THE RELIEF OF PENTANE VAPOUR-AIR EXPLOSIONS IN VESSELS

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SUMMARY

The explosion of pentane-air mixtures, initially at atmospheric pressure, in two cylindrical chambers of internal diameter 4 ft 2 in. and length-to-diameter ratios approximately 1 : 1 and 3 : 1 has been studied. The vessels had capacities of 60 and 200 ft^3 respectively.

Rates of pressure rise are greater than can be predicted on a basis of data for the laminar burning velocity, the difference being greatest for mixtures considerably richer than stoichiometric (2.56% pentane). The fastest pressure rise occurs with the mixture containing 3.5% pentane. The difference between observed and calculated rates may be attributed to the diffusional instability of the flame envelope and to other causes.

Rates of explosion are increased by distortion of the initially spherical flame envelope, either by mechanical stirring or by the outflow of gases through a relief opening in the vessel. In consequence, the effect of a relief area in lowering the peak pressure is less than would be expected.

The bursting of a diaphragm covering the relief opening also causes acceleration of combustion. A closure consisting of a smoothly-opening plate-valve avoids this effect and gives a peak pressure little, if any, greater than that which occurs in the absence of any closure.

For the two vessels examined, the relief area necessary to give a certain peak pressure appears to be a function of the least cross-sectional areas of the vessels (which are the same) rather than of their volumes or total surface areas. However for mixtures whose rate of explosion is influenced to varying degrees in different vessels by combustion wave instability or other disturbances, such relations are bound to be obscured.

Introduction

It is possible, in principle, to control the pressure to which a vessel is subjected by a gas or vapour explosion occurring within it by the provision of areas of relief through which the explosion gases can be released. In making such provision, knowledge is required of the area of relief necessary in relation to the size and strength of the vessel and of the manner in which the relief opening is to be covered for normal working.

The theoretical treatment of the subject presents a number of difficulties, and in the present state of knowledge it is not possible to calculate relief requirements from first principles. Even the relatively easier problem of scaling the results of practical measurements contains some pitfalls. In these circumstances, empirical information has considerable value, although to be of the widest possible use it should be so obtained as to give information either on the scaling problem or on the prospect of theoretical computation, or both.

The measurements recorded in this paper were made for a practical purpose, but are perhaps of wider interest in that they are in a corner of the field that has hitherto been not much explored. The explosion volumes, though compact, were fairly large (60 and 200 ft^3) and the relief areas used were small enough to give fairly high explosion pressures. The explosive media employed consisted of pentane vapour-air mixtures of various strengths, the pressure and temperature prior to explosion being in all cases atmospheric.

Experimental Equipment

The explosion vessel used in the experimental work was an adapted marine boiler shell of internal diameter 4 ft 2 in., and 11 ft 6 in. long (excluding the curved ends). The total volume was about 200 ft^3 but for many of the experiments approximately two-thirds of the volume was filled with tightly-packed sandbags and walled off with cement-faced brickwork from the remaining free space, which amounted to 60.6 ft^3. An outline plan of the vessel is shown in Fig. 1.

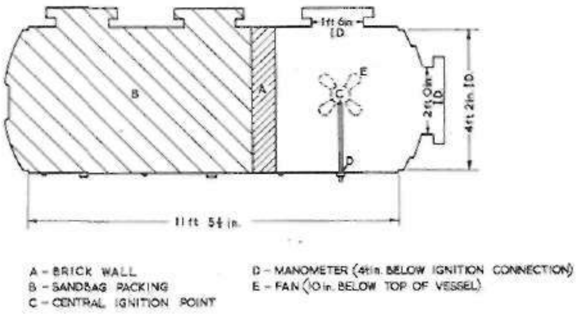

Fig. 1.—*Outline plan of explosion vessel*

For the purpose of these experiments the vessel had four large holes, three x 18 in. diameter along one side, and one x 24 in. at the end. These could be used as open vents, but each had a flange drilled and tapped so that orifice plates, relief closure devices, or blank flanges could be attached. Small holes for the introduction of pentane, for ventilation, for pressure measurement, and for ignition were provided opposite the 18 in. holes and the shell was tested hydraulically to 350 lb/in^2 after modification.

As indicated in Fig. 1, a fan was situated near the top of the 60 ft^3 space. This was used for mixing and it could be run during an explosion to promote turbulence. It was operated by a 1420 r.p.m. constant-speed motor and the intensity of stirring could be varied by using blades of different lengths.

