frac{1}{10}$ ft³), 9 litres ($\frac{1}{3}$ ft³) and 28 litres (1 ft³). Each vessel had open flanged ends with provision for bolting on covers provided with vents. Each cover had circular openings which could be fitted with metal foam flame arrester panels. Fig.1 shows the 9 litre ($\frac{1}{3}$ ft³) vessel with a metal foam arrester panel having an effective diameter of 110 mm (4.3 in). The dimensions and the number of vents used with each vessel are shown in Table 1.

Table 1. Numbers and diameters of vents used

Diameter of vents	Volume of Vessel litres		
	2.8 l ($\frac{1}{10}$ ft ³)	9 l ($\frac{1}{3}$ ft ³)	28 l (1 ft ³)
64 mm (2.5 inches)	-	1	-
110 mm (4.3 inches)	1	1	1 and 2

The amount of venting is usually specified by the ratio K,
where $K = \frac{\text{cross-sectional area of vessel}}{\text{total area of vents}}$

Pressure measurement

The pressures developed inside the explosion vessels were measured using a piezo transducer screwed into the centre of one of the side walls of the vessel. The transducer was connected via a charge amplifier to a cathode ray oscilloscope from which the pressures were recorded using a polaroid camera.

Ignition

Ignition of the flammable mixture inside the vessel was achieved using a pair of spark electrodes (spaced 2 mm apart) connected to a 12 volt automotive induction coil. The ignition electrodes were used in three different positions along the central axis of the vessel. In the case of the 2.8 litre ($\frac{1}{10}$ ft³) vessel, 25 mm (1 in) from each end or in the centre, and for the other vessels 50 mm (2 in) from either end or in the centre.

Test chamber

The explosion vessel under test was situated inside a 400 litre (14 ft³) test chamber, one whole wall of which consisted of a light explosion relief panel (0.004 cm thick polyethylene) see Fig 2 and 3.

The chamber was fitted with a gas inlet and outlet, and various inlet points for service to the explosion vessel. A pair of ignition electrodes situated close to the polyethylene panel permitted deliberate ignition of the 'outer' mixture inside the test chamber. A small electric fan was provided to stir the flammable mixture within the chamber.

Temperature measurement on arrester surface

In order to time the arrester failure the temperature of the outer surface of the arrester was recorded during some of the tests. This was achieved using a fine 0.5 mm diameter thermocouple and a pen recorder. The junction was placed within 1 mm of the outer surface of the arrester not less than 20 mm from the periphery.

Stabilised flame 'flash back' tests

In order to examine the effects of stabilised flames on the surface of a metal foam arrester a series of tests were carried out using the apparatus shown in Fig.4. It consisted of a metal tube 40 cm (16 in) long with facilities for fixing a circular specimen of the metal foam 33 mm (1.4 in) diameter just inside the open end of the tube. A gas

metering and mixing system was attached to the other end in order to provide facilities for passing propane/air or ethylene/air mixture, along the tube and out through the specimen at various velocities.

An optical, disappearing filament pyrometer was set up near the open end of the tube in order to measure the temperature of the surface of the foam whilst the emerging gases were burning on it.

A number of holes 1 mm diameter were drilled in the tube in order to insert thermocouples into the arrester at various distances from the outer surface. A pen recorder was provided to record temperature changes throughout the 'flash back' tests.

Gases and gas metering

The flammable mixtures used during the tests were

4.2 per cent propane/air

6.5 per cent ethylene/air

The gas mixtures were obtained by metering the gases and then mixing in a packed column.

The gas was fed through the chamber via a non-return valve into the explosion vessel whence it passed through the flame arrester into the test chamber and was subsequently vented to atmosphere. An inlet and outlet valve were fitted to the test chamber in order to isolate it during each test explosion See Fig 3.

METAL FOAM

The metal foam is manufactured in various porosity grades 10, 20, 30, 45, etc. these being determined from measurements of permeability of the material. Only the 45 grades were used in these tests although samples representing the coarsest and the finest end of the 45 grade production range were tested.

The thickness of the specimens supplied was nominally $\frac{1}{2}$ inch, but varied from 10.8 to 14.2 mm. The specimens were also examined for density and air permeability. The density was determined by weighing a known volume of each specimen. The air permeability was measured according to a standard test set up by the manufacturer⁴ wherein a sample of the foam (25 mm, 1 inch diameter) is cut out and fixed in a 25 mm (1 inch) internal diameter tube, and the pressure drop across the sample measured whilst air is passing through it at a velocity of 1.78 m/sec. Tables 2 and 3 give the results of density and air permeability determinations.

Table 2 Results of density determinations

(a) Finest 45 grade		(b) Coarsest 45 grade	
Sample	Density g/cm ³	Sample	Density g/cm ³
A	0.49	D	0.47
B	0.44	E)
C	0.62	F) 0.57
		G)
		H)

Table 3 Results of air permeability determinations

Finest 45 Grade			Coarsest 45 grade		
Sample	Thickness mm	Permeability millibars	Sample	Thickness mm	Permeability millibars
A	14.2	1.41	D	12	0.74
B	12.2	1.27	E	12	0.70
C	13.0	1.35	F	12	0.89
			G	11.8	0.70
			H	12.2	0.81

The results of air permeability tests
are plotted against thickness in Fig.5

PROCEDURE

(i) Explosion venting tests

With the fan running, the flammable mixture was metered into the apparatus until a complete change of atmosphere had been achieved. The inlet and outlet valves were shut and the fan turned off.

The mixture inside the explosion vessel was ignited and the pressure developed, recorded photographically from the CRO. If the explosion did not pass into the outer chamber the contents were disposed by exploding. Some tests produced ignition of the outer mixture only after a delay of many seconds, this time delay was recorded along with the duration of any audible oscillations heard after each test. During several tests the transmission of flame to the outer mixture was recorded with a perspex sided vessel, using a high speed motion picture camera.

(ii) Stabilised flame 'flash-back' tests

A series of tests were carried out with specimens of foam 36 mm (1.4 inches) diameter cut from the samples used in the venting tests.

The specimens were placed in turn in the apparatus shown in Fig 4 and a flammable mixture passed through the metal foam at a known, constant velocity. The mixture was ignited, with a match, where it emerged through the metal foam and the time taken before the flame penetrated inside the apparatus was recorded. The test was continued until 30 minutes had elapsed or the upstream gas was ignited.

Each test was repeated 3 times for each of the three different gas mixture velocities (0.24, 0.165 and 0.082 m/sec) on each specimen. The gas mixtures used were the same as were used in the venting tests.

RESULTS

Pressures and minimum safe vent areas

The maximum explosion pressures obtained with both types of metal foam under various venting conditions are given in Table 4. These results are plotted in Figs 6 and 7 and show the relationship between vent area and maximum pressure, each point is a mean value of not less than 3 tests, results obtained with crimped ribbon flame arrester in a previous investigation^{1,2} are plotted for comparison. These results were obtained with arresters made from various ribbons, the crimp height ranged from 1 - 0.5 mm and the length of aperture from 38 - 20 mm. The minimum vent areas for operation without failure in ten tests are shown in Table 5.

Table 5 Minimum safe vent areas in cm² (in²) of arrester area per 10 l(ft³) of flammable mixture

Arrester	Flammable Mixture	
	Propane-air	Ethylene-air
Coarsest	65 (29)	Not Determined
Finest	33 (14.5)	98 (43.5)

Whilst the remote ignition tests gave the highest pressures, the near ignition position was found to lead more readily to arrester failure.

