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Gas Explosions in Partially Filled, Large Twin Enclosures Connected with an Open Door and Having Variable Vent Sizes on Both Compartments

Gary B.Tomlin[1*], Herodotos N. Phylaktou[2], Mike Johnson[1], Gordon E. Andrews[2], Saul Algar[1]

[1]DNV-GL, Holywell Park, Ashby Road, Loughborough LE11 3GR, UK
[2]School of Chemical and Process Engineering, University of Leeds, LS2 9JT, UK
*Corresponding author email: gary.tomlin@dnvgl.com

ABSTRACT

Accidental gas explosions are a recognised hazard in process industries but they are also common in residential buildings. Whilst process plants have specifically designed vent reliefs to limit the enclosure damage, in homes a similar effect is achieved due to the presence of doors and windows whose failure often protects the building. There are empirically based correlations for predicting overpressure and for vent sizing, however these are limited in application to simple enclosures. In practice, enclosures have interconnected spaces which would potentially increase the flame acceleration considerably. In this paper we present the results of full scale natural gas layer tests in a twin chamber, which consisted of two 22 m^3 enclosures connected by an open doorway. Layered natural gas/air mixtures of 8, 10 and 12% by volume, were ignited at the rear of one of the chambers. Explosion relief was provided by vent openings of 2.48, 1.49 or 0.74 m^2 on the far walls of both chambers. With tests with equal large vents on each of the chambers, the dominant influence was the external explosion. The maximum overpressure was produced by tests involving a 12% natural gas concentration. The use of a smaller vent in the adjoining enclosure had a significant effect on the maximum overpressure and the mechanism of the explosion development. However, altering the size from 1.49 m^2 to 0.74 m^2 had little overall effect. This was largely due to the greater generation of turbulence and the venting process which predominantly occurred via the doorway and through the ignition-chamber vent opening. The use of a smaller vent in the ignition enclosure also altered the manner in which the explosion developed. A venting driven 'jetting' expanding flame, propagated into the adjoining enclosure and towards the far vent opening, generating the dominant pressure peak in these type of tests.

KEYWORDS: gas, explosion, twin, enclosure.

NOMENCLATURE

K_A	vent coefficient (cross-sectional area of the enclosure in the plane of the vent divided by the area of the vent opening)	$K_{A,F}$	vent coefficient (far enclosure)
$K_{A,I}$	vent coefficient (ignition enclosure)	Pv	Pressure peak due to vent opening (mbar)
		P_{max}	Maximum pressure (mbar)

INTRODUCTION

Accidental gas explosions inside enclosures are a recognised hazard in process industries but they are also common in residential buildings where natural gas or LPG are used for heating and/or cooking. Whilst in process plants pressure relief vents are specifically designed and installed to limit the enclosure damage, in homes a similar effect is achieved due to the presence of (weaker than the structure) doors and windows whose failure often protects the rest of primary building and its neighbours (although not always the case). There are empirically based correlations for the prediction of overpressure and for vent sizing (e.g. EN 14994 [1]; NFPA 68 [2] etc.), however these are limited in application to simple, compact enclosures. A typical process plant enclosure or a typical building has interconnected spaces which would potentially increase the flame acceleration considerably. Therefore, the simple guidelines and correlations, referred to above cannot be applied with any confidence to these situations for either design or post-incident investigation purposes. NFPA 68 [2] makes an attempt to account for turbulence generated by obstacles in the enclosure but it explicitly states that such approach is only applicable to cases where “the enclosure is isolated from possible flame jet ignition and pressures caused by a deflagration in an interconnected enclosure”.

There have been very few large-scale experimental studies of the effects of interconnected rooms on gas explosions [3-7]. In this paper, continuing the work of Pedersen et al. [8], we present analysed data from a series of tests of full scale natural gas layer accumulation and ignition in two identical enclosures with an interconnected open door with low pressure vent relief from both enclosures.

