THE USE OF FLAME ARRESTERS FOR PROTECTION OF ENCLOSED EQUIPMENT IN PROPANE–AIR ATMOSPHERES

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SYNOPSIS

Flame arresters have been applied to the protection of industrial equipment which may contain a source of ignition and which may cause an explosion hazard in a flammable atmosphere. The arresters release pressure resulting from ignition of gas in the equipment, but prevent flame emerging through the vents. Cubical vessels up to 3 ft^3 in volume have been tested in a propane–air mixture and were safely protected with crimped-ribbon arresters.

The vent area required depended on the volume of the vessel and the distribution of the vents and was a small fraction of the area of one side of the vessel.

The maximum explosion pressure was related by theory to the vent area and the dimensions of the flame arresters.

Introduction

In industry equipment capable of generating a source of ignition, such as a flame or an electric spark, may be used where flammable gas or vapours could be present. If the flammable material penetrated into the equipment it could ignite, propagate flame outside the equipment, and cause an external explosion or fire. The initiation of flame is usually accompanied by an increase in pressure in the enclosure. A method of protecting such equipment using flame arresters is being investigated; the arresters cover vents in the casing of the equipment thus preventing the emission of flame but permitting relief of the explosion pressure. The method has several advantages including cheapness, relatively light construction of the casing, and the minimising of weight. The type of equipment to which this technique could be applied includes instrumentation, control gear, motors, and switchgear.

There are several existing methods by which equipment is customarily protected against explosion risk in flammable atmospheres. The methods include flameproofing of electrical equipment,[1] design of electrical circuits to ensure intrinsic safety,[2] pressurizing or purging with air or inert gas, and encapsulation. Each of the methods suffers from one or more limitations which restrict its application. The limitations include protection from electrical sources of ignition only, increased weight of equipment, relatively small maximum permissible operating currents, the necessity for the permanent installation of pressurized air or gas lines with associated equipment, and increased capital and running costs. If protection is obtained by installing flame arresters these limitations are avoided or minimised. Because of the increasing use of flammable liquids and gases in industry and the introduction of new manufacturing processes additional methods of protection giving economic advantages are desirable.

To ensure adequate protection by means of flame arresters the maximum pressure developed in an explosion in the equipment must be known. There must also be no cumulative mechanical or thermal damage to the arresters after a series of explosions. The experiments have, therefore, initially been concerned with the variation of explosion pressure with size of vent for vessels of practical dimensions, the determination of the type and size of flame arresters that gave protection without being damaged, and evaluation of external protective covers over the vents. The explosible gas mixture was propane–air, taken as representative of Group II gases.[1]

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Experimental Apparatus and Materials

Explosion vessels

Three cubical explosion vessels were used, having capacities of ½, 1, and 3 ft^3. Each vessel had two open flanged ends with provision for bolting on to them covers provided with vents. Each cover had circular openings which could be fitted with flame arresters or closed individually by bolting on blank circular plates. Fig. 1 shows the ⅓ ft^3 explosion vessel with covers attached; the top cover was fitted with two flame arresters and the remaining three vents were blanked off. For experimental purposes the explosion vessels were constructed with substantial flanges; it is envisaged that for industrial applications enclosures will be designed to incorporate adequate venting and lighter forms of construction could safely be used. In addition, of course, the relative proportions of the vessel can be varied; cubical vessels were chosen for the experiments because these would be expected to give the severest test conditions. The dimensions and number of vents used with each vessel are shown in Table I; all the vents were situated in one cover unless stated otherwise in the text.

TABLE I.—*Number and Diameter of Vents Used*

Diameter of vents (in.)	No. of vents used		
	⅓ ft^3 vessel	1 ft^3 vessel	3 vessel
1·15	1–5	—	—
2·25	1	1–5	—
4·30	1	2–4	1–4

TABLE II.—*Details of Crimped-ribbon Arresters and Minimum Areas to Avoid Structural Damage*

Diameter of arrester (in.)	Ribbon metal	Ribbon thickness (in.)	Crimp height (in.)	Thickness of arrester (in.)	Fraction of area open to flow	Volume of vessel (ft^3)	Area of arrester per unit volume of flammable gas (in^2/ft^3)	Maximum explosion pressure (lbf/in^2)	Distribution of arresters
1·15	Cupro-nickel	0·0025	0·017	1·5	0·79	—	—	—	—
	Cupro-nickel	0·0025	0·024	1·5	0·82	—	—	—	—
	Cupro-nickel	0·0025	0·045	1·5	0·90	$\frac{1}{3}$	13	2·0	In two covers
	Nickel	0·003	0·020	1·0	0·87	$\frac{1}{3}$	6	10·0	In one cover
	Nickel	0·005	0·020	1·0	0·82	$\frac{1}{3}$	6	—	In one cover
	Nickel	0·007	0·020	1·0	0·80	$\frac{1}{3}$	3	30·0	In one cover
	Alloy A*	0·0076	0·020	1·0	0·80	$\frac{1}{3}$	3	27·0	In one cover
2·25	Cupro-nickel	0·0025	0·017	0·75	0·79	—	—	—	—
	Cupro-nickel	0·0025	0·024	0·75	0·82	1	20	0·8	In one cover
	Cupro-nickel	0·0025	0·045	1·5	0·90	1	16	2·2	In one cover
	Nickel	0·003	0·020	1·0	0·87	—	—	—	—
	Nickel	0·005	0·020	1·0	0·82	1	4	18·5	In one cover
	Nickel	0·007	0·020	1·0	0·80	1	4	20·0	In one cover
4·30	Cupro-nickel	0·0025	0·045	1·5	0·90	$\frac{1}{3}$	44	0·3	In one cover
						1	29	0·5	In one cover
						3	20	0·3	In two covers
	Nickel	0·003	0·020	1·0	0·87	3	10	8·0	In one cover
	Nickel	0·007	0·020	1·0	0·80	3	10	12·5	In one cover
	Alloy A*	0·0076	0·020	1·0	0·80	—	—	—	—

* Nickel-chromium-iron alloy.

The amount of venting is usually specified by the ratio K, where K = (cross-sectional area of vessel)/(total area of vents). This ratio is only applicable when all the vents are in the same cover of the explosion vessel.