Table 4. Maximum explosion pressures obtained under various venting conditions

Arrester diameter		Enclosure volume		Venting factor (K)	Area/vol. ratio in ² per ft ³	Finest 45 grade				Coarsest 45 grade						
						Ignition position	Propane		Ethylene		Sample No.	Ignition position	Propane		Sample No.	
mm	in.	L	ft ³		kN/m ²		(lb/in ²)	NT	kN/m ²	(lb/in ²)			T			
64	(2.5)	9	($\frac{1}{3}$)	14.2	14.7	Near	50.8 (7.5)	NT	- - -	-	C	Near	464.6 (6.7)	T	D	
						Centre	83 (12)	NT	- - -	-		Centre	6363 (9.2)	T		
						Remote	83 (12)	NT	173 (25)	-		Remote	5952 (8.6)	T		
110	(4.3)	28	(1)	10	14.5	Near	34 (5.0)	NT	- - -	-	B	Near	13.8 (2.0)	T	E	
						Centre	- - -	-	8303 (12)	T			Centre	20.7 (3.0)		T
						Remote	41.5 (6.0)	NT	9605 (14)	T			Remote	17 (2.3)		NT
2x 110	2 (4.3)	28	(1)	5	29	Near	- - -	-	17.3 (2.5)	T	A	Near	4.1 (0.6)	NT	G	
						Centre	9 (1.3)	NT	28.5 (4.1)	T			Centre	55 (0.8)		NT
						Remote	15 (2.2)	NT	41.5 (6.0)	NT			Remote	9.6 (1.4)		NT
110	(4.3)	9	($\frac{1}{3}$)	4.8	43.5	Near	4.2 (0.6)	NT	15 (2.2)	NT	A	Near	5.1 (0.75)	NT	H	
						Centre	5.6 (0.8)	NT	23.5 (3.4)	NT			Centre	5.7 (0.82)		NT
						Remote	9 (1.3)	NT	31 (4.5)	NT			Remote	6.5 (0.95)		NT
110	4.3	2.8 (1/10)		2	14.5	Near	0.35 (0.05)	NT	1.4 (0.2)	NT	A					
						Centre	- - -	-	- - -	-						
						Remote	2.4 (0.35)	NT	5.6 (0.8)	NT						

T Transmitted

NT Not transmitted

Prolonged burning

After the initial explosion had occurred within the explosion vessel, fresh flammable mixture was drawn in from the outer atmosphere due to cooling and contraction of the combustion products in the vessel. This fresh mixture could be ignited and burn close to the inner surface of the flame arrester, the burning usually being accompanied by an audible note, the frequency of which varied from vessel to vessel but was generally in the region of 100 Hz. By timing the duration of this note and by visual observations using a perspex sided vessel it was possible to assess that this prolonged burning continued for up to 35 seconds in some tests unless ended by ignition of the outer mixture. Fig 8 shows the time-temperature curves obtained from the failure indicating thermocouple for fail and non fail tests.

The photographs in Fig 9 are taken from a high speed film taken during an explosion test using a perspex sided box. The three separate phases can be seen and compared with the temperature record in Fig.8.

Phase 1

This shows the ignition of the flammable mixture within the vessel at point A and the subsequent expansion of the reacting gases which eventually reach the walls of the vessel and the arrester.

Phase 2

After all the flammable mixture inside the arrester has reacted the remaining hot combustion products begin to cool and in so doing suck in more fresh flammable mixture which burns immediately after it passes through the arrester at B.

Phase 3

After prolonged burning as described in phase 2 the arrester gets hot and eventually ignites the outer flammable atmosphere at point C.

Thermal damage to arrester

The photograph in Fig 10 shows a metal foam arrester after several experiments in which prolonged burning led to eventual ignition of the outer mixture.

As well as extensive oxidation the arrester shows deep cracks, penetrating the entire thickness of the material and up to 3 mm wide in some places. Similar cracks were found in most of the specimens tested to failure point.

In all the tests where the arrester did not fail no structural damage was observed, although some superficial oxidation occurred in all tests.

Results of stabilised flame 'flash-back' tests

The observations made during the tests showed that there were four possible types of behaviour.

- (a) Where the surface of the arrester did not produce any visible glow, the flame appearing to stabilize one or two millimetres away from the arrester surface.
- (b) When the flame burnt on the arrester surface, producing a red glow which reached a maximum and did not decrease thereafter.
- (c) Where the arrester surface began to glow brightly then gradually cooled to reveal a brighter glow within the arrester matrix.
- (d) As in (c) above but leading to ignition of the upstream gas.

In all tests the maximum surface temperatures were taken with the optical pyrometer and recorded together with the time taken before ignition of the upstream gas, see Tables 6 and 7 for propane/air and ethylene/air mixtures respectively. Wherever the temperature was measured by a thermocouple this was very close to the value recorded by optical pyrometer.

A graph of the thermal gradient measurements within a specimen with a flame stabilized on the surface is shown in Fig.11. The graph in Fig.12 shows time/temperature curves measured at the front and the back of the arrester.

The two curves were obtained from two separate tests, both of which led to transmission of flame to the upstream gas.

These curves show clearly that the high temperature recorded at the front surface (800-1000°C) can eventually penetrate the whole thickness of the specimen.

Table 6 Flash-back with propane/air mixture

Grade of Retimet	Specimen	Permeability M.Bars standard test	Velocity of flammable mixture					
			0.245 m/sec		0.165 m/sec		0.082 m/sec	
			Temp °C	Time sec	Temp °C	Time sec	Temp °C	Time sec
Finest 45 grade	A	1.41	900	-	900	-	840	-
			900	-	900	-	840	-
			900	-	900	-	840	-
	C	1.35	970	-	910	-	>500	-
			960	-	910	-	>500	-
			990	-	910	-	>500	-
	B	1.27	985	-	>500	-	>500	-
			995	-	>500	-	>500	-
			995	-	>500	-	>500	-
Coarsest 45 grade	F	0.89	1000	445	1010	690	>500	-
			1000	465	1010	740	>500	-
			1000	450	1010	860	>500	-
	H	0.81	1050	-	960	-	720	-
			1050	-	960	-	720	-
			1050	-	960	-	720	-
	E	0.70	1090	345	1070	710	>500	-
			1090	410	1070	460	>500	-
			1090	595	1070	450	>500	-

- indicates no flashback within 30 min

Table 7 Flash-back times using ethylene/air mixture

Grade of Retimet	Specimen	Permeability M.Bars standard test	Velocity of flammable mixture					
			0.245 m/sec		0.165 m/sec		0.082 m/sec	
			Temp °C	Time sec	Temp °C	Time sec	Temp °C	Time sec
Finest 45 grade	A	1.41	955	135	960	-	840	-
			955	140	960	-	840	-
			955	130	965	-	845	-
	C	1.35	950	18	965	34	880	6
			955	20	965	36	880	6
			950	22	965	38	880	6
	B	1.27	1025	19	1025	35	950	-
			1025	20	1025	35	950	-
			1025	20	1020	38	950	-
Coarsest 45 grade	F	0.89	940	15	900	30	850	150
			940	16	900	27	850	155
			940	15	900	28	850	170
	H	0.81	965	32	900	10	850	10
			965	22	900	10	855	10
			965	18	900	10	860	9
	G	0.70	1010	11	980	22	890	-
			1010	17	980	22	890	-
			1010	16	980	22	890	-

- indicates no flashback within 30 min.

DISCUSSION

Previous work on metal foam flame arresters

The performance of metal foam arresters in pipes was investigated³ and evidence was produced, that foam having pores of diameter of half, or smaller, than the quenching distance of the gas mixture, extinguished flames travelling with substantial velocities. In these experiments various grades of metal foam were exposed to flames travelling at velocities up to 200 m/sec. No flame front penetrated the metal foam of 45 grade under these conditions and overall performance was no worse than that of crimped ribbon arresters with crimp height similar to the pore diameter of the foam. When coarser grades of metal foam failed to arrest the flame, photographic evidence showed that no visible flame front emerged from the arrester, but a point flame front started some distance downstream from the arrester. It was concluded that at higher flame speeds the arrester quenched the flame but subsequently the hot combustion products emerging from the flame arrester reignited the flammable gas.