EXPERIMENTAL

Sixteen large-scale vented explosion experiments were carried out in a twin enclosure explosion chamber (**Figure 1**). The chamber consisted of two 22 m^3 (2.4 m x 3.6 m x 2.4 m approx.) enclosures that, in the tests we present here, were connected by an **open** doorway (1.98 m x 0.76 m) halfway across the common boundary (**Figure 2**). Natural gas/air mixtures of 8, 10 and 12% concentration by volume, filling the upper half of both chambers (i.e. layer depth of 1.2 m) were ignited by an electric spark positioned at the centre of the rear wall of the left enclosure. The required natural gas/air mixtures were pre-mixed prior to admission into the explosion chamber and were introduced into each enclosure through a large diffuser located in the ceiling of each enclosure, thus allowing the formation of natural gas/air layers extending downwards from each enclosure ceiling. The fuel concentration was measured by withdrawing samples of the natural gas/air mixture at various heights in the enclosures through remote monitored sampling probes. The sampling probes were withdrawn from the enclosures prior to ignition.

The pressures generated in the explosions were measured by eight piezoelectric pressure transducers located in the ceiling and front of the enclosures.

Explosion relief was provided from low pressure vents on the upper half of each of the front enclosure walls (**Figure 1**), in varying combinations of 2.48, 1.49 or 0.74 m^2 openings, corresponding to vent coefficients, K_A, (defined as the cross-sectional area of the enclosure in the

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plane of the vent divided by the area of the vent opening) of 2.4, 4 and 8 respectively. Video footage was used on the analysis of the flame position and pressure transducers were used to monitor the pressure changes in each chamber and externally whilst the corresponding pressure differences were used to estimate the mass flows and velocities through the openings.

Figure 1. The explosion chamber.

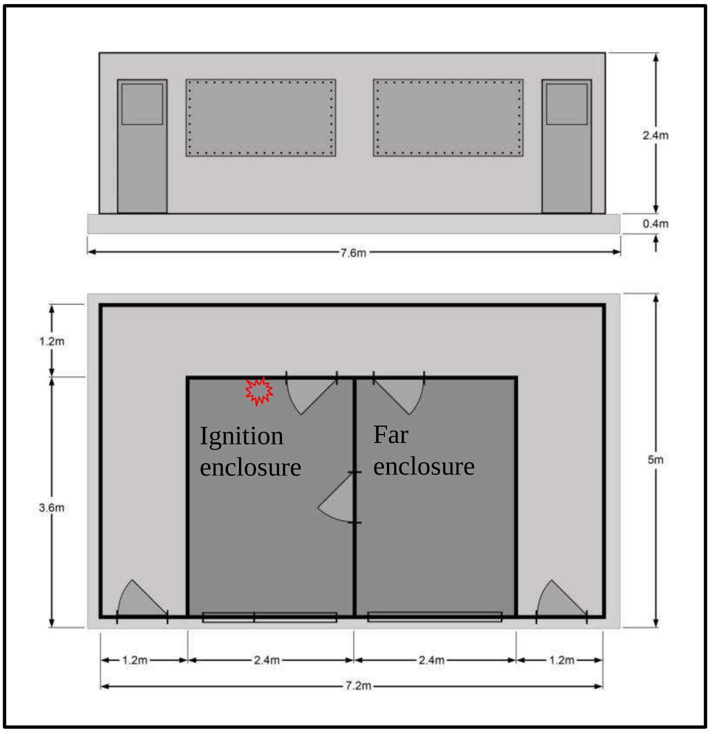

Figure 2. Explosion chamber configuration (only the ignition & far enclosure spaces, with their connecting door open, the back doors closed, and the front openings used for vents were used in the tests reported here).

RESULTS AND DISCUSSION

General

A summary of the experimental considitions and test data is given in **Table 1**. The rate of pressure rise and flame speed, in vented explosions in empty enclosures, are directly proportional to the flame surface area. As the experiments described in this paper were all ignited at the centre of the rear wall of the left enclosure, a height, which is at the flammable mixture/air interface, the expanding flame front would have started to propagate in the shape of a quarter-sphere. Accordingly, the total surface area of the flame would have been significantly less than the case of an experiment involving a full volume of gas/air mixture (the full volume flame would have initially propagated in a hemispherical shape), and overpressures and flame speeds would be expected to be lower. This was found to be the case when compared to full volume tests to be reported in a further paper.

Table 1. Summary of experimental conditions and test data.