All the explosion vessels used in these experiments had provision for the insertion of a pressure gauge and an igniting source. The pressure gauge was always situated in the centre of one vertical wall of the vessel and the igniting source either in the centre or on the axis of the vessel 2 in. away from either cover. Thus when all the vents were in one cover the igniting source could be near the vents, central, or remote from the vents.

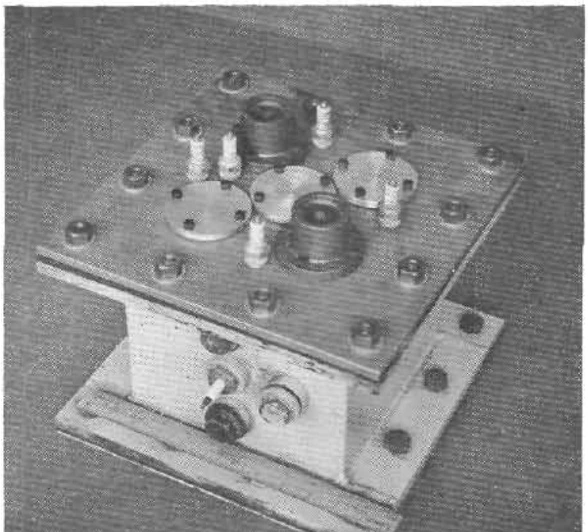


Fig. 1.—$\frac{1}{3}$ ft^3 explosion vessel with covers attached

Usually the explosion vessels were tested inside a 15·6 ft^3 cubical enclosure having one open side. When the vents were fitted with flame arresters the open side of the enclosure was sealed with a polyethylene diaphragm consisting of two layers of 0·0015 in. thick film. The diaphragm was not used in experiments with open vents, *i.e.* no arresters. The enclosure, with the $\frac{1}{3}$ ft^3 explosion vessel in position, is shown in Fig. 2.

Flame arresters

Three types of arresters were used; crimped-ribbon, perforated metal sheeting, and wire gauze. The crimped-ribbon arresters were of three types of construction: nickel arresters were constructed as packs of alternate crimped and flat ribbons sandwiched between two brass plates (Fig. 3). Arresters made of a proprietary alloy, here designated alloy A, were assembled similarly to the nickel arresters, but had no brass plates on the outside and the ribbon was held together by welds made outside the venting area. Alloy A consists of nickel, chromium, and iron. Cupro-nickel arresters consisted of a length of crimped and flat ribbon wound round a brass central core and cased in brass (Fig. 3). Table II gives further details of the crimped-ribbon arresters.

The perforated sheeting arresters were made of brass with circular holes spaced in a regular pattern. Details of these are shown in Table III. The wire gauze was of steel and was a normal commercial product; the dimensions are given in Table IV.

TABLE III.—*Perforated Sheeting Arresters*

Diameter of arrester (in.)	Diameter of perforation (in.)	Thickness of arrester (in.)	Area of aperture per unit area of sheeting
1·15	0·10	0·03	0·44
1·15	0·03	0·02	0·26

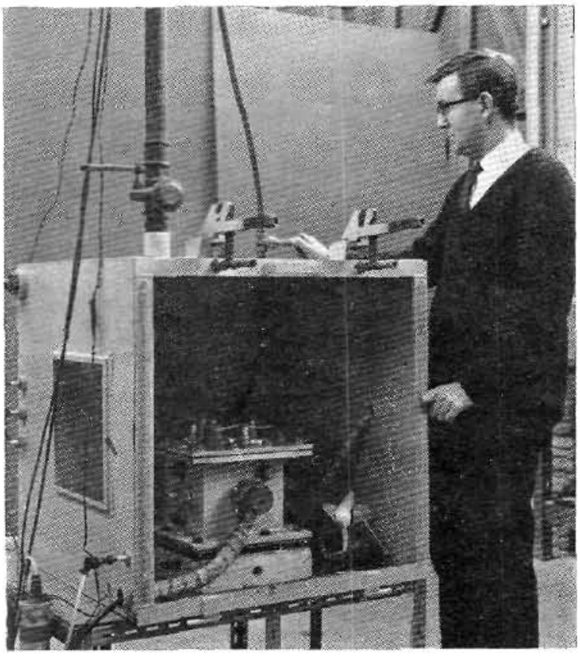


Fig. 2.—*The enclosure with the $\frac{1}{3}$ ft^3 explosion vessel in position*

Flammable gas and igniting source

A propane–air explosive mixture of four per cent by volume was used in all experiments. It was ignited by an induction spark 0·05 in. long.

Pressure measurement and flame movement

Explosion pressures were determined using variable-capacity or quartz-piezo gauges and the pressure-time curves were recorded by photographing a screen of a cathode ray tube to which the amplified signals were fed. At least two tests were carried out with each set of experimental conditions. The arrival of the flame front at the arresters and at the centre of a blank cover was also recorded. Each vent was fitted with an ionization gap and all the gaps on a cover were wired in parallel, thus recording the most advanced part of the flame.

Protective covers

Four different types of protective cover were tested; (*a*) plastics diaphragms, (*b*) solid covers either resting on top of the arresters or held by magnets, (*c*) plastics-backed magnetic ferrite sheet, and (*d*) mechanical shield.

The diaphragms were made from polyethylene film 0·0015 in. thick and were tested without arresters in position being clipped to the outside of the arrester holder. The solid covers were made from fibre insulating board skinned with aluminium foil; the weight of these covers was varied by attaching lead sheets. The solid covers held by magnets were of similar construction, but four mild steel plates were attached at each corner, to engage the magnets situated on the periphery of the arrester holder. The plastics-backed magnetic ferrite covers were made from 1/16 in. thick, six-inch square sheets. The covers were anchored at one side of the flame arrester so that the sheets rested flat on the mild steel mounting frame of the arresters and were thus held by a magnetic force over the whole upper surface of the frame. When the explosion took place the ferrite sheet was deflected, bending occurring near the anchoring line. The mechanical shield was a mild steel plate placed in front of the arresters, and the position of the plate was varied, so that the area on the periphery of each arrester was between one-half and double the cross-sectional area of the arrester.