Mechanism of arrester failure when venting explosions in small vessels

The mechanism of flame transmission described above cannot operate when arresters are fitted over the vents in small vessels. It has been shown⁵ that in an empty cubical vessel of 9 l volume maximum flame speeds did not exceed 11 m/sec and 21 m/sec for propane-air and ethylene-air mixtures respectively and were well below the minimum flame velocity required for the arrester to fail. The timing of the arrester failure gave further evidence. In all tests the failure of the arrester occurred some time after the peak pressure but never before the combustion of inflowing mixture ceased, indicating that the transmission is a result of combustion of inflowing flammable mixture. High speed photographs clearly indicate that on transmission of explosion the combustion is initiated very close to the surface of the flame arrester, suggesting a point of ignition on the surface of the hot arrester. However more light is thrown on how the process of transmission takes place by considering the flash back tests.

Ignition of flammable gas by stabilized flame on the arrester surface in flash-back tests

It was evident in the tests when the metal foam failed to prevent the ignition of the gas mixture on the upstream side of the arrester that the flammable mixture reacted within the arrester voids, after the surface of the matrix was heated by convective heat transfer. Such a combustion zone was narrow and it appeared that the reaction was completed within the matrix there being no luminosity on the arrester surface. If this zone

started to progress it quickly penetrated the arrester matrix.

For the combustion to occur within a small channel or enclosed space it is essential that the dimensions of these are larger than the respective quenching distance at a given temperature. The slot quenching distances for propane/air and ethylene/air mixtures at room temperatures are 2.2 and 1.25 mm respectively. This is considerably less than the diameter of the largest voids within the metal foam, which were approximately 1 mm diameter. If however the quenching distance values are extrapolated to the temperatures prevailing during the test, namely 950°C, assuming that the quenching distance varies as the inverse square root of the absolute temperature, they became 1.0 mm and 0.6 mm. These figures may not be accurate as the slot quenching distance may not be directly applicable to metal foam voids. However, the argument provides some basis for the acceptance of the flame reaction process within the hot matrix and also explains the better performance of finer metal foam.

Matrix of the arrester

Once the reaction zone arrives at the upstream side of the arrester, the flowing mixture is in direct contact with heated matrix and also with the reaction zone of the flammable mixture which may be well above the measured temperature of the metal, and the ignition of the flammable mixture follows either by contact with the hot metal or reacting gas. It is possible that either mechanism can operate, as the temperature of the arrester metal is well above the spontaneous ignition temperatures of propane and ethylene mixtures which are 449 and 466°C respectively⁶.

Practical implications

When arresters are used in situations where a stationary flame may be established on the arrester surface, it is often desirable to provide a heat sensing device which would detect the presence of the non-transient flame, shut the fuel supply and possibly sound an alarm. Thus damage to equipment is prevented. To provide further safeguards or when automatic detection is not possible, users may request that the arrester should hold a burning pre-mixed gas flame for a minimum period of time without flash-back occurring.

When the arresters are fitted on a vessel to vent explosion, then the stationary flame front following the explosion lasts for relatively short periods of time and the duties of the matrix are less arduous. Nevertheless there were some failures with small vent areas. These however should not restrict the usage of metal foam as the arrester areas required to secure reasonable pressure reductions are considerably in excess of areas which

can give flash-back of flame. All materials used as flame arresters will accept finite thermal load, and when critical input of heat is exceeded they will fail by melting or oxidation. It would however be desirable to improve the performance of the metal foam and some short experiments indicated that this indeed was possible. Certain simple modifications of the arrester surface cause the flame to lift off the arrester surface, reducing the rate of heat transfer from the flame to the arrester matrix. Alternatively, a simple self-closing vent cover can prevent flame stabilizing. In cases when pressure drop across the matrix is unimportant, the advantage of better performance of finer grades may be taken.

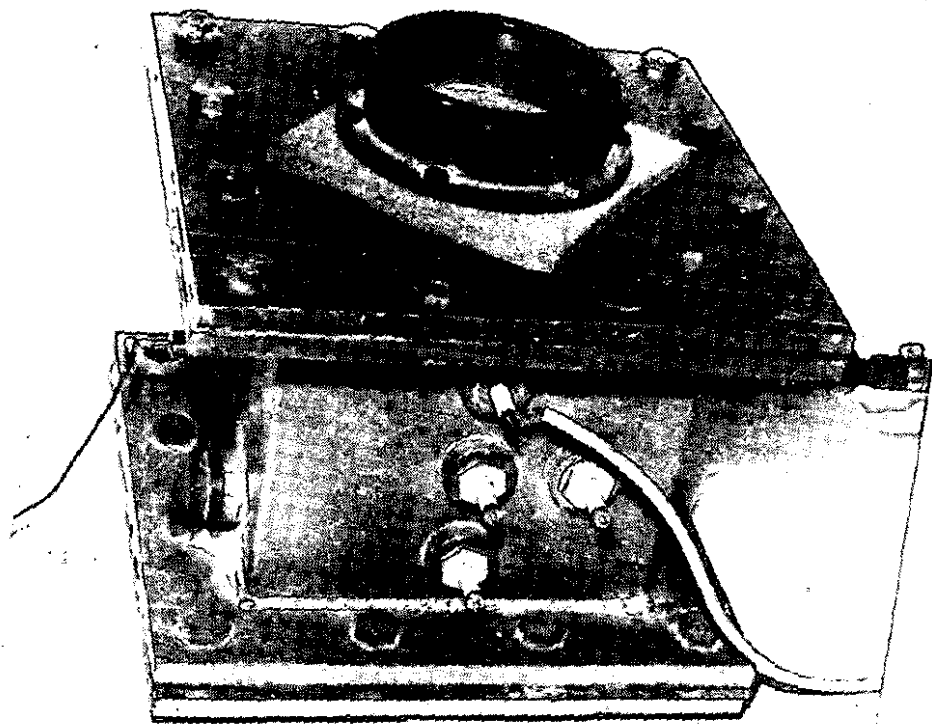
The thermal damage to the arrester shown in Fig 10 was caused by the oxidation and subsequent loss of plasticity after repeated tests. The massive failure occurred on cooling of the arrester matrix. This occurred only when very small vent areas are used, and in practice this problem can be readily avoided.

CONCLUSIONS

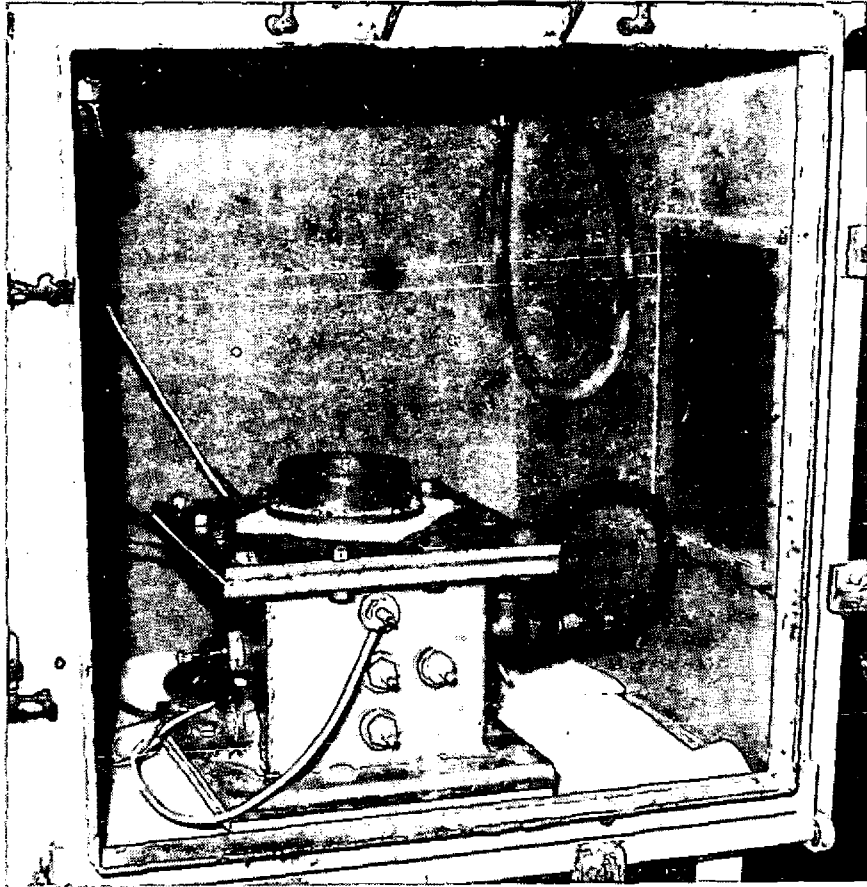
Metal foam is an efficient flame quenching material. Although it failed under certain operating conditions, these were very severe and unlikely to occur in use. The particular advantage metal foam offers are lightness, ease with which it can be shaped and mounted, and good corrosion resistance.