Original Test No.	Gas Conc. (% v/v)	K_A Ignition enclosure	K_A Far enclosure	P_V (mbar)	P_{Max} (mbar) Ignition enclosure	P_{Max} (mbar) Far enclosure
1	8	2.4	2.4	38	37	38
2	8	2.4	2.4	39	39	39
3	10	2.4	2.4	40	83	103
4	10	2.4	2.4	41	82	85
6	12	2.4	2.4	44	152	179
7	12	2.4	2.4	44	76	83
23	8	2.4	4l	44	55	62
24	10	2.4	4l	46	83	90
28	12	2.4	4l	44	117	145
30	8	2.4	8	44	103	131
32	12	2.4	8	46	110	152
48	8	4r	2.4	51	69	69
49	12	4r	2.4	51	117	110
50	8	8	2.4	50	103	83
51	10	8	2.4	62	324	234
52	12	8	2.4	47	159	138

In almost all of the experiments reported here, the explosion overpressure-time profiles displayed pressure peaks similar to that observed by Cooper et al. [9], Bauwens et al. [10, 11], Harrison and Eyre [12], Bimson et al. [13], van Wingerden [14, 15] and van Wingerden and Zeeuwen [16] in large-scale vented explosion experiments in a single compartment; that is, pressure peaks related to the opening of the vent, the onset of burnt gas venting, the external explosion, acoustic and hydrodynamic instabilities and maximum flame area were observed. Similar pressure peaks were also reported in small scale tests by Fakandu et al. [17].

In general terms, three dominant pressure peaks were exhibited during the tests, not all of which were present in each test, but each produced the maximum peak in one or more tests. The first dominant pressure peak was always associated with the removal of one or both of the explosion relief vent panels (in either of the two enclosures) and its magnitude was equal to or slightly greater than the failure pressure of the vent panel. The pressure peak occurred, because initially, combustion was taking place in a totally confined enclosure and the expansion of the hot products of combustion generated a pressure rise. As soon as the vent covers failed, unburnt fuel/air mixture was allowed to escape through the openings causing the pressure to fall and giving rise to a pressure peak, labelled P_V. The P_V value reported in Table 1 is the lowest vent failure pressure of either of the vents. Interestingly, in many of the tests with a large vent opening in each enclosure (i.e. K_A = 2.4), immediately after the P_V pressure peak, the pressure dropped rapidly to below ambient and then immediately increased to form a second positive peak that was approximately the same value as the negative pressure trough (i.e. if the pressure dropped to -10 mbar, it would then 'bounce back', with a compression wave, to form a peak of approximately +10 mbar [see **Figure 3**]. The negative pressure phase is caused by the momentum of the outflow of unburnt gas/air mixture, which 'over-vents' the explosion chamber and as the explosion is still in its early stages, the expanding flame front does not generate sufficient pressure to maintain a positive pressure within the chamber. The difference in pressure across the vent opening subsequently causes air and unburnt gas/air mixture to flow back into the vessel which creates turbulence.

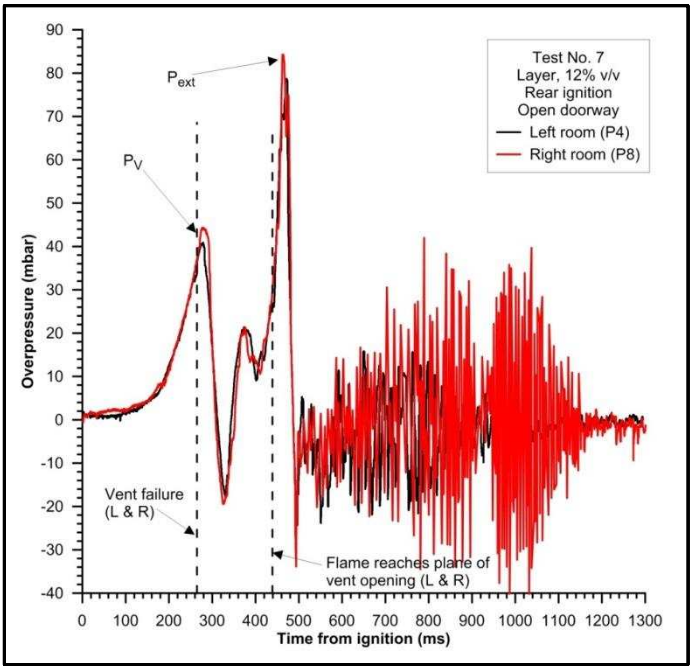

Figure 3. Overpressure-time profile for test no 7 (K_A = 2.4).

The second dominant peak was caused by the external explosion in a similar manner to that observed in a single compartment explosion (Cooper et al. [9], Bauwens et al. [10, 11], Harrison and Eyre [12], Bimson et al. [13], van Wingerden [14, 15]).