TABLE IV.—*Wire Gauze Arresters*

Diameter of arrester (in.)	Mesh number	Wire gauge (SWG)	Mesh width (in.)	Wire diameter (in.)	Area of aperture per unit area of gauze
1·15	28	28	0·021	0·015	0·35
1·15	60	37	0·010	0·007	0·35

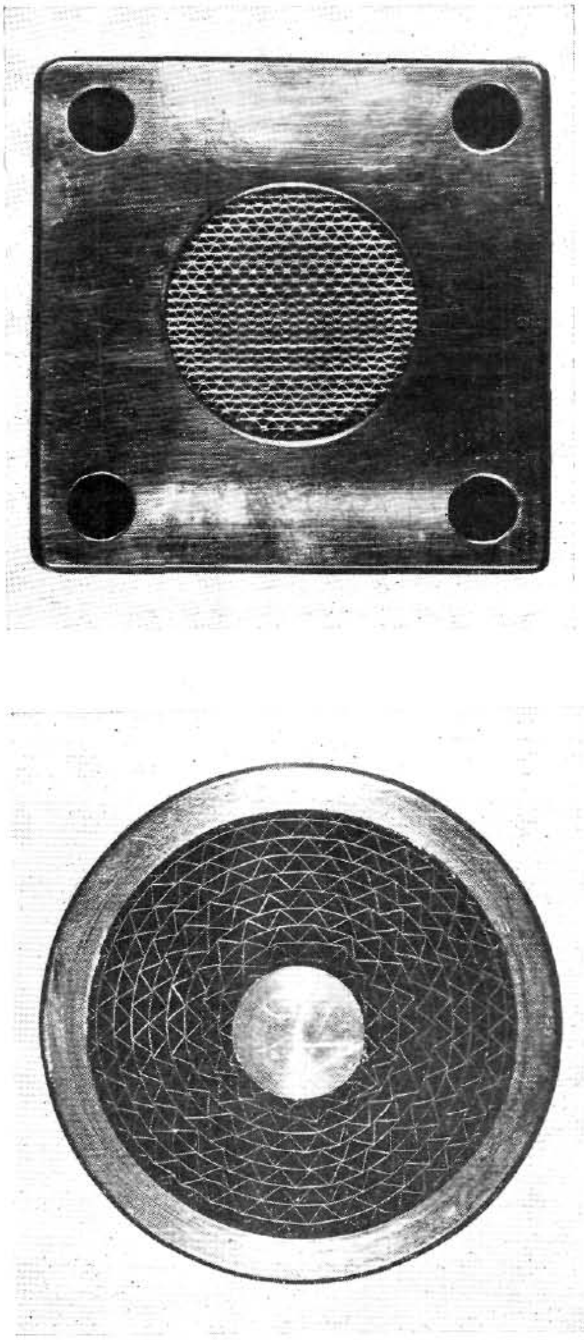


Fig. 3.—*Two types of arrester.* UPPER: *nickel arrester.* LOWER: *cupro-nickel arrester.*

Procedure

The propane–air mixture was fed into the explosion vessel and passed into the outer enclosure through the vents and from there ran to waste. A volume of gas equal to ten changes of the larger enclosure was used for each experiment; throughout the charging period the gas in the outer enclosure was stirred by a fan. After charging was completed the flammable mixture in the explosion vessel was ignited. Absence of explosion in the outer enclosure indicated that the arresters contained the explosion within the vessel; the mixture in the outer enclosure was subsequently fired to prove its flammability.

Visual examination of the arresters was made with every rig after the completion of the tests. With arresters which were expected to suffer damage, inspection was carried out after each test. No explosion pressures are quoted for tests in which the arresters suffered structural damage.

For experimental convenience in all tests with protective covers no gas mixture was present in the outer enclosure, the polyethylene diaphragm being absent, and the charging was terminated after ten volumes of the explosion vessel had passed. In these tests the gases did not escape through the arresters, but through a valve closed after completion of charging, and were dispersed by a fan.

Results

Dependence of explosion pressure on vent area

OPEN VENTS

The maximum explosion pressures obtained in all the vessels with vents in the top surfaces are summarized in Fig. 4. The explosion pressures shown in Fig. 4 are the maximum values obtained irrespective of the position of the igniting source.

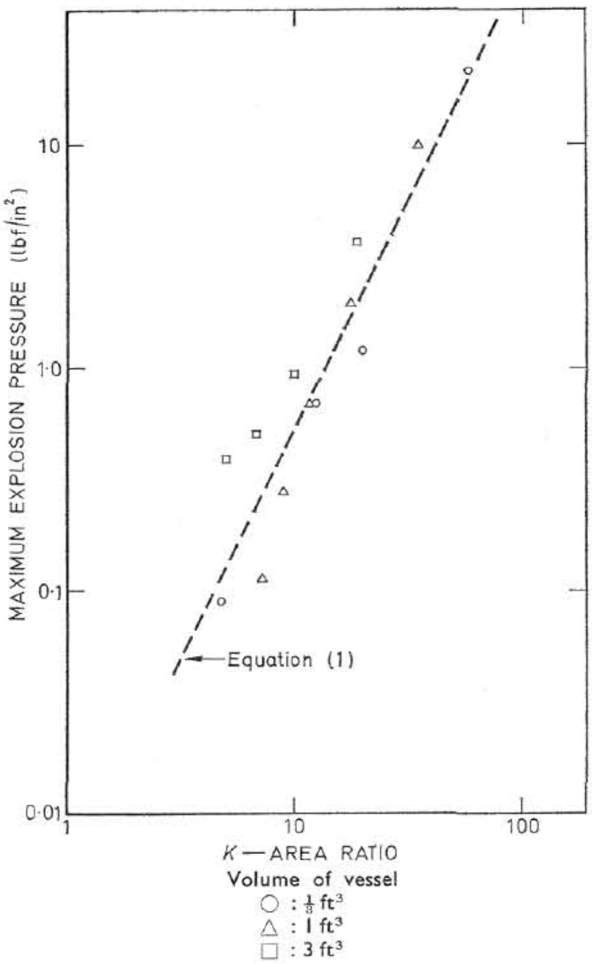


Fig. 4.—*Relationship between vent area and the maximum explosion pressure*

TABLE V.—*Maximum Explosion Pressures in* $\frac{1}{3}$ *ft*^{3} *Vessel with Different Vent Distributions*

Distribution of vents	Maximum explosion pressure (lbf/in^2)		
	Explosion source near vents	Explosion source central	Explosion source remote from vents
One cover with four vents	1·0	1·5	2·4
Two covers, each with two vents	1·8	2·0	

When single vents were used there was little difference between the maximum pressures obtained with the igniting source remote from the vent or in the centre of the vessel; often the central position gave the highest pressure. With multiple vents, the highest maximum pressures occurred with the igniting source remote from the vents, and the lowest pressures were obtained with the igniting source near the vents. Values for the 1 ft^3 vessel are shown in Fig. 5.