The manometers used were of types described elsewhere. They included two optical instruments developed by the U.S.

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Bureau of Mines and the Safety in Mines Research Board respectively. It was soon found, however, that explosions were being obtained which produced transient pressure effects and in order to obtain better records in these circumstances a piezo-electric manometer due to Margerson and Robinson[1] was adopted. Each manometer used was calibrated at intervals with a reservoir of compressed air adjusted to a series of known pressures.

In the earlier part of the work the source of ignition was a coil spark, though a condenser discharge was used for weak mixtures. Later, the method used was to discharge a 16 microfarad condenser at 360 volts through a short length of 0•1 mm aluminium wire. This proved a reliable source and gave consistent results. Photographs showed however that this source occasionally threw off small particles of aluminium which started separate flames, thus giving rise to multi-point ignition over a small volume.

Before each experiment, the vessel was thoroughly ventilated by means of an air blower. The predetermined amount of liquid pentane (in the range of 200-300 ml for the 60 ft^3 space) was forced by nitrogen pressure through a spray nozzle into the vessel. The fan was run during injection of the hydrocarbon and for about one minute afterwards. The composition of the mixture produced was checked occasionally by analysis of a sample in a Bone and Wheeler apparatus. If an explosion vent was to be used it was covered with waxed paper, cellophane, or otherwise, before injection of the pentane.

Results

Pressure-time records were first obtained for the explosion of various pentane-air mixtures in the 60 ft^3 space without any form of relief. With more than about 2•7% pentane, pressure oscillations developed and reasonably satisfactory records could only be obtained using the piezo-electric manometer. Records for the 2•7 and 3•5% pentane mixtures are compared in Fig. 2. In the latter case the oscillations that developed were initially of a smooth waveform, later becoming sharp-peaked. Such explosions produced a loud note, audible for about a second, having a frequency similar to that of the recorded oscillations, *i.e.* a little over 300 cycles per second. In Table I data from the pressure records are shown. These are derived from the mean pressure-time curves where oscillatory records were obtained.

The oscillations with rich mixtures were almost completely suppressed by running the fan during the explosion. Otherwise the form of the pressure record and the maximum pressure attained were unchanged by stirring, but, as is illustrated in Table II, the rate of pressure rise was increased in accordance with the fan size.

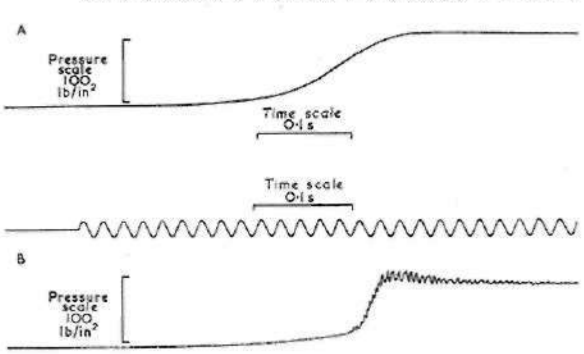


Fig. 2.—*Explosion pressure-time records for pentane-air mixtures in* 60•6 ft^3 *vessel*

A 2.7% 8 3.5% pentane

TABLE I.—*Explosions of Pentane-Air Mixtures in* 60.6ft^3 *Vessel with Central Ignition*

Mixture : pentane (%)	Maximum pressure lb/in^{2}g)	Maximum rate of pressure rise (lb/in^2 ms)	Time to maximum pressure (ms)
2.0	93	0.39	600
2.3	108	0.75	420
2.7	113	0.9	330
3.0	117	1.7	290
3.25	122	3.3	244
3.5	110	3.7	316
4.0	106	3.2	508
4.3	109	2.8	435

TABLE II.—*Effect of Stirring on Explosion of 2.7% Pentane-air Mixture in Closed* 60.6 ft^3 *Vessel*

Maximum pressure attained, about 113 lb/in^{2}g in each case.
Fan speed : 1420 r.p.m.

