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In this newsletter:

THE DEVELOPMENT AND TESTING OF A LOW INERTIA, RAPID ACTING EXPLOSION RELIEF PANEL FOR HYDROGEN APPLICATIONS

Written by:

M. V. Hasson[1], R. Crewe[2], C. Norris[3], A. Davies[4], M. Gilmore[5], S. Lawrence[3]

[1]**Hasson Engineering Solutions Ltd, Northern Ireland, UK**

[2]**DNV Spadeadam Research & Testing, UK**

[3]**Rhino Engineering Group Ltd, UK**

[4]**Rhino HySafe Ltd, UK**

[5]**Rhino Systems Ltd, UK**

Abstract

The Rhino Engineering Group has developed and is patenting a new low inertia, rapid acting explosion relief vent for applications in the hydrogen economy, battery energy storage systems and other related sectors in which protection from deflagration hazards is a critical requirement.

Based on the Group's extensive design, fabrication and installation experience, the new HySafe Vertex vent panel has been developed and tested to demonstrate its reliable and rapid activation, and assured prevention of debris and missile hazards. A design process using outline analytical methods, simplified preliminary testing, before proceeding to extensive explicit dynamics FEA was undertaken ahead of full-scale hydrogen deflagration testing.

Satisfactory full-scale experimental substantiation of relief vent performance was obtained, across a wide range of overpressure and impulse conditions, leading to the production of a validated, convenient pressure-impulse curve to assist specifiers and hazard modelling specialists in their selection of the HySafe Vertex panel system.

Keywords: Vapour cloud explosion, deflagration, explosion venting, overpressure relief, hydrogen safety, hazard mitigation, passive safety, NFPA 68, NFPA 2, ISO 19880-1.

1 Introduction

Perhaps the earliest example of an industrial explosion subjected to scientific investigation occurred in Turin in December, 1785, at the bakery of Signor Giacomelli [1]. In his contemporary account of the incident, included within the memoirs of the Academy of Sciences of Turin, Count Morozzo astutely identified many of the factors which contributed to the "spontaneous inflammations", and observed how the explosion "threw down the windows and window frames of [Signor Giacomelli's] shop". It is possible that this observation may be the first documented recognition of explosion venting via a weaker part of a structure, albeit unintentional in nature.

In the centuries since elapsed, a rigorous and detailed understanding of accidental explosion phenomena has been developed, including the means to quantify the consequences of such events, and comprehensive guidance on how those consequences should be mitigated. Some of the events underpinning today's understanding are examined briefly, below.

Signor Giacomelli's misfortune was to be suffered a great many times by those involved in the handling, storage and processing of grains, flour and similar materials, with dust explosions being responsible for substantial losses across the globe. In the United States alone, during the period from 1860 through 1975 there were 340 grain elevator explosions, resulting in the deaths of 170 persons and causing injury to 638 others [2]. Furthermore, a number of particularly serious grain elevator explosions occurred in the short interval from December 1977 through January 1978, resulting in 62 deaths and 53 injuries. This disastrous sequence of events led to members of the United States Congress instructing the General Accounting Office to examine factors felt to be relevant to the number and severity of these incidents [3]. Of particular interest in the present context was the finding that environmental concerns to prevent the escape of fine dust particles had tended to reduce the previously more readily available means for explosions to vent from grain elevators and similar facilities. Greater enclosure, with the aim of containing fine dust, had resulted in increased risk of explosion and more severe explosion consequences. It was also found that the extant, relevant standard for explosion venting from the National Fire Protection Association (NFPA) required development, updating and more emphatic application within the industry. At this point it is useful to note that the standard in question, NFPA 68, first emerged in 1945 as “tentative” guidance before eventually becoming permanent guidance in 1954. As will be discussed below, NFPA 68 has emerged as an essential standard today for the specification of explosion venting.

Clearly, explosions originating in grain dusts, flour and similar materials had become a major factor in defining the need for, and the nature of, explosion venting as a means of mitigation. However, other sectors were found to present explosion hazards, similarly driving interest in venting measures and how those measures should be defined and specified. An example is to be found in the growing problem of explosions in surgical operating theatres, which manifested during the 1930s and 1940s. The use of anaesthetic, flammable gases in oxygen-enriched atmospheres of the kind readily found in operating theatres, combined with the persistent presence of static electricity, resulted in a number of explosions, some of which resulted in fatal injuries to patients and staff. In view of its obvious relevant experience in explosion hazards, the US Bureau of Mines investigated this issue [4], and made use of the contemporary, 1950 edition of NFPA 68. Consideration was given to how explosion venting could be achieved, somewhat informally, by way of windows, doors and frangible partitions around the perimeter of operating theatres.

In Europe, similar developments took place regarding the characterisation of (mostly dust) explosions, and how their consequences could be mitigated through the use of dedicated means of relief. In June 1975 the first edition of VDI 3673 was published as a green paper [5]. In his article of the same year, Heinrich observes how VDI 3673 brings more formality to the process of explosion vent specification, having been based on explosion tests performed under defined conditions [6].