The effects of distribution of vents over two covers was investigated with the $\frac{1}{3}$ ft^3 vessel. The maximum explosion pressure with four vents, 1·15 in. in diameter, in one cover are listed in Table V, together with the pressure for two vents of the same diameter in each of two opposite covers. Distribution of the vents reduced the maximum explosion pressure obtained with the most unfavourable position of the igniting source.

VENTS FITTED WITH ARRESTERS

A summary of the results obtained with each of the explosion vessels fitted with flame arresters is given in Fig. 6. For the purposes of the summary no differentiation is made in Fig. 6 between the various types of flame arrester; this point is considered separately below.

In Fig. 6 the maximum explosion pressure and K are plotted on logarithmic scales; the results for the $\frac{1}{3}$ and 1 ft^3 vessels were grouped together whereas higher pressures were obtained with the 3 ft^3 vessel.

In Fig. 7 the results for different types of arrester are differentiated, for the $\frac{1}{3}$ and 1 ft^3 vessels only. The maximum pressure and K are again plotted on logarithmic axes. Because of the higher pressures obtained with the 3 ft^3 vessel, Fig. 6, the results for the nickel arresters with this vessel are given separately in Table VI.

Some indication of the effect of variation of crimp height on the maximum explosion pressure is given in Fig. 8. In all experiments the arresters were mounted in the cover of the vessel. The effect of variation in arrester thickness was not investigated because the dominant factor in determining the maximum explosion pressure was the area of the arrester and increased thickness was not required to prevent propagation of flame through the arrester.

The possibility was investigated of ignition very close to the crimp allowing a slow flame to propagate through the arrester to the external gas mixture. A cupro-nickel arrester of crimp height 0·045 in., diameter 4·3 in., was mounted in the $\frac{1}{3}$ ft^3 explosion vessel and a series of tests was carried out in which the igniting spark was at the periphery of the arrester. The spark passed directly from an electrode to the arrester ribbon or between electrodes sited at distances up to 1 in. below the arrester. In a further series of tests the

TABLE VI.—*Maximum Explosion Pressures for Nickel Arresters on 3 ft³ Vessel*

Ribbon thickness (in.)	Number of vents	K	Position of igniting source	Maximum explosion pressure (lbf/in^2)
0·003	1	21	Remote	8·0
	2	10	Remote	2·2
0·007	1	21	Centre	12·6
	2	10	Remote	2·9

spark passed directly from an electrode to the ribbon 1 in. from the periphery of the arrester. In eight tests in each position no external ignitions occurred.

Some exploratory tests were carried out with wire gauze and perforated metal sheeting arresters, using the $\frac{1}{3}$ ft³ explosion vessel fitted with four vents 1·5 in. in diameter in the cover. Both types of arrester failed to contain the explosion within the vessel when the igniting source was remote from the vents. In addition, both the 28- and the 60-mesh gauzes were seen to glow during and after the explosion. Because of the unfavourable results, experiments with gauze and perforated metal sheeting were not continued.

Thermal damage to arresters

For a casing to be successfully protected with flame arresters it is essential that not only should the maximum explosion pressure be reduced but also that the arresters should not suffer structural damage due to mechanical or

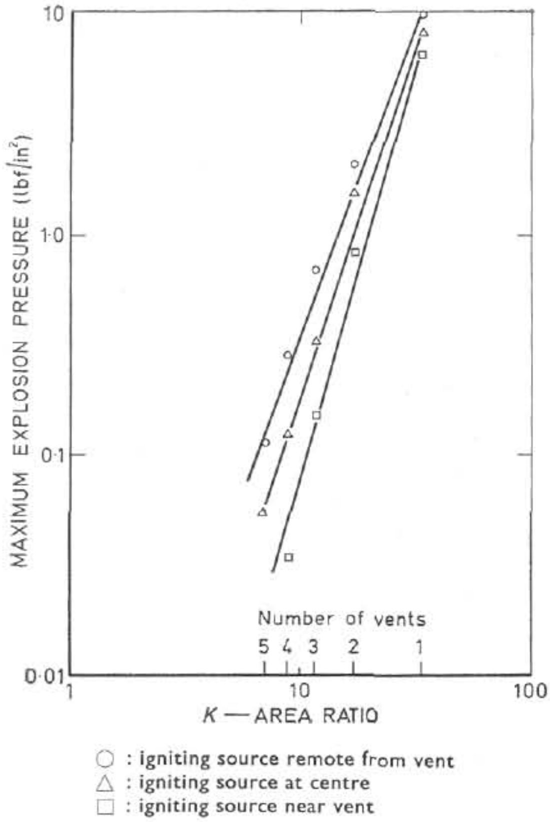


Fig. 5.—*Relationship between vent area and the maximum explosion pressure for 1 ft³ vessel*

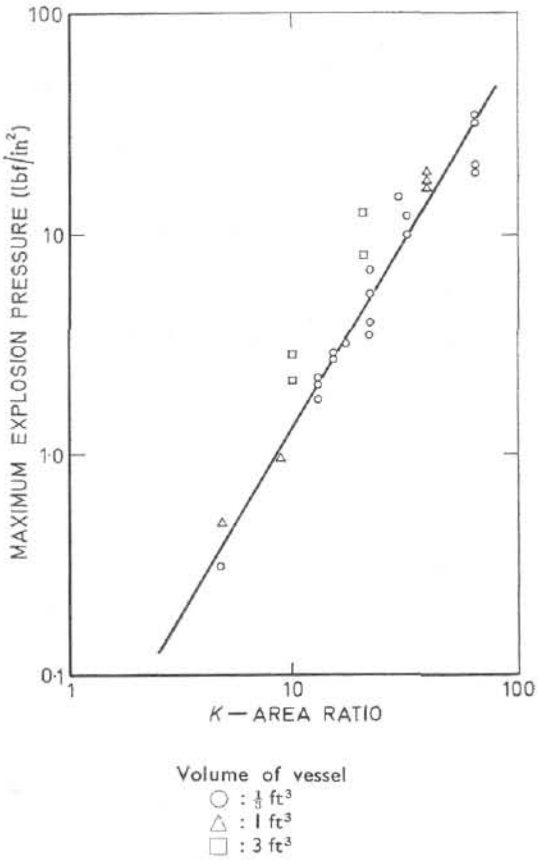


Fig. 6.—*Relationship between vent area and the maximum explosion pressure for vessels with vents covered by arresters*

thermal effects, even after repeated exposures to the explosions.