Fan diameter (in.)	Maximum rate of pressure rise (lb/in^{2}ms)	Time to maximum pressure (ms)
None	1.1	340
12	2.1	135
17.5	3.95	95
24	5.75	75

Characteristics of pressure records obtained with a series of pentane-air mixtures while using a paper-covered 12 in. diameter relief area are shown in Table **III.** In this series, pressure oscillations became pronounced between 2.4 and 2.5% pentane and combustion, was markedly accelerated, resulting, with the presence of the vent, in a sharp rise in the maximum pressure recorded. As with the unvented vessel however, the maximum rate of explosion was observed with the 3.5% pentane mixture.

TABLE III.—*Explosion of Pentane-air Mixtures in* 60.6ft^3 *Chamber with* 12 *in. diameter Paper-covered Vent*

Mixture : pentane (%)	Maximum pressure (lb/in^2 g)	Time to maximum pressure (ms)
2.4	7	735
2.45	11	576
2.5	35	382
2.7	43	289
3.5	56	249
4 0	53	347

Table IV shows the effect of (paper-covered) vent diameter and of stirring with fans of various sizes upon the maximum explosion pressure observed with a 2.7% pentane-air mixture. Records for the unstirred mixtures with 6, 12, and 18 in. vents are shown in Fig. 3. These show, in addition to the pressure-time curve, a 50-cycle timing wave up to the moment of ignition, followed by the signal from a photocell pointing across the vent. Oscillations become more marked with increase in vent size and in mixture strength. Stirring reduced oscillation somewhat (see Fig. 4), but although it accelerated combustion in most cases, the effect on the maximum explosion pressure in the presence of vents was not large and with the 18 in. vent the maximum pressure was actually reduced by stirring at the lower rates.

TABLE IV.—*Effects of Diameter of Paper-covered Vent and of Stirring on Maximum explosion Pressure for 2·7% Pentane-air Mixture. Fan Speed 1420 r.p.m.*

Vent diameter (in.)	Fan diameter (in.): None	12	18	24
	Maximum explosion pressures (lb/in² g)			
None	113	113	113	113
6	73	80	—	—
12	43	45	47	65
18	22	9	18	33
24	4	—	—	12

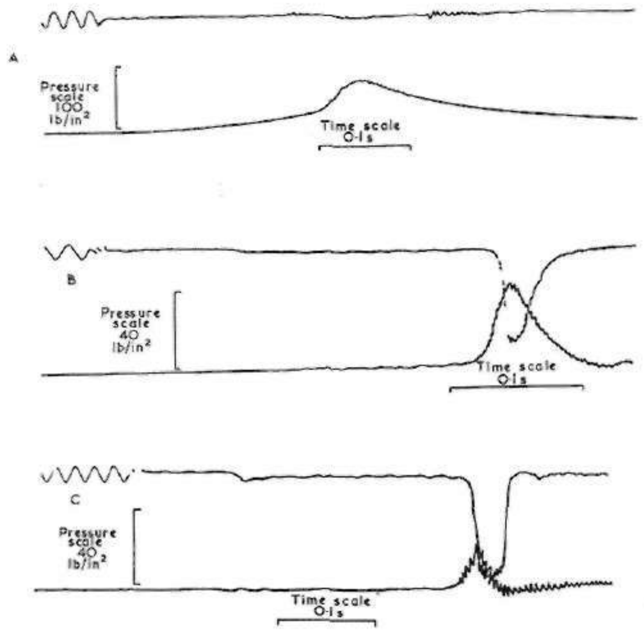


Fig. 3.—*Explosion pressure-time records for 2-7% pentane-air mixture in 60 -6 ft³ vessel, with circular (paper-covered) vents of diameter:*
A 6 in. 8 12 in. C 18 in.

The upper trace, after ignition, is that of the signal from a photocell viewing the emergence of flame from the vent.

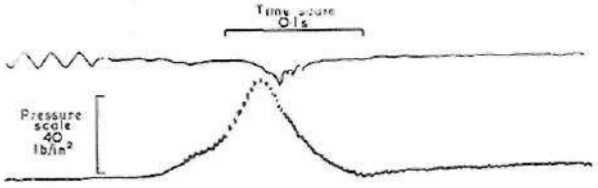


Fig. 4.—*Explosion pressure-time record for* 2.7% *pentane-air mixture in* 60.6 *ft³ vessel, with* 12 *in. diameter (paper-covered) vent, stirred by* 12 *in. fan at* 1420 *r.p.m.*

The upper trace, after ignition, is that of the signal from a photocell viewing the emergence of flame from the vent.