Since then, ongoing developments have taken place including the expansion of explosion relief design into other hazardous contexts, such as flammable gases and hybrid mixtures of dust and gas, right up to emergent hazards arising from lithium ion battery off-gases and applications within the nascent hydrogen economy.

It is the explosion hazard management requirements of this latter sector that was of particular concern to Rhino HySafe in their development and testing of the Vertex low inertia, rapid acting relief panels (patent pending).

2 Overview of hydrogen explosion hazards

At the outset, it is important to clarify that throughout this article the word “explosion” refers specifically to the deflagration mechanism, by which combustion proceeds in a manner principally influenced by turbulence in the flow field, and with a velocity substantially below that of the speed of sound in the unburnt gas-air mixture. The distinction is made between deflagration and detonation; the latter being characterised by shock propagation of the combustion front. From this distinction it will be clear that, once established, detonation consequences cannot be mitigated by relief panels as there is no forward communication ahead of the combustion/pressure front. Explosion relief by means of venting panels is, therefore, only available during deflagration.

Hydrogen is among a number of flammable gases which has the potential to undergo deflagration to detonation transition (DDT) in the presence of specific, suitable conditions [7]; a characteristic which compounds the overall explosion risk found in some of its applications. However, as implied previously, the objective in mitigating hydrogen explosions is to ensure venting is available and effective whilst the developing explosion is still in the deflagration mode of combustion. Early emphasis is placed on this issue as it is fundamental to understanding the context for mitigating the consequences of hydrogen explosions by means of venting through relief panels. It is also vital to note that by having effective venting in place, the risk of DDT is itself reduced, providing relief occurs before any transition [8]. This fact alone underscores the significant potential benefit of venting in reducing the risk of the highly damaging hydrogen detonations.

Returning to more rudimentary considerations, it is useful to compare and contrast some fundamental properties for hydrogen, versus natural gas, which are relevant to ignition, combustion and deflagration, as shown in Table 1. This exercise serves to highlight that, broadly speaking, hydrogen may be more amenable to ignition in the first instance, and, having ignited will produce more severe explosion consequences [9].

It can be seen that the minimum energy required to ignite a flammable atmosphere of hydrogen in air is approximately one twentieth of that needed to ignite such an atmosphere of natural gas in air. This relative ease of ignition is compounded by the relatively wide range of flammability in air possessed by hydrogen, and that once ignited, flame acceleration is much more vigorous, as indicated by the laminar flame speed (an order of magnitude greater). The higher energy density for hydrogen must, of course, be viewed in the context of its lower mass density.

PARAMETER	HYDROGEN	NATURAL GAS (85% CH_4)
Minimum ignition energy in air (mJ)	0.017	0.31
Flammable limits in air (%)	4–75	5–15
Energy density LHV (MJ/kg)	120	50
Laminar burning velocity (cm/s)	265–325	38

* Standard temperature & pressure, as defined by NIST (293.15 K / 101.325 kPa)

Table 1 Selected physical properties of hydrogen and natural gas at STP*

Nevertheless, the totality of these properties underpins the tendency for hydrogen deflagrations to ignite more easily, accelerate more rapidly, and produce more damaging overpressures in consequence. It is also noteworthy that gaseous hydrogen is often stored at relatively high pressures, up to 700 barg and beyond, in order to achieve stored energy density comparable to that of cryogenic liquid hydrogen. It will be obvious that accidental releases from inventories at such pressures will rapidly generate substantial flammable volumes.

3 Explosion relief venting in the context of the hydrogen economy

In recent years there has been renewed interest in expanding the use of hydrogen as an energy vector, within the wider context of renewable and low carbon power production and transport. The current initiatives build on experience gained in the early 2000s, during which time a number of international initiatives saw the introduction of high pressure gaseous and cryogenic liquid hydrogen into the public arena. One such project within the authors' direct experience was the CUTE programme, by which 27 hydrogen fuel-cell powered buses contributed to the public transport network in nine European cities [10]. The programme called for the development of pre-packaged hydrogen electrolysers, compressors, vaporisers, storage systems, dispensers and related equipment, designed to be situated within public and municipal settings. In view of the relative novelty of the combination of equipment, inventory and the public nature of the sites, a conservative approach was often taken to explosion hazard management, including the provision of blast-resistant barriers and other substantial measures.

Today's applications, which form part of the efforts to establish and grow the hydrogen economy, entail the same fundamental issues as previous initiatives. However, it is the large scale deployment of containerised hydrogen equipment packages, potentially over thousands of sites, which (partly) alters the overall risk profile. The first priority of all parties engaged in designing, manufacturing and installing such facilities will be to minimise the risk of explosions occurring. However, as deployment expands and the number of installations increases, so too does the likelihood of explosion. It has been the authors' experience that attempting to design enclosures to contain hydrogen deflagrations tends to result in unfeasibly heavy structures, requiring significant fabrication effort and associated costs. As such, explosion overpressure protection by means of relief venting is considered significantly more practical for many hydrogen applications.