The nickel arresters behaved very satisfactorily; within a practical range of explosion pressures, no thermal damage to the arresters was obtained. With the 3 ft³ explosion vessel, no structural damage was obtained with any thickness of nickel ribbon, although some substantial pressures were recorded (Table VI). After some explosions using the 1 ft³ vessel, with arresters constructed of the thinnest nickel ribbon (Table II), some distortion was noticeable although in no case did an arrester fail and transmit the explosion. Inspection showed that some sections of the crimped and straight ribbon were distorted and gaps up to 0·02 in. opened up between the ribbons. With the $\frac{1}{3}$ ft³ vessel a similar distortion was obtained with both the thinnest and the intermediate nickel ribbon thicknesses. In all cases where distortion occurred the maximum explosion pressure was impracticably high for industrial equipment generally and within a practical range of pressures no damage was observed. The minimum areas of arrester required to avoid damage are summarised in Table II.

The alloy A arresters were tested with the $\frac{1}{3}$ ft³ vessel only one thickness of ribbon being available and no damage to the arresters was evident after the tests (Table II).

With the cupro-nickel arresters the acceptable vent area for the two large explosion vessels was in fact governed by the problem of avoiding thermal damage to the arresters. The thermal damage increased in a stepwise manner as the area of the arresters was reduced. The smallest detectable damage was a yellow discoloration, followed by a discoloration to a dark blue shade sometimes accompanied by a loss of lustre. The next stage of damage was structural

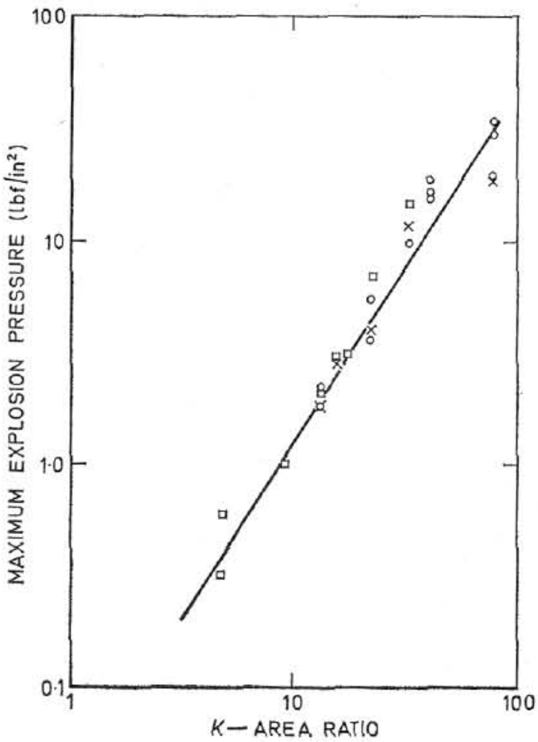


Fig. 7.—Relationship between vent area and the maximum explosion pressure for ⅓ and 1 ft³ vessels with vents covered by arresters made of different materials

and was noticeable at the leading edge of the metal ribbon exposed to the explosion; the edge was eroded and it curled over in places. Further reduction of the arrester area resulted in melting of the ribbon edge and beads of molten metal or oxide were observed accompanied by a reduction in arrester thickness. In all explosion vessels damage was greatest when the ignition source was situated near the vents; under these conditions the maximum quantity of hot combustion gases would pass through the arrester. A summary of the results is included in Table II which gives approximate values for the minimum safe areas of arrester, within the size intervals available.

Flame speeds

Measurements were usually made of flame speeds in at least one test for each vent area and each position of the igniting source. The highest flame speed occurred when the igniting source was remote from the vents, a value of 19 ft/s being obtained with each explosion vessel; the speeds with the igniting source in the centre of the vessel were lower. The minimum flame speeds were measured between the igniting source and the wall opposite to the vents and were 3·7, 1·7, and 4·4 ft/s for the ⅓, 1, and 3 ft³ vessels respectively. These were for open vents in the cover of the explosion vessel. In most cases the maximum explosion pressure developed when the flame front arrived at the vent; in some tests with the smallest vessel, the maximum pressure occurred after the flame arrived at a vent, but before it had propagated to the bottom of the vessel. The insertion of flame arresters in the vents made little difference to the flame speeds.

Protective covers

The maximum bursting pressures obtained with vents covered with plastics diaphragms are shown as a function of the diameter of the vents in Fig. 9. All the diaphragms were clipped round the periphery of the arrester holder. Three vents were used with the smallest diameter diaphragm but only a single vent for the others. In every case the maximum explosion pressure was governed by the bursting pressure of the diaphragm. The results, given in Fig. 9, were for vents not fitted with arresters, the pressures obtained with arresters being very similar.

Tests with rigid protective covers were carried out in the ⅓ ft³ vessel with central ignition. The covers were either held magnetically or were loose and rested under their own weight; the maximum explosion pressures are shown in Fig. 10. The increase in maximum pressures with magnetic covers was directly additive to the pressures with identical loose covers; the presence of a flame arrester had relatively little effect on the pressure. Tests with plastics-backed magnetic ferrite covers, over a flame arrester, gave a maximum pressure of 1·6 lbf/in², similar to that for rigid covers (Fig. 10). The ferrite covers closed after the explosion and showed no damage after repeated tests.

In industrial use some form of protection may be required on the exposed face of the arresters to prevent mechanical damage. A simple method of protection would be to fix a shield a short distance away from the arresters. Some experiments were carried out to investigate the effect of such a shield on the maximum explosion pressures developed in the ⅓ ft³ vessel. A mild steel plate was placed in front of four arresters 1·15 in. in diameter and the position of the plate was varied so that the area on the periphery of each arrester was between one-half and double the cross-sectional area of the arrester. The results showed that to avoid increase in explosion pressure the peripheral area had to be at least double the cross-sectional area.