The third dominant peak, which occurred in many of the explosion tests, and which was observed to produce the maximum pressure in many experiments, was found to be more complex in origin and significantly more variable in its magnitude. The generation of this pressure peak was found to arise from the complex interaction of the combustion in each of the two compartments.

The effects of large vents of equal size

Figure 4 shows the overpressure-time profile for an experiment with a concentration of 8% (v/v) in each enclosure. The pressure measurements shown in the diagram were taken from pressure transducers located at the front of the enclosures. The pressure measurements taken from other transducers had similar profiles. As the natural gas/air mixture was moderately lean in concentration, there was an initial, relatively slow pressure rise up to approximately 580 ms after ignition, followed by a rapid drop in pressure to below ambient. It can be seen that the maximum pressure was generated in the first pressure peak and was recorded at 38 mbar. The video footage showed that both enclosure vents began to fail simultaneously at 540 ± 40 ms and were clear of the vent openings approximately 80 ms later. The pressure peak of 38 mbar at 580 ms therefore corresponds to the vent opening and onset of venting. The flame reaches the plane of the vent opening at 900 ± 40 ms but no significant pressure rise was measured inside the explosion chamber (usually seen shortly after an external explosion). However, bulk oscillations about ambient pressure start very shortly afterwards, at approximately 1 s, and occur at a frequency of approximately 60 Hz. The pressure oscillations recorded for each enclosure appear to have an opposite phase indicating that there is bulk movement between rooms via the doorway. In general terms, the pressure-time profile was similar to that expected of an explosion of a lean mixture in a single enclosure with a similar vent opening and failure pressure.

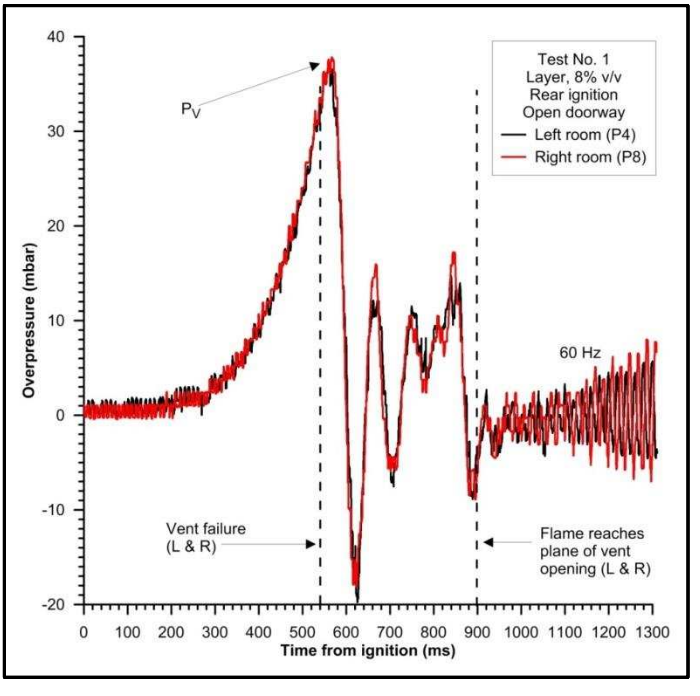

Figure 4. Overpressure-time profile for test no 1 (K_A = 2.4).

The dominant pressure peak in the fuel lean layered tests generally corresponded to the failure of the vents and the onset of venting, with the external explosion being less influential. This was because the entrainment of air, as the unburnt fuel/air mixture was expelled from the vent openings, diluted the forming cloud to a point where it was either not flammable or the severity of the external explosion was not sufficient to generate further overpressure within the explosion chamber.

Figure 5 shows the overpressure-time history for an experiment involving a near stoichiometric concentration (10% concentration (v/v), ϕ = 1.05) in each enclosure. In comparison with the overpressure-time history of test number 1, there were a number of significant differences observed. The initial pressure rise is considerably more rapid in this test because of the higher burning velocity associated with the near stoichiometric concentration. Observation of the video footage showed that both enclosure vents began to fail simultaneously at approximately 270 ± 40 ms and were clear of the vent openings approximately 80 ms later. However, as a consequence of the vent opening, and in a similar manner to test number 1, a rapid pressure drop to below ambient pressure occurred, giving rise to a pressure peak of similar magnitude (approximately 40 mbar) at 300 ms after ignition. Following this pressure drop to below ambient, a number of bulk gas oscillations occurred with flow reversal through the vent opening. However, these oscillations were interrupted by a sudden, very rapid pressure rise beginning at 460 ms, giving rise to a sharp pressure peak of 86 mbar at 480 ms.