The planned expansion of hydrogen installations has been anticipated by standards bodies, including for example, the NFPA in the United States. It is noteworthy that the 2023 edition of NFPA 68 includes, for the first time, an Annex which provides a worked example of how the standard is applied to a typical 20' ISO container, housing hydrogen equipment and inventory [8]. Based on representative values of container strength and explosion relief vent properties, the worked example illustrates the relative challenges of hydrogen explosion mitigation by concluding that the entire roof area would require venting in order to prevent catastrophic rupture of the container.

Previously, under the auspices of the HySEA Project, the work of Skjold *et al.*, involving a comprehensive programme of full-scale hydrogen explosion testing in Norway, provided very valuable insights into the effects of congestion, confinement, relief and gas mixture characteristics on explosion severity within container structures representative of those being deployed in hydrogen applications [11]. Indeed, this work is directly referenced by NFPA 68 [8], and key results are cited within the 2023 edition of that standard in order to illustrate the sensitivity of peak overpressures to hydrogen concentration. As will be discussed below, a similar sensitivity was observed in the full-scale experiments performed to substantiate the design reported herein.

It is against this backdrop that Rhino HySafe has sought to develop a new venting panel with characteristics making it highly suited to hydrogen applications, and to demonstrate its suitability through full-scale testing under a wide range of hydrogen deflagration conditions. An essential requirement for the wide uptake of hydrogen infrastructure will be the ability to demonstrate to customers, the general public and regulatory authorities that facilities have been designed and built to ensure explosion risks are adequately managed. Reliable, rapid acting relief venting will play a role in this process.

4 Engineering development of Rhino HySafe Vertex explosion relief panels

The development of the Vertex relief panel began with consideration of relevant codes and standards used in the layout and design of hydrogen facilities, such as vehicle fuelling points, hydrogen production units and related infrastructure. For planned hydrogen installations, the most relevant standards include ISO 19880-1 [12] and NFPA 2 [13]. The most pertinent consideration is that both standards refer to NFPA 68 [8] as a basis for determining the required explosion relief venting.

Insofar as it helped identify key design drivers for relief panels, NFPA 68 [8] was reviewed and the following factors were identified:

- Achieve the lowest practical static activation pressure, P_{stat},
- Reduce the mass inertia of the panel such that the "low inertia" threshold, M_T, is met comfortably,
- Consider the design, manufacturing and installation aspects which may have a bearing on the reliability, repeatability and sensitivity of panel activation[1], and
- Minimise or eliminate the risk of missile or hazardous fragment production.

The factors noted above are, of course, consistent with other relevant codes, including BS EN 14994 [14].

4.1 Development of initial concept & geometric form

The essential feature of the initial concept design was to eliminate the need for material yielding, material tearing or the rupture of any fixings, bolts or screws during and immediately after the time of activation of the panel. This approach sought to reduce or eliminate physical processes which may add latency or uncertainty to the response of the panel, especially in the earliest phases of its activation.

In addition, it was thought that producing a vent geometry which was free from three-dimensional effects may also help to reduce latency in its response. Accordingly, the concept for the panel evolved such that a single, continuous sheet of thin gauge, stainless steel would be restrained at mid-span, and have its outer, free edges restrained by strips, overlapping the edges. As shown in Figure 1, this concept was expected to undergo initial bending in response to the overpressure transient (stage 2), leading to catenary shortening, and in turn, unlatching of the panel edges. The moment this unlatching process is fully completed (stage 3), the panel is deemed to have activated, with the two halves proceeding to fold open and eventually converge along the centreline of the vent (stages 4 & 5).

Preliminary calculations indicated that the system could be configured such that unlatching of the panel free edges could take place before the onset of any yielding in the stainless steel sheet. This was considered advantageous, as the potential complications associated with variability in yield properties would not affect the unlatching process. Moreover, whilst reliable and widely used nonlinear material models are available for common stainless steels, an entirely elastic response in this most critical, early phase of panel operation was judged beneficial.

It will be apparent from Figure 1 that, having activated and been blown open to the converged position (stage 5), retention of the sheet would be of critical importance in preventing the formation of missiles and debris. Further preliminary calculations were performed, considering

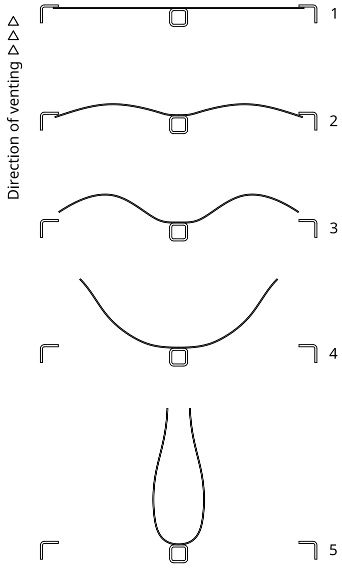

Figure 1 Conceptual geometry & sequence of panel response through activation to full opening

the angular momentum of each "leaf" such that an estimate of the number, size and type of fasteners could be assessed for use down the central "spine" of the system. It will also be clear that the system is amenable to treatment as a two-dimensional, plane strain problem. At this point, further development was based on the use of finite element analysis (FEA), and specifically the ABAQUS/Explicit ssolver [15].