Discussion

The use of flame arresters

The experiments have shown that casings up to 3 ft³ in volume can safely be protected with flame arresters against propane–air explosions. External ignitions were prevented, the explosion pressures could be reduced to low values and, thermal or mechanical damage to the arresters could be avoided. Adequate protection could readily be obtained with crimped-ribbon arresters which are commercially

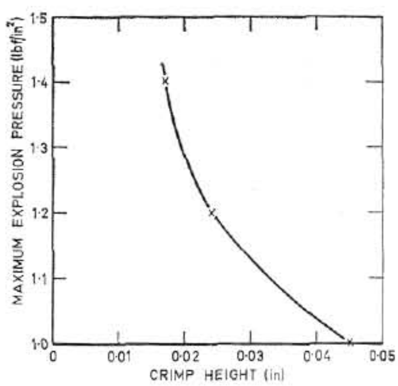


Fig. 8.—Variation of maximum explosion pressure with crimp height for 1 ft³ vessel fitted with four vents (K = 9·0) and cupro-nickel arresters of 2¼ in. diam. Central ignition source

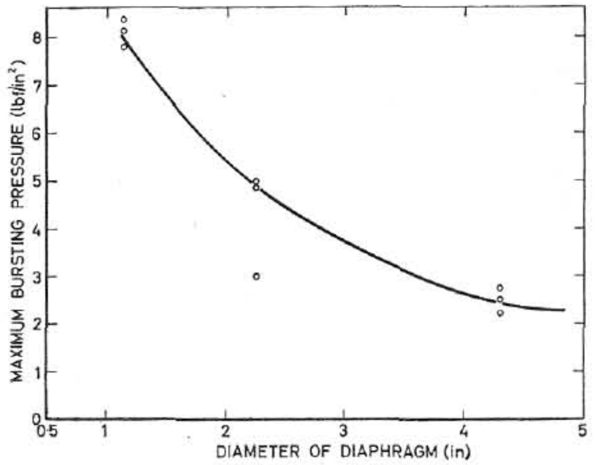


Fig. 9.—*Relationship between the diameter of the diaphragm and the bursting pressure for $\frac{1}{3}$ ft^3 explosion vessel without arresters*

available but arresters made from wire gauze or perforated metal were not successful and were not considered further. In assessing the adequacy of an arrangement of crimped-ribbon arresters two principal factors have to be considered. These were the maximum explosion pressures developed and the avoidance of structural damage to the arresters.

Maximum explosion pressures

The relationship between the vent area and maximum explosion pressure, was determined for open vents (Figs 4 and 5) and for vents protected with arresters (Figs 6 and 7). In each figure the explosion pressure was plotted as a function of a ratio, K, on logarithmic scales, and the approximately linear relationships were obtained. All vents were in the cover of the explosion vessels. For each system the maximum explosion pressure was approximately proportional to K^2.

Relationships of this type may be derived on simple theoretical grounds (see Appendix). On inserting numerical values:

$$P = 0{\cdot}0056\, K^2\ \text{lbf/in}^2 \quad . \quad . \quad . \quad (1)$$

Equation (1) is represented by a broken line in Fig. 4, which summarizes the maximum pressures measured with a range of explosion vessels. The equation gives good agreement with the results over the relevant low pressure range (that over which compression of the gas could be neglected). This agreement is of interest because the maximum pressure varied with K^2 and also appeared to vary with V^2. These findings differ from the behaviour observed in the explosion venting of industrial drying ovens[3] in which the maximum pressure with lightweight vent covers varied directly with K and with the standard burning velocity of the gas mixture. The values of K were usually small, less than four, and hence the pressure drop across the vent may not have been the principal effect governing the explosion pressure. The oven volumes ranged between 8 and 98 ft^3 and were much greater than in the present work.

When vents are covered with flame arresters there is an increase in the explosion pressures, which may also be calculated (see Appendix). As the maximum flame speed was only 19 ft/s the crimped-ribbon arresters were easily able to quench flames. For instance, it may be calculated[4] that an arrester 1·5 in. thick of 0·045 in. crimp height and 0·90 free area would be able to quench propane–air flames with velocities up to 490 ft/s at near atmospheric pressures. The arresters of smaller crimp height would be even more effective. On the basis of this calculation failure of equipment in practical situations due to the passage of flames through the crimps may therefore be discounted for propane and other gases of similar burning velocity.

Structural damage to arresters

With crimped-ribbon arresters the correct choice of the metal for the ribbon has been shown to be important. Both nickel and alloy A ribbons were shown to give satisfactory performance within the range of pressures likely to be encountered in practice; the important properties are resistance to oxidation and high melting point. It is likely that the distortion of the ribbon arresters observed with thin nickel ribbons could be avoided by a different design of arrester but as explained above the problem is unlikely to be serious in practice because it only occurred with small vent areas.

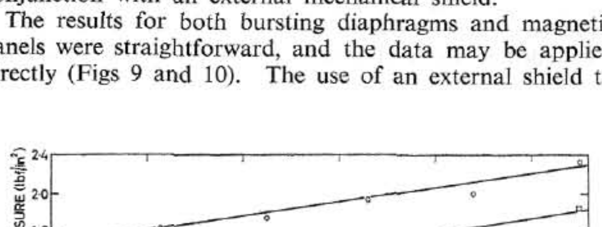
With the cupro-nickel crimped-ribbon arresters the avoidance of thermal damage governed the area of arresters required. The necessary area, per unit volume of the vessel, was shown in Table II and diminished as the crimp height decreased. The area of arrester could also be reduced if it were divided equally between two opposite walls of the vessel. Because of restrictions on the available diameters of the arresters, the relationship between the area of arrester and the volume of vessel could not be established precisely.

Crimped-ribbon arresters are available commercially in nickel, alloy A and cupro-nickel.