In the experiments with vents so far described, the opening was covered with waxed brown paper which burst at about 0-5 lb/in². It appeared from a study of the records that the bursting of this cover was itself tending to cause oscillation and this effect was further studied by substituting different forms of vent cover. Results are summarised in Table V. Bursting or opening pressures were read from the pressure records and were not determined independently. Although with the 2.7% pentane mixture reduction of the bursting pressure of the cover resulted in substantially slower explosions and lower maximum pressures, no such effect was apparent with the faster-burning 3.5% mixture.

Table VI shows results obtained with an 18 in. diameter spring-loaded plate valve having a plate thickness of 1 in. Fig. 5 shows the pressure records for the 2.7 and 3.5% pentane mixtures. Also included on the same time base are records of the lift of the valve plate. The pressure required to open the valve against the spring loading was 4 lb/in² but higher opening pressures were sometimes observed, due presumably to sticking and friction, although these were eliminated as far as possible. The travel or the plate war limited by a rubber buffer to about 3 in. and the maximum cylindrical relief area was about 170 in² as compared with 255 in² **for**

TABLE VI.—*Pressures Obtained in Pentane-air Explosions in* 60 . 6 *ft³ Vessel with* 18 *in. Vent Closed by Plate-Valve Opening at* 4 *lb/in² g*

Mixture : pentane (%)	Maximum pressure lb/in² g)
2 0	10
2.7	23
3.5	33

TABLE V.—*Effect of Method of Closure on Relief of Pentane-air Explosions in 60·6 ft³ Vessel. Central ignition*

Vent diameter (in.)	Cover: Material	Cover: Opening pressure (lb/in² g)	2·7% mixture: Maximum pressure (lb/in² g)	2·7% mixture: Time to maximum pressure (ms)	3·5% mixture: Maximum pressure (lb/in² g)	3·5% mixture: Time to maximum pressure (ms)
12	Card (1)	Negligible	25	377	58	192
	Card (2)	0·2	41	265	—	—
	Paper	0·5	43	289	56	249
18	Card (1)	Negligible	8	396	30	260
	Card (2)	0·2	21	348	—	—
	Paper	0·5	22	375	32	286
	Cellophane (slit before firing)	0·5	14	367	—	—
	Cellophane	2·4	29	215	—	—
	Cellophane (three layers)	6·2	29	241	—	—

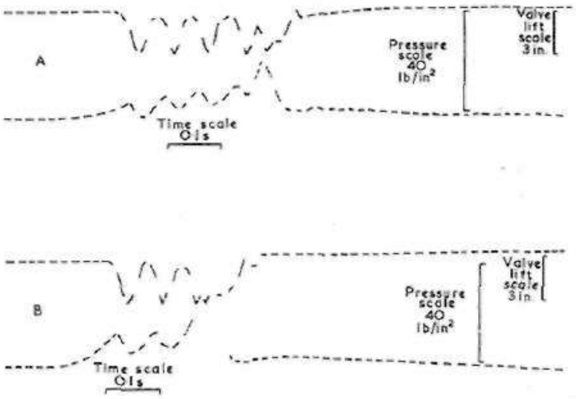


Fig. 5.—*Explosion pressure-time records for pentane-air mixtures in 60-6 ft³ vessel with 18 in. diameter relief valve:*
A 2-7% B 3-S%pentane

the 18 in. diameter opening. In spite of this, and of the relatively high opening pressure, the maximum pressures recorded were not significantly greater than with the paper-covered 18 in. vent. With a ¼ in. thick valve-plate and an opening pressure of 1.15 lb/in^2 the maximum pressure with a 2.3% pentane mixture was only 7 lb/in^2. Stirring with the 12 in. diameter fan at 1420 r.p.m. had little effect on the explosion pressure with such a relief valve.

It will be seen from Fig. 5 that the valve plate " bounces " during the explosion, with the consequence that there is a low frequency oscillation of the pressure. With the faster-burning mixtures the greatest pressure is reached on the last oscillation, whereas with weak mixtures it is the first pressure oscillation which has the greatest amplitude. The higher frequency oscillation noted in the closed vessel and with paper-covered vents was scarcely observable when relief valves were used.