4.2 Refinement of geometric form & detailed transient analysis

Throughout the design development process, careful consideration was given to manufacturing processes, material selection, ease of handling during manufacture and installation, and durability of the vent panels in service. These factors, alongside more detailed transient analysis, led to a more refined form for the panel, its free edge retaining strips and the relationship between those strips and the panel edges.

As shown in Figure 2, the form of the edge retaining strips (a) was developed to include features which would provide security to the panel edges under normal operating conditions, whilst also facilitating the smooth and predictable departure of those edges during the early stages of overpressure application. This process of unlatching – the completion of which constitutes activation of the panel – received considerable attention, with numerous sensitivity analyses being performed to examine effects of varying friction, overlap, pressing radii, pre-stressing and so on. These analyses, performed using the ABAQUS/Explicit solver [15], explored in addition the sensitivity of activation time to overpressure transient shape, rate of pressure rise (dP/dt) and attendant impulse. It is noted that this

[1] The term "activation" is used within NFPA to refer to the operation of a vent panel. In this article, the term activation refers specifically to the completion of the process of the panel releasing from its closure mechanism

approach to retaining the panel edges arose after consideration of other methods, such as clamping and retention by way of sealing strips, all of which were found to introduce increased latency and uncertainty, due to variability in manufacture and site assembly.

More detailed consideration was given to fixings required along the central spine (b), as the transient analyses were run until complete merging and rebound of the vent "leaves" along the mid-plane of the system. It was also established in this phase of design that the introduction of two, shallow corrugations (c) had the combined benefits of introducing transverse stiffness to the panel, improving its robustness and ease of handling, and, reducing the latency in catenary action, thus reducing the time taken for unlatching and activation of the panel. This latter effect, being somewhat counterintuitive, only became apparent through the use of explicit dynamics analysis.

Figure 3 shows a typical sequence of deformation in the panel leaf edge during the unlatching process. Finite element edges are shown.

As overpressure increases on the inside face of the panel, its flexural and catenary responses combined to draw the welted edge of the sheet material along and around the pressed, radiused corner of the retaining strip. The unlatching process is thus not dependant on any yielding, tearing or failure mechanisms which in themselves would add latency. It can be seen that the retaining strip, at this design stage, was modelled using an analytically rigid surface.

Figure 4 shows a sequence of panel opening stages, commencing with the first impingement of overpressure, through activation (unlatching), to merging of the two leaves along the mid-plane of the vent. The only regions where plasticity of any significance was observed was along the two hinge lines that are adjacent to the central spine; with plastic hinges only forming substantially after unlatching of the free edges.

Throughout all transient simulations, the overpressure time-history was applied to the loaded faces of the vent panel. It was understood that, in practice, a complex process of fluid-structure interaction