Protective covers

There is a clear need for some form of protective cover for flame arresters in certain environments. The covers would be required to prevent accidental damage to the arresters and the ingress of moisture and dust into the equipment casing. The necessary protection must be obtained without increasing the maximum pressure to such extent as to adversely affect the performance of the arresters. In addition, the covers should be so designed that damage or lack of maintenance would reduce rather than increase the pressure required for operation and the performance of the covers should be sufficiently predictable to facilitate design. It would also be desirable that covers should be robust enough not to be removed or damaged accidentally. The types of cover examined (bursting diaphragms and magnetic panels) could satisfy most of the requirements either directly or in conjunction with an external mechanical shield.

The results for both bursting diaphragms and magnetic panels were straightforward, and the data may be applied directly (Figs 9 and 10). The use of an external shield to



× : loose cover
□ : cover held by magnetic force of 40 lbf/ft²
○ : cover held by magnetic force of 80 lbf/ft²

Fig. 10.—*Relationship between maximum explosion pressure and the weight of the vent cover or the weight of vent cover plus magnetic force for $\frac{1}{3}$ ft^3 explosion vessel with a single vent of 4·3 in. diam*

protect the arresters from mechanical damage was shown to be feasible and no pressure increase would occur if the peripheral area around each vent was twice the cross-sectional area.

Further development work would be necessary before any of the methods of covering the vents could be used on an item of equipment but the effectiveness of the principle of the vent covers has been demonstrated. The design of covers for a particular piece of equipment is likely to require, at least initially, individual tailoring of the design to that of the equipment and its usage.

Practical aspects of technique

Sufficient laboratory work has now been carried out to show that it would be practicable to use flame arresters to protect equipment for use in propane–air atmospheres. As propane may be regarded as a typical Group II gas, the same conclusion will apply to other gases in this group. From the information given the dimensions of vents required to keep the maximum explosion pressure down to any predetermined value may be obtained directly. For many applications a useful working maximum explosion pressure would be several pounds per square inch; in many cases this would allow construction from sheet metal either by pressing or by welding of the casing. Arresters able to protect safely such vents are described and these arresters would not permit passage of flames through their apertures and would not suffer thermal damage from repeated explosions. For vessels with no internal partitioning, and with all vents in one side, the total vent area would need to be about 10% of the area of the largest side of the vessel.

It is foreseen that this amount of venting could readily be provided for most industrial equipment in rectangular casing; if difficulty were experienced in accommodating all the venting on one side it may be sub-divided between several sides and some reduction in total area of vent may then be permissible. All the data obtained have been for cubical vessels—the worst case—and if the same venting is applied to rectangular vessels with one dimension appreciably different from the others then a safety margin is again introduced provided that the vents are on the largest side of the vessel. The area of this side should be taken as the cross-sectional area of the vessel.

By using flame arresters for protection the explosion pressure is vented safely and the casing does not have to be so constructed as to withstand the full pressure of an unvented explosion. It is envisaged for many applications that a modified standard type of construction for equipment not designed for hazardous atmospheres may be used and the cost may be assessed accordingly. The cost of such equipment protected with flame arresters would be approximately that of the standard item, plus the cost of flame arresters and fittings. The latter would be a fairly standard cost directly additive to the original cost of the equipment.

In designing equipment casings protected with flame arresters, it is important to consider the effect of the contents of the equipment on the explosion flame and also the amount of clearance permissible for shafting and lids. At present relatively little information is available, and these aspects are being investigated.

Conclusions

1. Equipment casings up to 3 ft^3 in volume can be safely protected by crimped-ribbon flame arresters.

2. A simple correlation has been found between the maximum explosion pressure and the vent area.

3. With arresters made from nickel or alloy A ribbon the vent area required would usually be governed by the maximum pressure permissible in an explosion rather than by the need to prevent damage to the arresters.

4. With cupro-nickel arresters somewhat larger vent areas are required to avoid thermal damage caused by the explosion.

5. Flame arresters on equipment casings may be covered effectively with bursting diaphragms, magnetic panels, or mechanical shields.

6. Approximate relationships between maximum explosion pressure, area of vent, and dimensions of the flame arresters can be accounted for by a simple theory.

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APPENDIX

Relationship between Explosion Pressure and Vent Area

Firstly consider open vents. It is assumed that the maximum explosion pressure is governed by the resistance to gas flow caused by the vents, and that the pressure gradient within the explosion vessel is relatively small. It is also assumed that the flame front acts as a piston expelling unburnt gas through the vent. The latter assumption is an approximation because the flame front is of complex shape but the experiments showed that pressures are higher when the igniting source is sited at a distance from the vents. The maximum explosion pressure usually occurs when the flame front arrives at the vents. For the isothermal flow of an ideal gas:[6]

$$G = Ca\sqrt{(2\rho P)} \text{ (approximately)}$$

where: a = area of vent.
C = discharge coefficient.
G = mass rate of flow through vent.
P = gauge explosion pressure inside vessel.
ρ = density of gas at atmospheric pressure.

For the present work we are interested in explosions in which the maximum explosion pressure is low, *i.e.* the gas behaves approximately as an incompressible fluid.

Therefore: $G = VA\rho = Ca\sqrt{(2\rho P)}$

where: A = cross-sectional area of explosion vessel.
V = gas velocity in explosion vessel.
$A/a = K$.

$$P = \frac{V^2 K^2 \rho}{2C^2}.$$

The maximum flame speed for each vessel was about 19 ft/s but the corresponding gas velocity was slightly less because the flame was propagating through the gas mixture. With no heat losses, the maximum flame temperature would be 2260°K and the expansion ratio, based on an initial temperature of 300°K, would be 7·5 approximately, *i.e.* one volume of initial gas mixture would yield 7·5 volumes of hot combustion products. For a vent ahead of the flame, the maximum gas velocity would then be $(19 \times 6{\cdot}5)/7{\cdot}5 =$ 16 ft/s approximately.

The Reynolds number with this gas velocity in a vessel of 1 ft square cross section is approximately 10^5; hence $C = 0{\cdot}6$ and is relatively insensitive to variation in the vessel dimensions and numbers of vents, over the range studied. Since $\rho = 0{\cdot}074$ lb/ft^3:

$$P = 0{\cdot}0056\, K^2 \text{ lbf/in}^2 \quad . \quad . \quad . \quad (1)$$

When vents are covered with flame arresters the increase in explosion pressures should be related to the structure of the arresters. For crimped-ribbon arresters the relation between pressure drop, P^1, gas velocity, U, fraction of area open to gas flow, e, thickness of arrester, L, and hydraulic diameter of aperture, d, is of the form:[5]

$$P^1 = 4{\cdot}1 \times 10^{-6} \left(\frac{U}{e}\right)^{1{\cdot}082} \frac{L^{0{\cdot}665}}{d^{1{\cdot}583}}.$$

For an arrester of crimp height 0·045 in. (Table II), $d = 0{\cdot}37$ in, $L = 1{\cdot}5$ in, $e = 0{\cdot}90$, and $U = VK = 16K$ ft/s because the maximum flame speed was the same as with open vents.