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EXPLOSION VESSEL
FIG. 1



TEST CHAMBER WITH EXPLOSION
VESSEL IN POSITION

FIG. 2

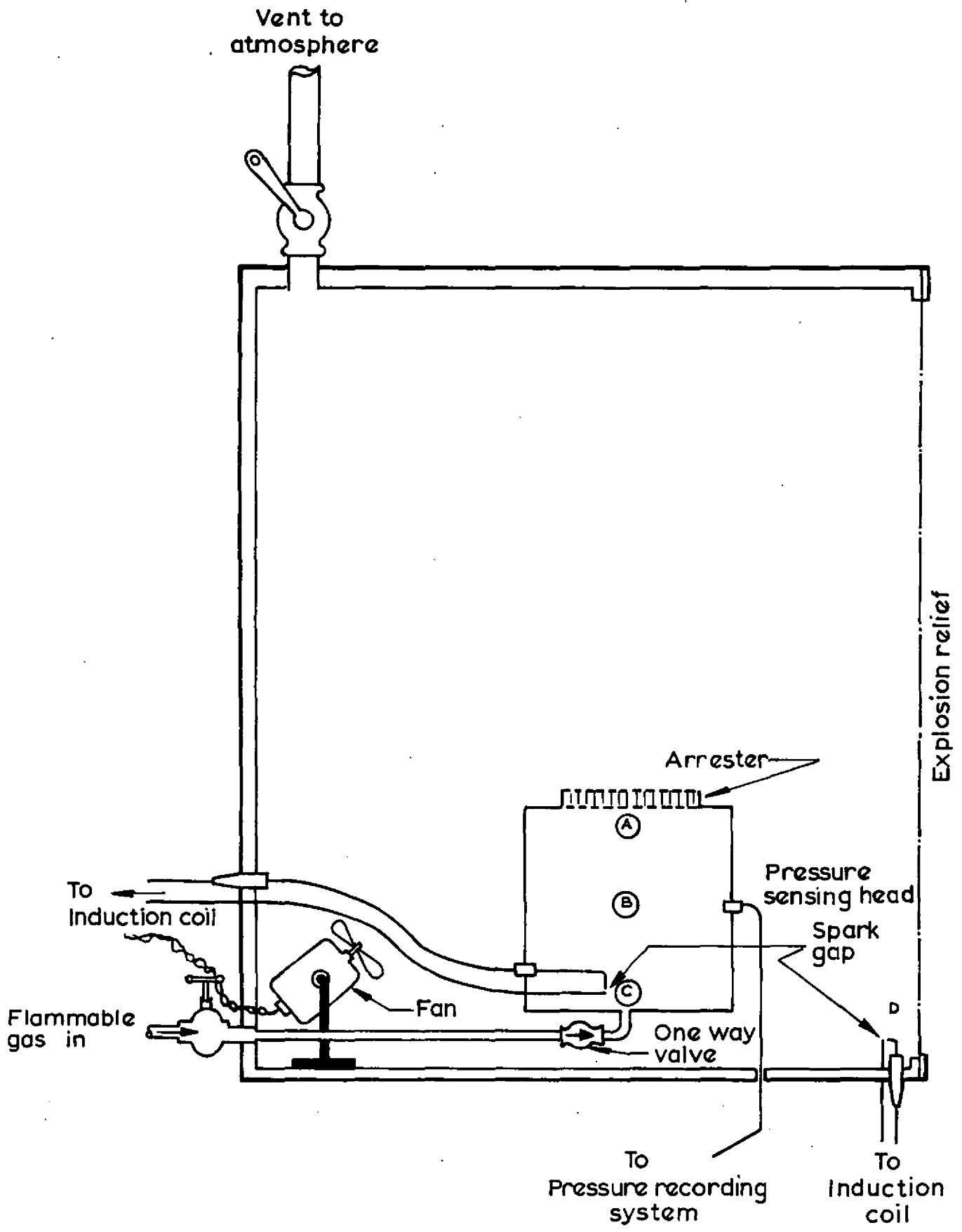
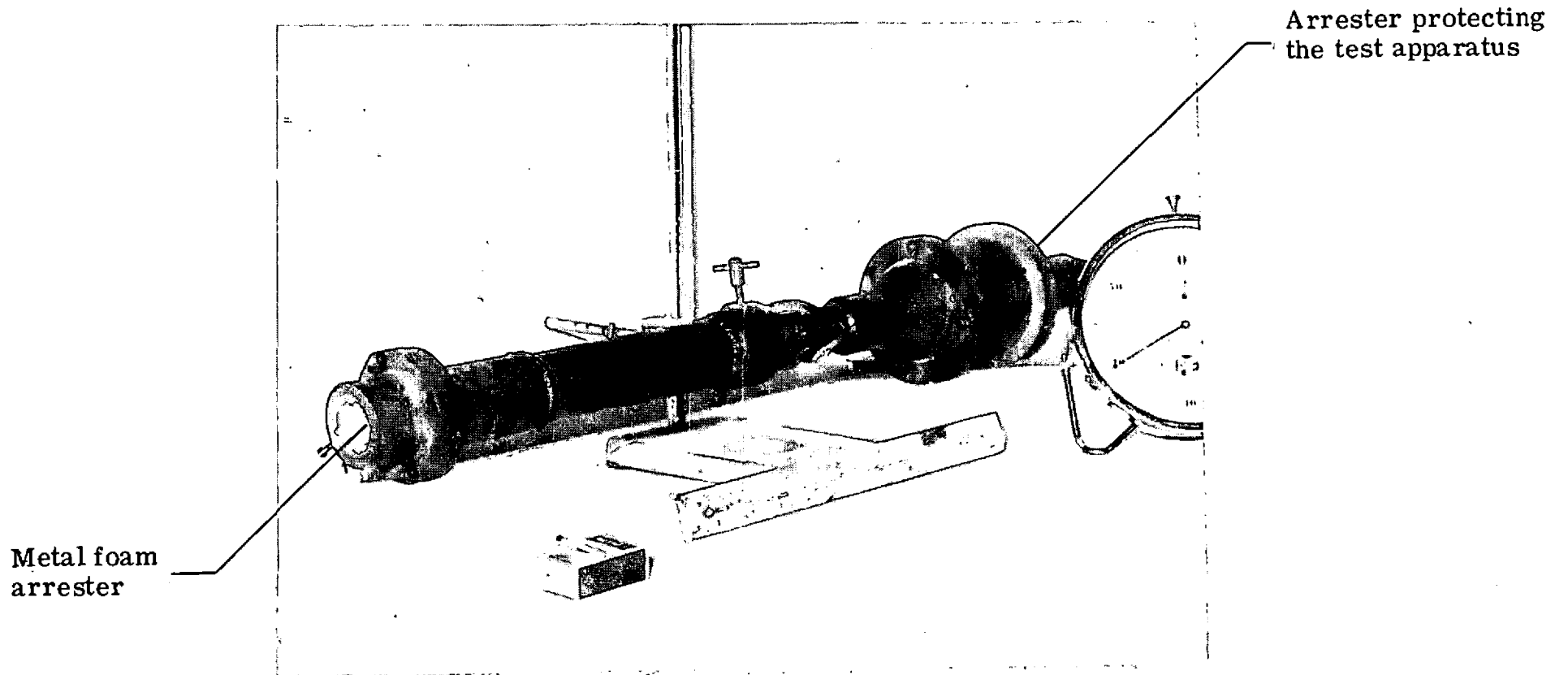