Experiments using the full capacity of the explosion chamber were confined to those mixtures which in the 60 ft^3 section had given the fastest explosions. The results with the vessel entirely closed are shown in Table VII, from which it may be seen that, although the maximum pressures are much the same as in the smaller vessel, the rate of pressure rise is substantially reduced, *i.e.* the explosion is of longer duration. In the larger vessel, the pressure oscillations were less marked than in the smaller chamber.

TABLE VII.--*Explosions of Pentane-air Mixtures in* 200 *ft* Vesse*

Mixture : pentane (%)	Maximum pressure (lb/in^2 g)	Maximum rate of pressure rise (lb/in^2 ms)	Time to maximum pressure (ms)
3 0	112	0-8	505
3-5	111	1 -26	440

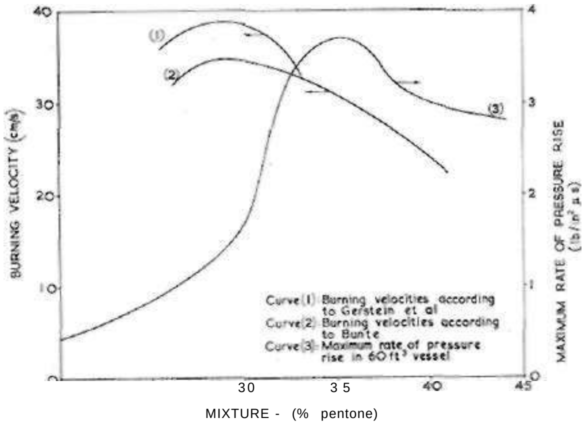
The effects of the following vent arrangements in the 200 ft^3 vessel were investigated :—

(i) One 18-in. vent in the mid-position along the side of the vessel,
(ii) One 24-in. vent in the end of the vessel.
(iii) Three 18-in. vents along the side of the vessel.

With the 18-in. side vents in use, the igniting source was placed in the centre of the vessel. With the 24-in. end vent, the source was on the axis of the cylinder but alternatively at the ends near to and remote from the vent. In all cases the vent openings were covered with light cards. The results obtained are summaried in Table VIII.

Discussion and Conclusions

In Fig. 6, laminar burning velocity data for pentane-air mixtures, derived from the literature, [2,3] are compared with maximum rates of pressure rise measured (for the 60 • 6 ft^3 chamber) in the present work. Whereas the maximum burning velocity is observed with a 2.9% pentane mixture, the 3.5% pentane mixture gives the greatest rate of pressure rise.



NOTE. The units along the right hand vertical axis should be milliseconds not microseconds as indicated.

Fig. 6.—*Comparison of burning velocities and maximum rates of pressure rise on explosion in* 60 • 6 *ft³ vessel for pentane-air mixtures*

It is possible to calculate the pressure development that can occur in a spherical vessel of given volume due to the central ignition of a gas mixture having known burning velocity characteristics. This has been done for a 2.7% pentane mixture for a sphere of 60.6 ft^3 capacity on the basis of values of the laminar burning velocity. The calculated pressure rise is, except perhaps in the early stages, considerably slower than was in fact observed with the same mixture in the 60.6 ft? chamber. The difference is greater than can be accounted for by the approximations involved.

It appears that for explosion in the 60.6 ft^3 closed vessel, with mixtures containing greater than stoichiometric propor-

TABLE VIII.—*Effect of Vents (card-covered) on Explosion of Pentane-air Mixtures in 200 ft³ Vessel*

Vents			Mixture : pentane (%)	Maximum pressure (lb/in^2 g)	Time to maximum pressure (ms)
Number	Position	Diameter (in.)			
1	Mid-side	18	3·25	22	655
1	Mid-side	18	3·75	35	760
1	End (ignition near)	24	3·5	4	680
1	End (ignition remote)	24	3·5	16·5	315
3	Along side	18	3·5	2·5–3·0	540–585
3	Along side	18	4·0	[illegible]·5–4·0	510–590

tions of pentane, there is some form of departure from laminar burning after the initial stage of the explosion, and that this is marked by the appearance of gas pressure oscillations in the record and of a corresponding audible note. Similar observations were made by Maxwell and Wheeler[4], but with their smaller explosion vessel (6 in. diameter, 15 in. long) the oscillatory phase of the explosion appeared only with a more restricted range of mixtures. The most marked effect, however, appeared, as in the present work, with about 3,5% pentane in the mixture.