Hence:

$$P^1 = 2{\cdot}2 \times 10^{-2}\, K^{1{\cdot}082} \text{ lbf/in}^2. \quad . \quad . \quad (2)$$

The contribution of the arresters to the explosion pressure, given by equation (2) was comparable with that from the vents given by equation (1). For example, when $K = 10$:

equation (1) gives: $P = 0{\cdot}56$ lbf/in^2,

equation (2) gives: $P^1 = 0{\cdot}26$ lbf/in^2.

Thus the total calculated explosion pressure is 0·82 lbf/in^2 and is in reasonable agreement with the experimental results (Fig. 7). As P^1 was approximately proportional to K, whereas P varied with K^2, the contribution of the arresters to the total pressure would be relatively greater at low values of K.

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DISCUSSION

Dr. C. R. Black asked whether the lines on Figs 7 and 8 were in fact the calculated best fit lines or were drawn to the points shown.

Mr. Rogowski replied that they were the best lines drawn to the points.

Mr. P. L. Klaassen said that a lot of information had been given about the arresters. He himself always looked upon flame arresters to be used if something else could not be used, as they could block up and foul up. Where you had a constant flame and could not use a liquid seal vessel, you could not do anything else but use a flame arrester. That was the only case where he would use a flame arrester. However, now he saw that it might be cheaper in the future to allow sparking in, for example, electric motors and then install a lot of flame arresters. Was that the trend of the introduction of the paper?

Mr. Rogowski said that in the present application there might be a danger of arresters blocking up, in certain situations, but this could be effectively remedied by suitable covers. Some tests on the effectiveness of these methods had been carried out.

As to the future, the method would not displace all other methods of protection but it was foreseen that it would be a useful additional method. The extent to which it would be used might be clearer after more work has been carried out. At some stage a standard would need to be laid down.

Mr. D. G. Furzey referred to the mixture of 4% by volume propane in air and asked what would be the effect of varying the limits of propane in the air on the transmission of flame across the arrester.

Mr. Rogowski replied that the effect would be very slight. The maximum pressures would be slightly higher when using 1·1 of stoichiometric. The effect would become more pronounced when other, faster burning, gases were used.

Mr. H. G. Riddlestone said that with flame-proof electrical equipment a lot of work had been done to determine the safety factors on flange gaps and the probability of flame transmission through the flange. He asked if Palmer and Rogowski had done any similar work on safety factors or on the effect of the flame-arrester dimensions on the probability of flame transmission. With electrical equipment it had been found with more explosive gases that an obstruction near the flange would reduce the safety margin and he wondered whether the presence of a plate or cover over a flame trap would have the same effect.

Mr. Rogowski replied that direct determinations had not been made of the probability of flames passing through a given arrester. As mentioned in the paper, past work showed that an arrester of thickness 1·5 in. and crimp height 0·045 in. would be able to quench propane-air flames with velocities up to 490 ft/s, at near atmospheric pressures. In the present work maximun flame speeds were only 19 ft/s. There is thus a very large safety factor involved.

As regards external obstructions near to the arrester, no indication had been obtained in the experiments that an obstacle close to an arrester adversely affected its performance. A metal plate at distance 0·15—0·6 in. from the arrester had been tested. One reason for difference in behaviour between flame arresters and flanged gaps could be that the mechanism of flame quenching were different in the two cases.

Dr. D. J. Lewis said that he had, in previous considerations of flame arresters, discovered that they were prone to temperature effects—in other words, if the temperature of the arrester were allowed to rise it could be very dangerous in that there could be propagation of the flame through it. The tests carried out so far obviously had not allowed for anything like that and it seemed to him that this might be a problem with that type of protection against ignition from hazardous atmospheres far more than with the flange-gap type where one had a much more solid construction and also because of the much larger vents required for the objective of keeping the pressure down. He suggested that it might be a severe limitation to the practicality of flame arresters in the long term and thought might be given to this in future work.

Mr. ROGOWSKI replied it was correct that the effectiveness of a flame was reduced if its temperature, and that of the unburnt gas passing through it, were raised. As an approximation, the flame velocity at which an arrester failed varied inversely with the square root of the absolute temperature, providing that it was well below the spontaneous ignition temperature. In the present application of flame arresters it was envisaged that gas and arrester temperatures would be as under normal working conditions.

Dr. LEWIS said that his point was that when a piece of electrical equipment like a motor was working, it increased in temperature and therefore the arrester got warm. After perhaps one minor explosion inside, the arrester would have a residual temperature and in certain cases and would possibly pass flame. He knew that the Electrical Research Association had looked at the effects of temperature on the flange gap protection and he thought that the thinner metal of an arrester might be more susceptible to this effect. He was putting this forward as a possible point.

Mr. ROGOWSKI replied that the temperature rise in an arrester fitted to a casing, following an explosion, was usually small because of the relatively large diameter of the arrester. In addition because the arrester was an efficient heat transfer unit, its temperature fell rapidly when cool gas passed through it.

When an item of equipment protected with flame arresters was tested it would be subjected to a series of explosions at short intervals so that if cumulative over-heating developed it would be noticed. However, the relatively large areas of vents used would be a safety factor. It can be foreseen that in some applications it might be necessary to limit the maximum working temperatures of the arresters.

Mr. J. R. CROWTHER asked if Palmer and Rogowski would recommend a suitable type of flame arrester for Group I gases, in any shape.

Mr. ROGOWSKI replied that the design of a suitable flame arrester depended not only on the flammable gas but also upon the design of the plant *etc.* in which it was installed (see Ref. 4 of the paper).

For small compact enclosures, such as those described in the paper, a crimped ribbon arrester of thickness 1·5 in. and crimp height 0·045 in. would be adequate for Group I gases in air.