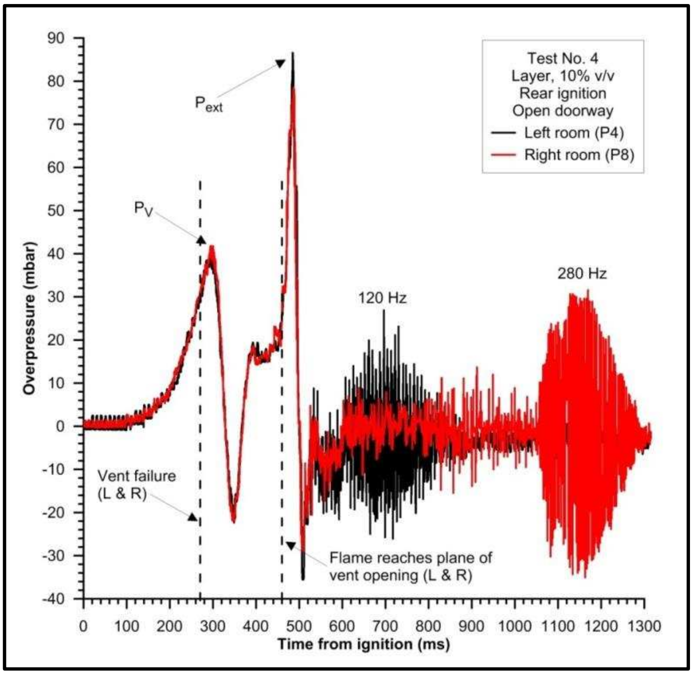

Figure 5. Overpressure-time profile for test no 4 (K_A = 2.4).

The video footage indicates that the flame reached the plane of both of the enclosure vent openings at 460 ms ± 40 ms. The sharp pressure peak therefore corresponds to the arrival of the flame at the vent openings and may be attributed to ignition of the flammable cloud expelled from the chamber during venting. In most of the tests observed during this series, there was a slight 'dip' in the overpressure-time profile just before the Pext peak. This slight reduction in overpressure was caused by the onset of burnt gas venting.

Experiments involving fuel rich concentrations (12% v/v) in each enclosure produced overpressure-time profiles similar to that of the slightly rich of stoichiometric mixture test (test No. 4), with the maximum pressure peak occurring immediately after the flame front had reached the vent opening. This indicates that the pressure peak was caused by the external explosion. Test No. 6 produced a maximum pressure peak of 179 mbar in the right enclosure, which was greater than the results of the near stoichiometric tests. The unburnt gas/air mixture entrains air as it is expelled through the vent opening and therefore stoichiometric mixtures are likely to be fuel lean when ignited by the explosion flame front and fuel rich mixtures are likely to be closer to stoichiometric, producing higher overpressures.

In summary, for tests with large vents of equal size, the maximum overpressure peak for the 8% gas concentration tests corresponded to the failure of the vents, resulting in an overpressure of 39 mbar, whilst both the 10% and 12% maximum peak pressure peaks were related to the external explosion, with maximum values measuring 103 and 179 mbar respectively.

The effects of vent size differences in the adjoining enclosures and of gas concentration

The effect of changing the size of the vent in the adjoining enclosures on maximum overpressure is given in **Figure 6**. The vent size difference is expressed in terms of the vent coefficient ratio - far enclosure over the ignition enclosure ($K_{A,F}/K_{A,I}$). This is effectively a ratio of the ignition chamber vent area divided by the far chamber vent area. So values under 1 indicate a vent in the ignition chamber that is smaller than that of the adjoining room.