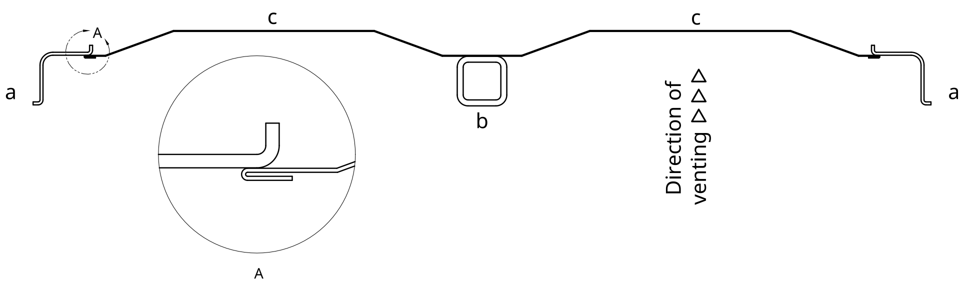

Figure 2 Key features of the refined vent panel design

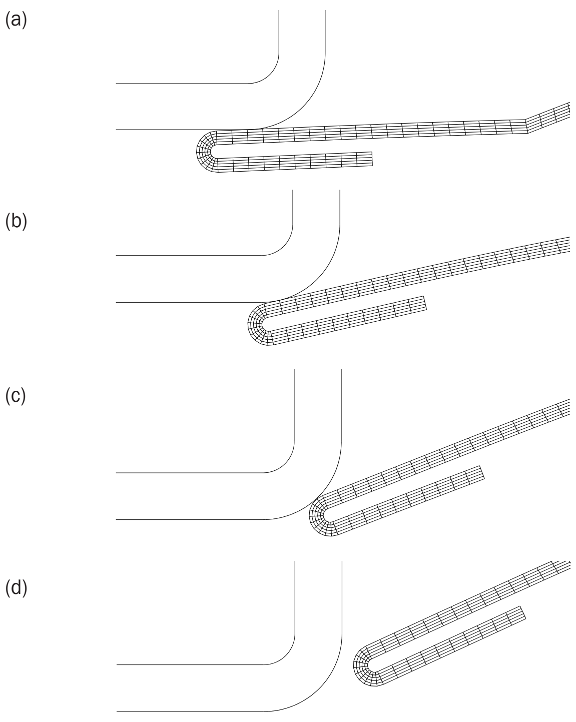

Figure 3 Selected sequence of panel edge deformation during unlatching process

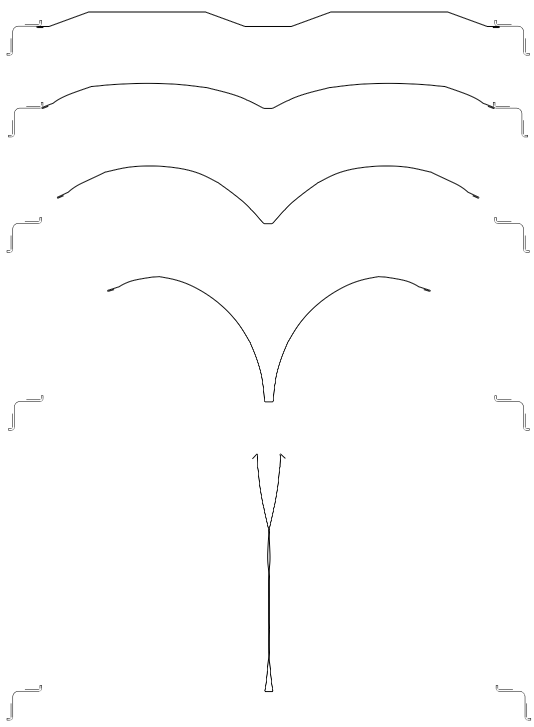

Figure 4 Selected stages of panel opening from typical transient simulation of refined design

would take place as ambient air ahead of the combustion front interacts with the opening vent leaves, followed by interactions with the flame front and combustion products. No attempt was made to predict the corresponding, complex variations in density and pressure, and thus the "true" nature of the overpressure transient affecting the panel in the latter stages of opening. Part of the reasoning for this simplification in the analysis lay in the expectation that the vents would be significantly, and perhaps completely open before significant flow velocities arose in and around the exit point. Subsequent examination of the high-speed video footage captured during the full-scale experimental programme validated this simplifying assumption.

In parallel with the dynamic simulations, manufacturing and detailing reviews were undertaken to ensure that the emerging design was also compatible with fabrication, assembly and other functional requirements. A specific example of such a consideration is shown in Figure 5. As the panels are intended to be used within the external walls and on the roofs of equipment containers and buildings, additional flashing and sealing elements were added. The flashing shown in Figure 5 was designed to be bonded to the main vent panel,

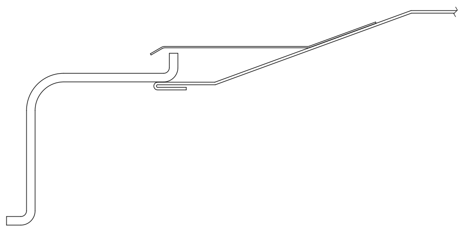

Figure 5 Flashing strip added as part of weather-tightness details

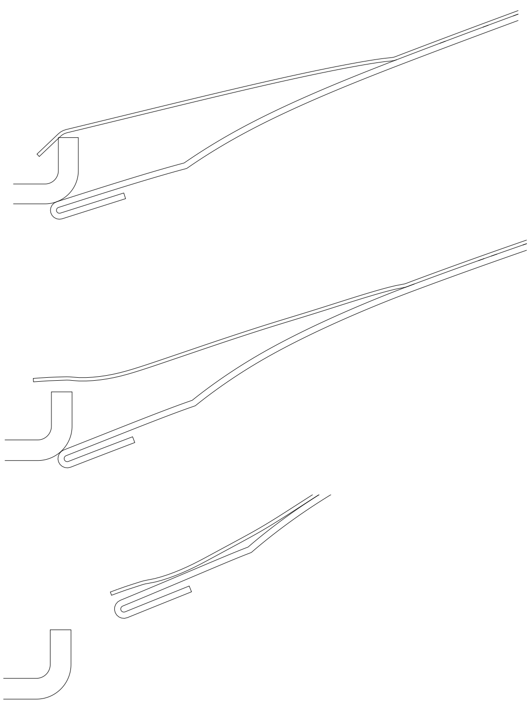

Figure 6 Interaction between flashing strip & retaining strip before & after contact

to add minimum mass (and hence minimum extra rotational inertia), and to shield against rain ingress. Omitted from the figure is a flexible silicone seal provided in the final design for added weather-tightness.

In order to assess the impact of the (albeit small) added mass of the flashing element and its expected contact interaction with the upstand of the retaining strip, further sensitivity simulations were performed. Figure 6 illustrates moments during a typical transient, before and after contact interaction between the flashing and the retaining strip. Comparative runs were carried out in order to assess the increase in latency resulting from the added mass and inertia. It was concluded that whilst a measurable increase in the time taken to activate and fully open occurred, the increase was only a small fraction of the un-flashed configuration.

It can be observed that the flashing element quickly collapses onto the thicker, heavier main vent panel leaf after activation, where it remains until merging of the leaves on the mid-plan of the vent.