FIG. 3 ARRANGEMENT OF EXPLOSION VESSEL ETC
INSIDE TEST CHAMBER

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APPARATUS USED IN STABILISED
FLAME 'BURNBACK' TESTS

FIG. 4

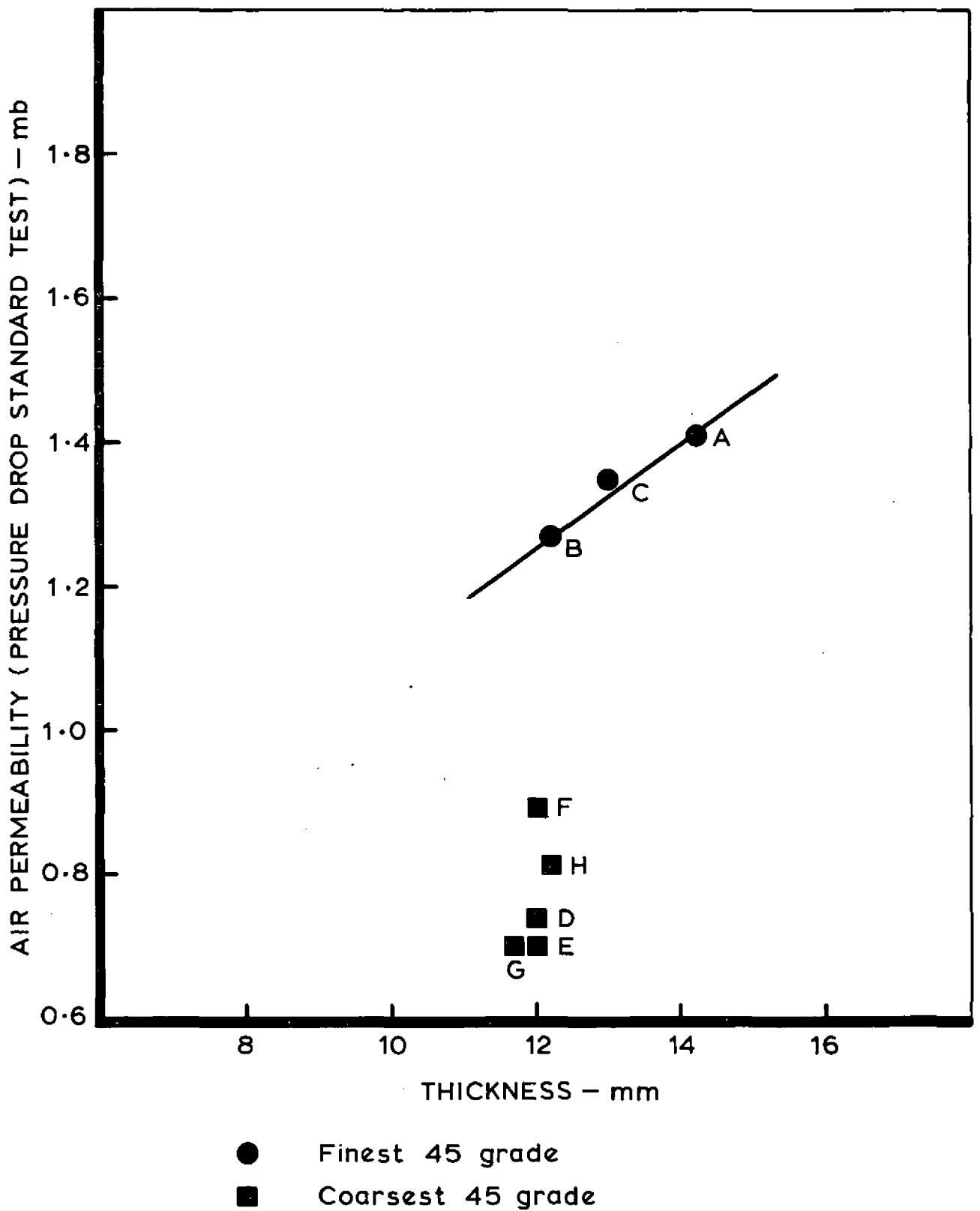
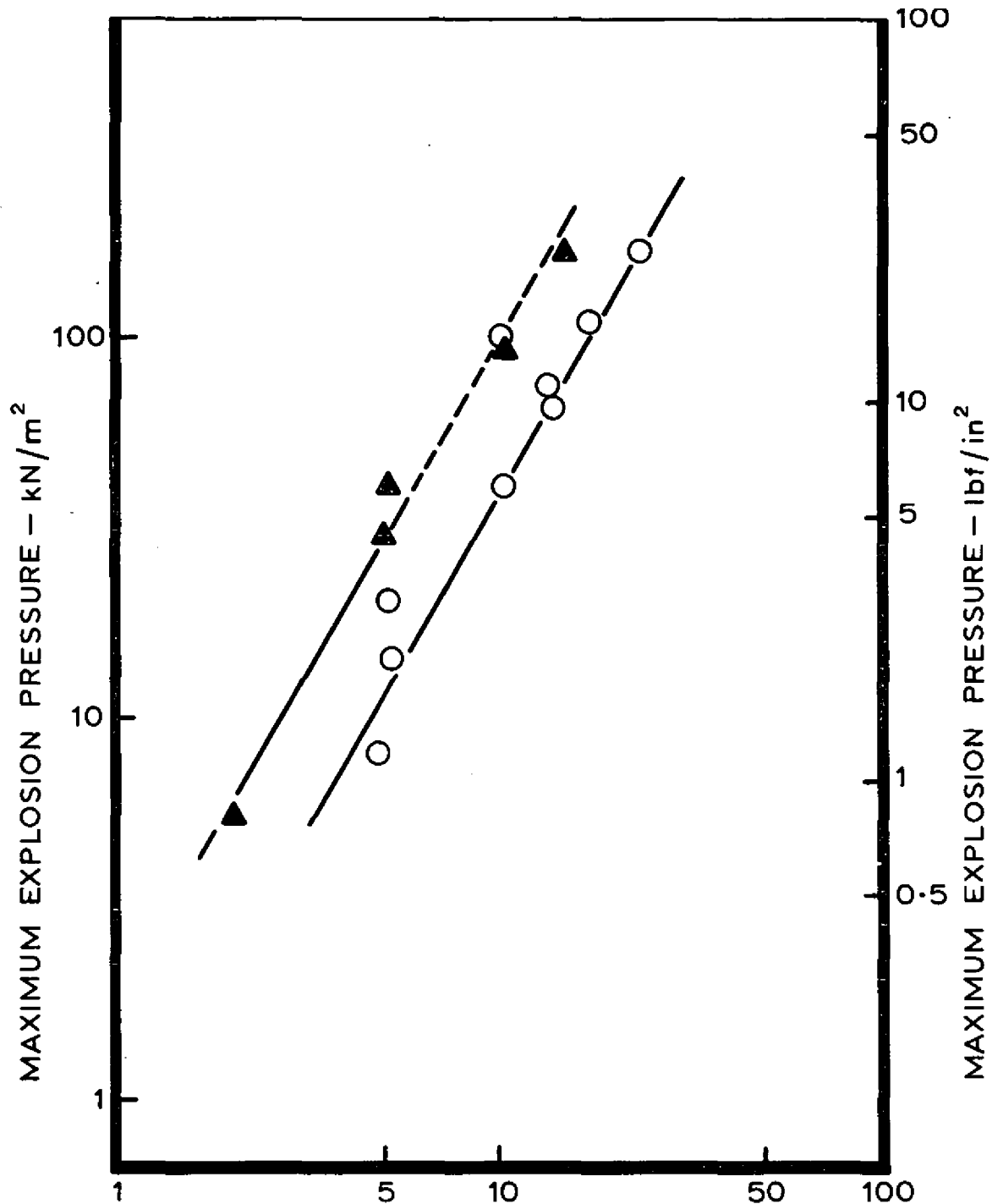