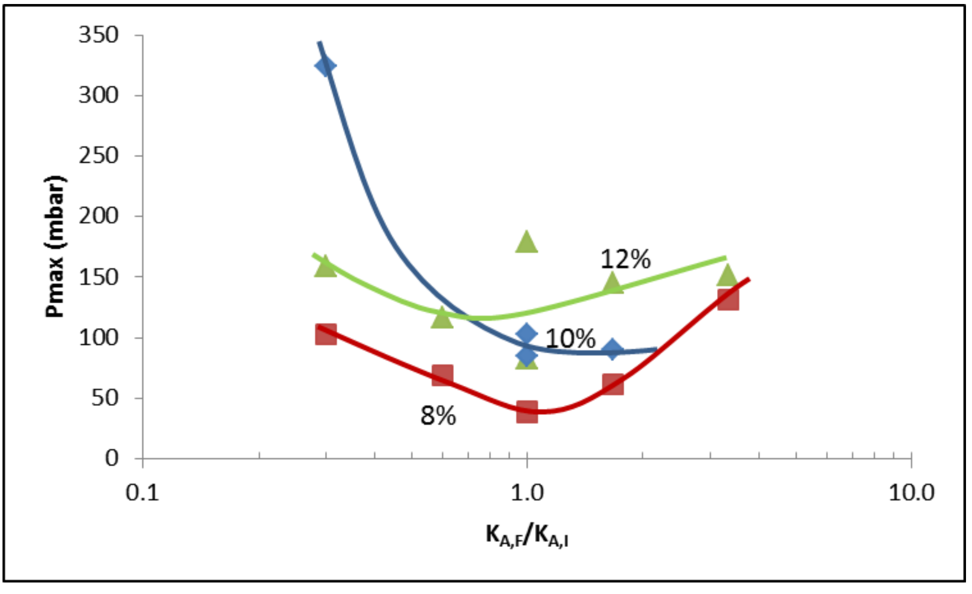

Figure 6. Maximum overpressure as a function of the vent area ratio between the two enclosures and the gas concentration..

The lowest overpressure for all mixtures occurred when the vent ratio was equal to 1, with effectively the larger vent being used in both vessels. When either side vent was reduced in size the overpressure increased. On balance the tests suggest that the overpressure was greatest when the vent in the ignition chamber was smallest.

As all vents were constructed of the same material, the larger vent had a lower failure pressure. Consequently, when the smaller vent was in the ignition chamber it would take higher pressures and longer time for the vent to break and since the larger vent was further away in the second chamber that would take a bit longer to open resulting overall in a higher Pv. It can be seen in Table 1 that the tests with smallest vent in the ignition chamber (last 3 tests in the Table) were associated with the highest Pv.

In the experiments where $K_{A,F}$ = 4, the vent could be fitted at either the left side or the right side of the front fascia panel. This was found to have no significant effect on either the maximum overpressure or the shape of the overpressure-time profile.

It is interesting to note the effect of mixture strength of the gas layer. In almost all but one of the tests the rich 12% mixture produced the highest overpressures. This can be attributed to the overall higher energy content of the 12% mixture which in a partially filled environment may result in diluted and therefore faster burning both within the enclosure and in the external explosion.

In the test with smallest vent in the ignition chamber the near stoichiometric (10%) mixture produced the maximum overpressure (twice that of the 12% mixture) and this may attributed in longer near stoichiometric burning the ignition chamber due the higher Pv of the vent as discussed above.

CONCLUSIONS

In this series of layered natural gas explosions of variable gas concentration, in two interconnected both with large low inertia vents of approx. 1/2, 1/4, and 1/8th of the far wall area it was shown that the lowest overpressures (for all gas concentrations) occurred when the largest vent was used in both enclosures.

If either chamber had a smaller vent, an increase in the maximum explosion overpressure was observed with the greatest effect being recorded when the smaller vent was fitted to the ignition chamber. In these cases a venting driven 'jetting' expanding flame, propagated into the adjoining enclosure and towards the far vent opening, generating the dominant pressure peak in these type of tests.

The richer 12% gas concentration produced the highest overpressures in almost all tests and this was attributed to the fact that further mixing caused by the explosion induced flow internally and dilution externally will result in mixtures that are nearer to stoichiometric (than the other starting concentrations) both internally and externally and hence stronger burning.

These observations have implications in the interpretation of dwelling gas explosion incidents. Fairly large fortuitous vents such as windows in both the initiating and adjoining rooms could result in less damage and the size of such vent in the ignition enclosure is particularly important. In partially filled enclosures, a rich layer is likely to result in more severe damage than a stoichiometric layer, however, it is indicated that if the vent in the initiating enclosure is small then a stoichiometric layer may be more damaging.

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