4.3 Preliminary physical testing

Once reasonable confidence had been established in the panel design, based on numerous sensitivity simulations using the plane strain, explicit dynamics model, two stages of preliminary physical testing were undertaken.

As noted above, the static activation pressure, P_{stat}, is a critical variable required for use in vent panel sizing codes, such as NFPA 68 [8]. A simple test rig was prepared to allow a test panel to be progressively loaded with sand bag ballast, with static displacements measured during loading, and the final total load at the moment of panel activation being recorded.

As shown in Figure 7, as the limiting mass of ballast was added, the welted edge of the panel leaf tended to slip over the radiused corner of the retaining strip, beyond which point the leaf burst open. Quasi-static simulations had been performed using the ABAQUS design model, and it was found that the predicted value of P_{stat} = 20 mbarg (2 kPa) accorded favourably with the static test,

Figure 7 Static load test with sand bag ballast progressively applied until activation & opening

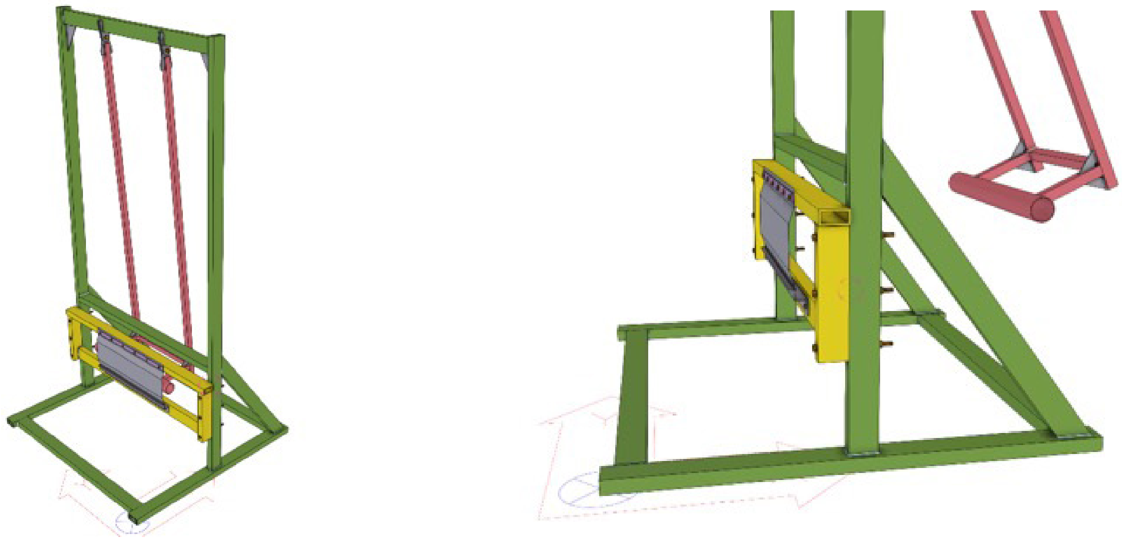

Figure 8 Design model of dynamic pendulum test apparatus

being within 15% of the activation pressure established physically. It is observed that straightforward, low cost physical tests can be of significant value in helping to anchor nonlinear analysis, especially when complicating factors such as contact interactions and strong geometric nonlinearity are in play.

The limitations of static loading were apparent, and in preparation for costly and time-sensitive, full-scale explosion testing, a simple dynamic pendulum test apparatus was designed and fabricated. As shown in Figure 8, this apparatus allowed for a typical panel leaf, its retaining strip and central spine to be subjected to transient impulses or varying magnitude, by adjusting the release height of the pendulum.

The pendulum itself was configured to span the full length of the panel leaf, and to apply its impulse along the centreline of the corrugation. Whilst an impacting mass clearly differs from a transient pressure pulse, it was judged nevertheless to provide a degree of dynamic response testing, with minimal associated cost. The ABAQUS design development model was used to estimate strain and kinetic energy values associated with activation of the panel under various overpressure impulse shapes. A corresponding kinetic energy was used in the pendulum, by virtue of release height, and a number of dynamic tests proceeded accordingly.

The pendulum tests demonstrated that the explicit dynamics model was providing a kinematically accurate prediction of the panel flexural and catenary behaviour, and corresponding unlatching of the panel edge from the retaining strip. High-speed video footage was taken of each test and compared with the response from the explicit dynamics model, itself configured with a matching pendulum.

Upon completion of these tests, and on the basis of satisfactory alignment between model predictions and these simplified experimental results, further analytical work was undertaken in readiness for the full-scale explosion test programme.

4.4 Calculation of “iso-opening” characteristics

As a general observation, it has been the authors’ experience that explosion hazards are often defined solely by reference to overpressure. Clearly that parameter is vitally important, however, the pulse shape of the transient and attendant impulse are also critical in anything beyond a cursory assessment of structural response to blast. Impulse is the integral of the overpressure pulse with respect to time; that is the area under the overpressure time-history.

An important objective from the outset of the project to develop the Rhino HySafe Vertex panel was to produce a fully defined threshold in the overpressure-impulse space by which specifiers could have a full appreciation of panel activation conditions.