Instability of the combustion wave is no new phenomenon. The vibratory stage, accompanied by increase of flame speed, has long been a recognised feature of flame propagation in tubes. Instability of propagation in flowing gases has aroused some interest in recent years, as has the question of the transition from deflagration to detonation during spherical flame propagation.

To discuss the matter in detail would be out of place in the present paper. Some aspects have been reviewed by Markstein.[5] It can be said however that various influences appear to be involved and that their relative importance depends upon the circumstances of flame propagation.

Since, with hydrocarbon fuels, instability is most noticeable, as in the present work, with fuel-rich mixtures, explanations based upon relative rates of diffusion of fuel and oxygen through the flame front have found favour.[5] A part may also be played however by natural oscillation of the burning gas of the column, by vibration of the containing vessel and auxiliary equipment, by the onset of turbulent flow conditions in the unburnt gas ahead of the flame,[6] and by the interaction of shock waves with the flame front.[7]

A spherical flame envelope represents the minimum surface enclosing a given volume of products and hence a minimum rate of burning at a given stage. Any disturbance of this spherical form, whether it consist of roughening due to turbulence, cell formation due to differential diffusion, or gross distortion due to external influences, will result in an increase in flame-front area and hence in an increase in the rate of burning. Gross distortion occurs when the mixture is stirred and hence there is an increase in the rate of burning which may be taken as a measure of the increase in area of the flame envelope brought about by the degree of stirring employed. (See Table II.) At the same time, the tendency to combustion instability is diminished, as Maxwell and Wheeler also observed.[4]

In a somewhat similar manner, the presence of a relief area will distort the flame envelope as the result of gas flow towards the vent. Thus, after the relief has opened, but before any substantial quantity of burnt gas has escaped, the rate of combustion may exceed the rate at the same stage in the closed vessel. This is actually observed and with small vent-areas the rate of pressure rise may exceed, for a time, the maximum rate occurring without any vent at all. The effect is more noticeable with the vent remote from the source of ignition than near to it, for in the former case the flame envelope whilst still remaining inside the vessel becomes more distorted due to outflow of unburnt gases. Hence a vent near the source of ignition is more effective in lowering the peak pressure than one at a distance from it. (Table VIII.) With a flame envelope distorted due to a vent, mechanical stirring of the burning mixture has relatively less effect.

So far as the closure of the relief vent is concerned, an increase in the opening pressure, by increasing the amount of combustion that has occurred before relief begins, generally increases the peak pressure finally attained. A closure, such as a diaphragm, which bursts suddenly at the opening pressure, appears to have its own disturbing effect upon the flame envelope, leading to acceleration of combustion. Therefore a closure that opens smoothly at a certain pressure, such as a plate valve, gives rise to a lower peak pressure than does a diaphragm which bursts at the same opening pressure. With rich mixtures, in which the flame envelope is disturbed in any case, this effect is not noticeable.

Explosion-relief areas have commonly been stated in relation to the volume they protect. This practice is unsatisfactory dimensionally, and it seems more rational to relate the relief area to some area function of the vessel itself. In the present instance two cylindrical chambers differing only in length by a factor of three, have been employed. For comparison of venting effects in the two chambers, the results with the 3.5% pentane-air mixture are most free from ambiguity, since they are least susceptible to effects due to the method of closure and to other disturbances. From an examination of these results (Tables IV, V, VI, and VIII) it is clear that equal relief areas are associated with substantially similar peak-explosion pressures in the two vessels. It appears therefore that the effect of the relief area in limiting the explosion pressure in vessels in the form of short cylinders (length/diameter less than 3) depends not upon the volume or surface area of the vessels but upon their cross-sectional area, which is the same for the two vessels used. The present results (though limited in number) indicate, in fact, that a linear relation exists between the peak explosion pressure and the logarithm of the relief area over most of the range of peak pressures. This suggests that for short cylindrical vessels differing in diameter a similar linear relation may exist between the peak pressure (*P_{max}*) and the logarithm of the ratio : cross-sectional area of vessel (*A*)/relief area *(a).* In this form, the results for the 3.5% pentane-air mixture may be related by :

$$P_{\max} = 68 \cdot 0 \log_{10} A/a - 28 \cdot 6 \text{ (lb/in}^2\text{)}$$

for values of $P_{\max}$ from 5 to 100 lb/in^2.

Such a relation cannot of course hold for very low pressures or for those near to closed-vessel values.

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