FIG. 5 RELATIVE THICKNESS AND AIR PERMEABILITY FOR BOTH GRADES OF METAL FOAM TESTED



$$\frac{\text{CROSS SECTIONAL AREA OF VESSEL}}{\text{TOTAL AREA OF VENTS}} = K$$

- Arrester failure
- Crimped ribbon
- ▲ Retimet finest 45

FIG. 6 MAXIMUM EXPLOSION PRESSURE AGAINST VENTING FACTOR FOR RETIMET AND CRIMPED RIBBON USING 6.5 PER CENT ETHYLENE / AIR

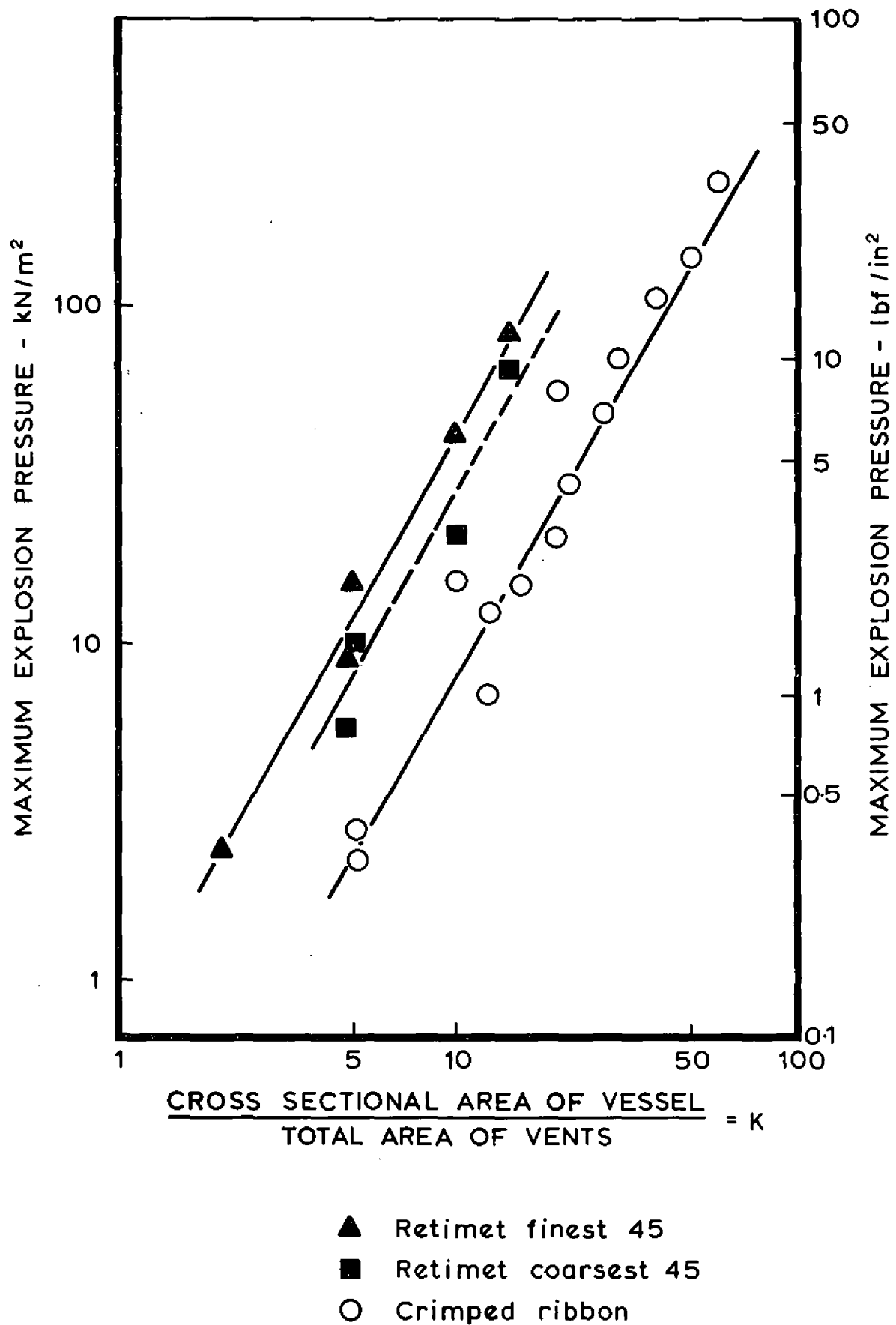


FIG. 7 MAXIMUM EXPLOSION PRESSURE AGAINST VENTING FACTOR FOR RETIMET AND CRIMPED RIBBON USING 4.2 PER CENT PROPANE / AIR

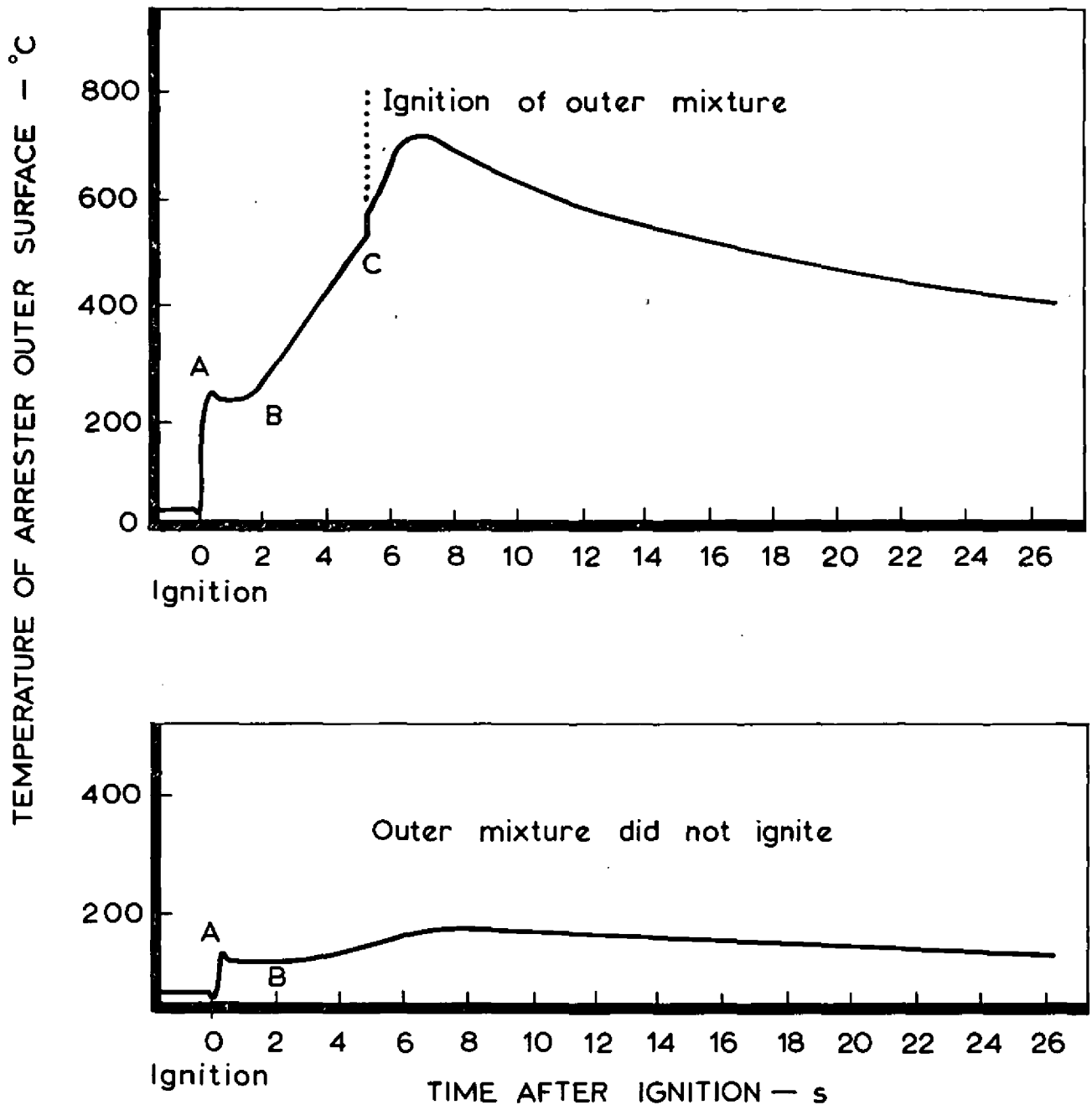
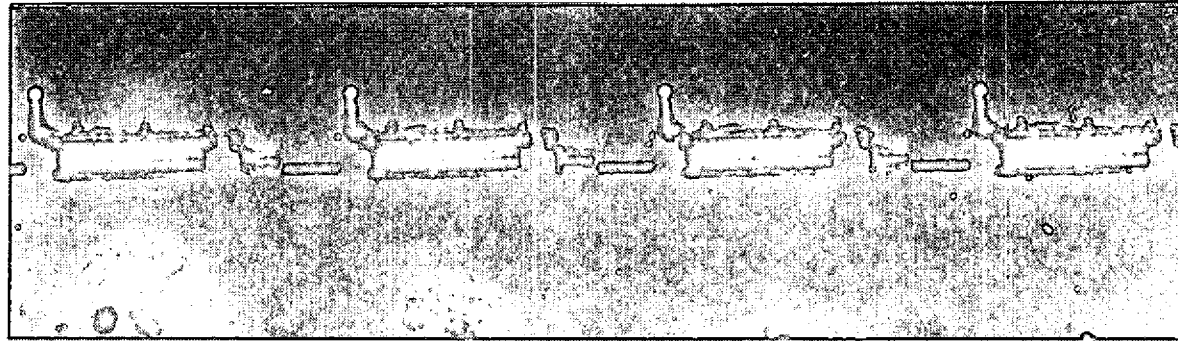
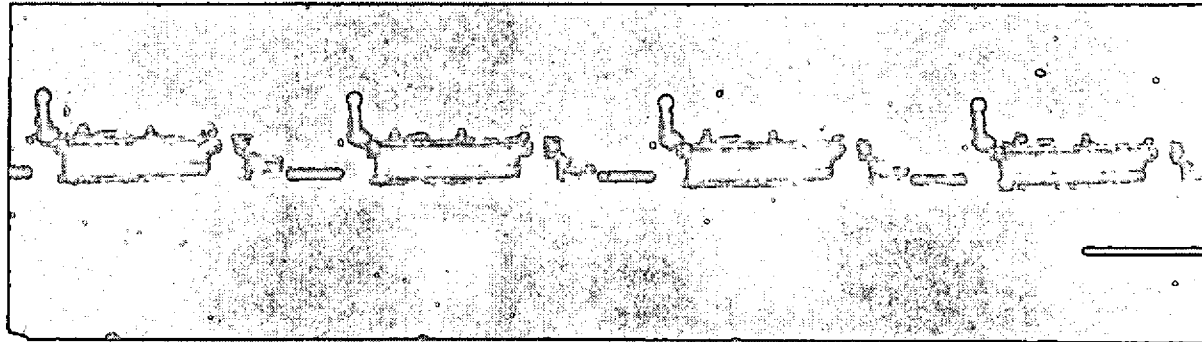