The concept of iso-damage curves is long established within blast engineering [16]. Sometimes referred to as iso-ductility curves or pressure-impulse (P-I) curves, they represent the locus of identical displacement (and hence ductility) of a structure or structural component when loaded by any combination of transient force and corresponding impulse. In practice, this means that for, let us say an isosceles-shaped pressure pulse, it is possible to plot the locus of similar structural displacement due to that pulse being applied with any variation in its duration, magnitude and therefore attendant impulse.

Figure 9 shows a generic representation of an iso-damage curve; two in fact. The solid curve is the locus of points at which the same level of structural response (displacement or ductility) results from a transient pressure pulse with varying combinations of pressure and impulse. The dashed curve is similar, but for an arbitrarily greater level of displacement. It will be observed that the curves are bounded by a pair of asymptotes. The pressure asymptote denotes the minimum pressure, applied statically (i.e. with infinite impulse), required to achieve the defined structural response. The impulse asymptote denotes the minimum impulse which a dynamically

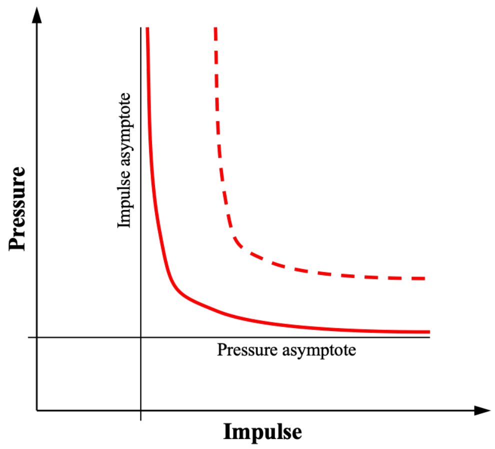

Figure 9 Illustrative generic iso-damage curve

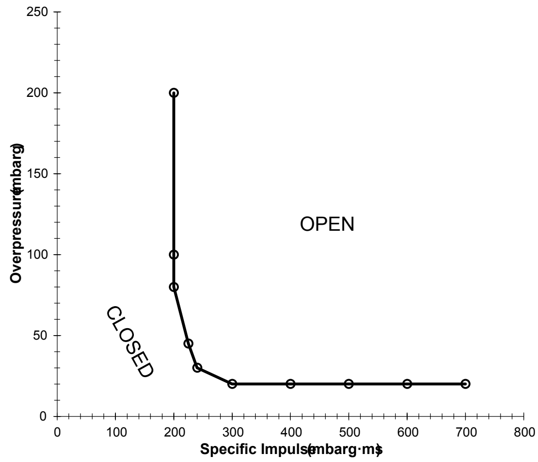

Figure 10 Vertex iso-opening curve based on isosceles overpressure pulse shape

applied pressure must possess in order to achieve the defined structural response. Both asymptotes accord with our intuition; for example, it is understood that a very large force, applied over a very short period of time, may not be enough to impart the required deflection in a structure. It will be apparent from Figure 8 that combinations of pressure and impulse which lie above, and to the right of a given iso-damage curve will produce a response greater than that defined by the curve.

Iso-damage, or pressure-impulse curves provide a versatile means of characterising structural response in a manner largely independent of how the structure will eventually be loaded in a blast situation. The curve's shape is defined exclusively by the properties of the structure, and the shape of the loading pulse (not its eventual magnitude). Accordingly, once pressure-impulse curves have been calculated for a structure or component, they provide an immediate indication of the expected response, or damage, once later calculations of explosion loading are made. This approach was adapted and used to define the complete envelope of overpressure and impulse combinations which would activate a Rhino HySafe Vertex vent panel.

Whereas deflection and ductility are of primary concern in the assessment and design of structural components to resist blast loading effects, in the case of relief vents it is the activation characteristics which are critical. Therefore, the pressure-impulse combinations defining the locus of panel activation were evaluated in two stages.

In the first stage, the explosion overpressure transient applied to the vent panel was assumed to be of an isosceles pulse shape; that is to say, the rise time to peak pressure is equal to the decay time back to ambient pressure.

The explicit dynamics model was used to simulate a large number of combinations of overpressure and impulse until a locus could be defined, based on those combinations that were just sufficient to fully activate the panel (see Figure 3(d)); that is to say, positively complete the unlatching process. The preliminary "iso-opening" curve is shown in Figure 10, with those discrete points in the pressure-impulse space found to just activate the panel indicated by circles. A simple straight line fit was used to approximate the curve itself.

It will be observed that the pressure asymptote lies along a value of $P = 20$ mbarg, which is consistent with static testing and model results. This value corresponds, of course, to P_{stat} for the panel. Similarly, the impulse asymptote indicates that for short-lived pulses, there must be an impulse greater than 200 mbarg ms in order to activate the panel. To more easily visualise this threshold, consider that a simple isosceles shaped pulse with peak overpressure of 80 mbarg would require a duration in excess of 5 ms in order to activate the panel; that is, an impulse in excess of ½ × 80 × 5 = 200 mbarg·ms.