FIG. 8 TEMPERATURE RISES ON ARRESTER SURFACE OBTAINED DURING TESTS ON 1 FT³ VESSEL WITH 2 x 4.3" ARRESTERS USING ETHYLENE/AIR MIXTURE

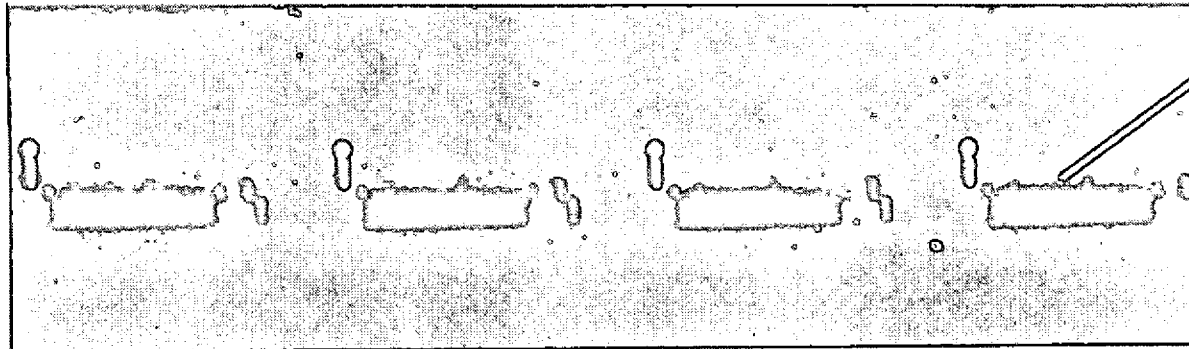
Phase 1
Ignition



Phase 2
Suck back



Phase 3
Transmission



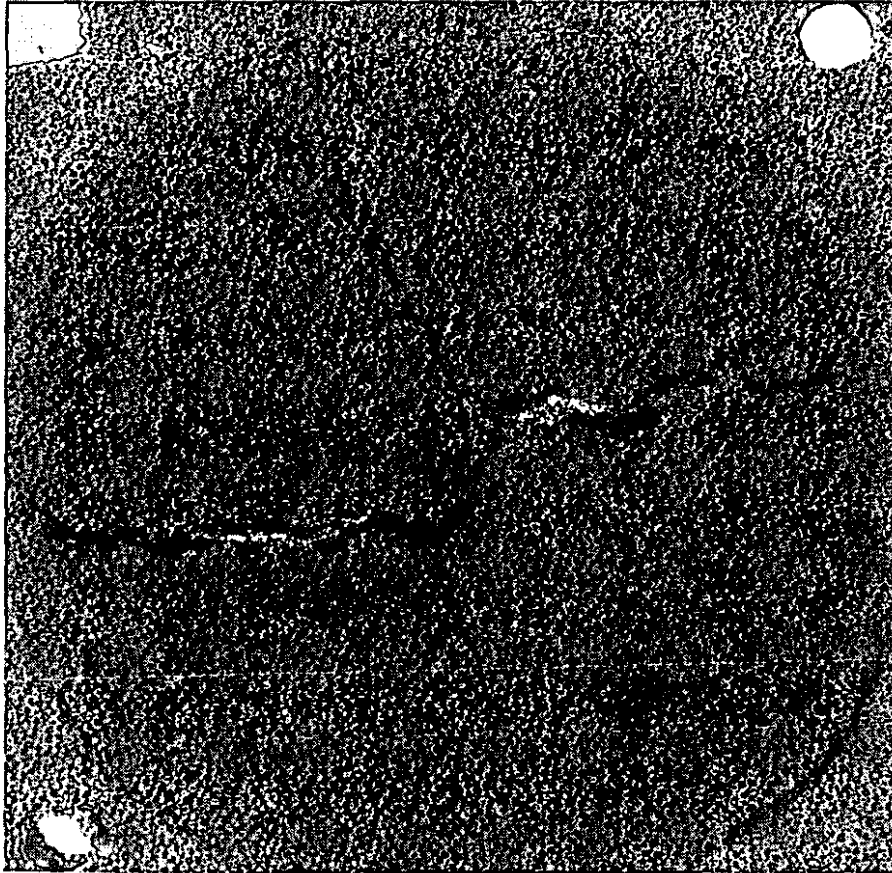
A

B

C

HIGH SPEED FILM OF ARRESTER FAILURE
FRAMING RATE 240 FRAME PER SECOND

FIG. 9



METAL FOAM FLAME ARRESTER SHOWING
OXIDATION AND SEVERE CRACKING AFTER
SEVERAL TESTS INVOLVING TRANSMISSION
OF FLAME TO OUTER ATMOSPHERE

FIG 10

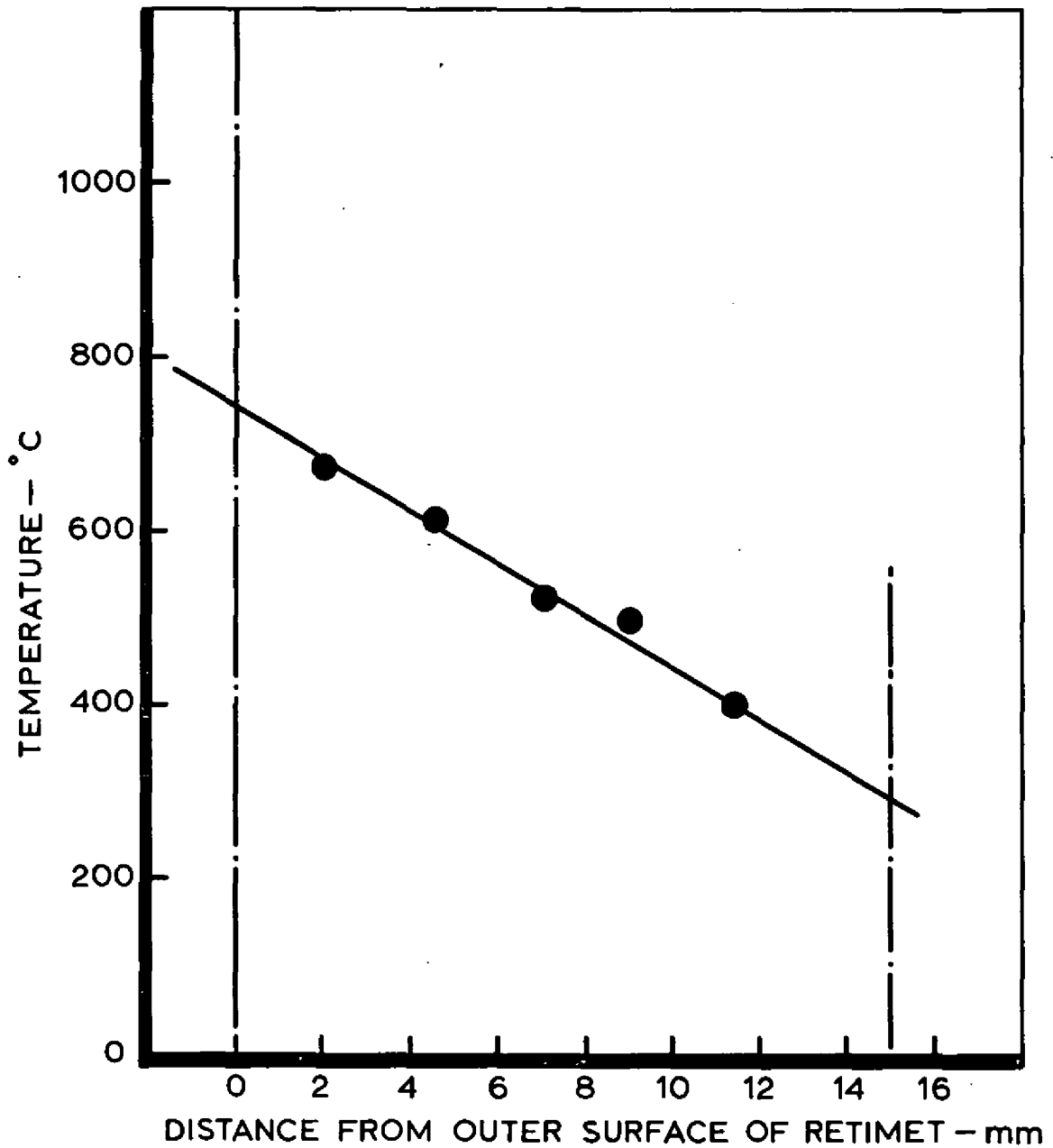


FIG. 11. TEMPERATURE GRADIENT THROUGH RETIMET SPECIMEN WITH FLAME, STABILISED ON SURFACE

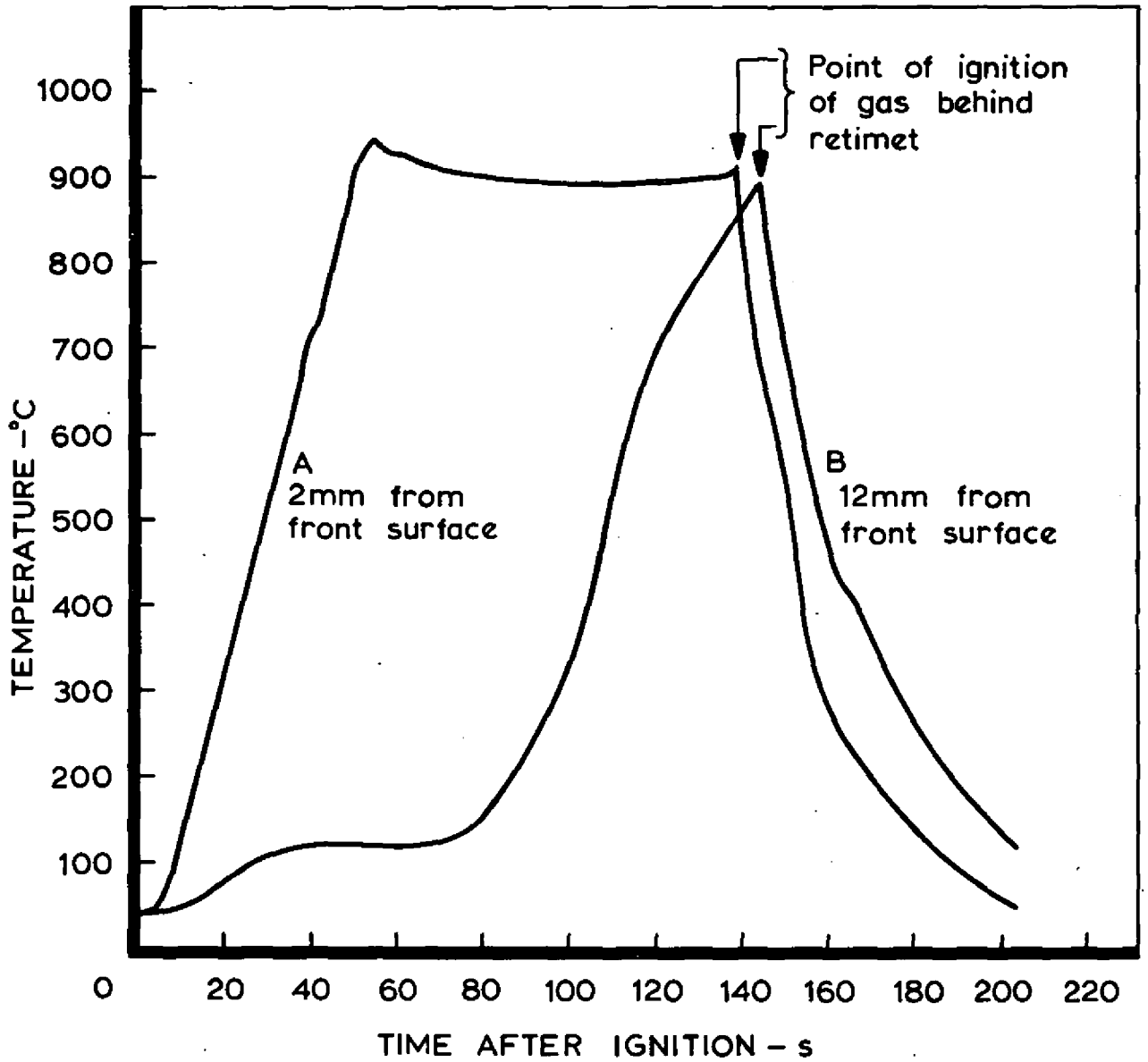


FIG.12 TEMPERATURE CHANGES AT TWO DIFFERENT POINTS WITHIN THE METAL FOAM DURING A 'FLASH - BACK' TEST