This first stage iso-opening curve was useful in providing an initial indication of the ranges of overpressure and impulse that would be of interest during the full-scale explosion testing, and contributed to planning discussions with specialists at the DNV Spadeadam test facility [17]. However, in order to improve the definition of the iso-opening curve, with particular regard to the shape of pressure pulses associated with hydrogen deflagrations in enclosed geometries, it was necessary to examine existing explosion test data, kindly made available by DNV Spadeadam [18]. The development of the second stage, or refined iso-opening curve is summarised below.

As noted above, the shape of a pressure-impulse curve is affected by the characteristics of the structure in question, and also the shape of the pressure pulse transient being applied. By this point in the development of the panel design, there was reasonable confidence in the calculations and testing used to characterise the mechanical properties of the panel. Therefore, focus was placed on the definition of the transients used to refine the iso-opening curve.

It will be recalled that deflagration is the mode of explosion combustion propagation which is relevant to venting. Deflagrations by their nature tend to exhibit a progressive growth in overpressure, commencing with a somewhat gentle rise in pressure, which becomes steeper with time. Based on examination of overpressure transients from previous testing by DNV, it was established that the domain of interest would be within the first ≈50 ms or so. Therefore, based on explosion test data which encapsulated slow, low pressure deflagrations, through to more rapid, severe events at the upper limit of the range of application of any venting system, it was possible to develop a generic exponential function to define the early pressure transient of any event between those two boundaries. That is to say, any number of "synthetic" overpressure time-histories could be produced, the shape of which would be anchored in experimentally derived transients.

Figure 11 illustrates the early stages of overpressure development in two, representative experimental deflagrations (solid curves). The lower, solid curve is an overpressure transient recorded during a deflagration with low hydrogen concentration, exhibiting lower average dP/dt rates during the period of interest. The upper, solid curve is correspondingly from a much more severe deflagration event, which exhibited peak overpressures at the upper limit of interest to this development project. Accordingly, significantly higher average

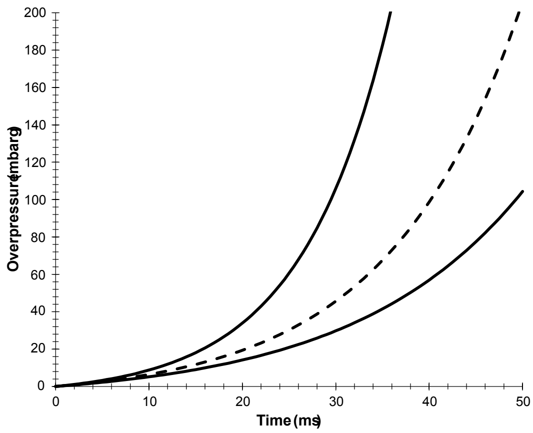

Figure 11 Bounding experimental overpressure transients with typical "synthetic" transient (dashed)

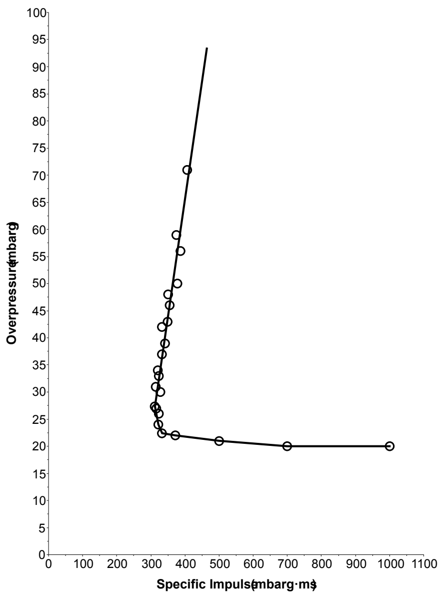

Figure 12 Refined Vertex iso-opening curve based on exponential overpressure transients

dP/dt rates are observed. These data defined two, exponentially varying functions such that it was possible to define a generic function which would produce a satisfactory, synthetic exponential curve at any point between these two boundaries. The dashed curve is a typical example. It will be noted that, due to the rapid activation and low inertia of the Vertex panel design, it was only necessary to consider this early stage of overpressure development, typically within the first 50 ms.

As with the preliminary iso-opening curve, production of the refined curve, shown in Figure 12, was based on a large number of explicit dynamics simulations. However, each of these was based on a loading transient defined as shown in Figure 11, with the exponential growth of overpressure, as distinct from a constant dP/dt. The circles in Figure 12 denote the overpressure and impulse combinations for a given exponential transient resulting in full activation of the panel. Straightforward line fitting is used to complete the curve.

It will be noted, as would be expected, that the overpressure asymptote (denoting P_{stat}) is consistent in its value of 20 mbarg. This reflects the fact that pulse shapes with very long durations (≈infinite impulse) have no influence on the static activation pressure. The impulse leg of the iso-opening curve is no longer asymptotic. This response was investigated and attributed to inertial effects at the free edge of the panel leaf, alongside the nonlinear (exponential) forcing function. It has been the authors' experience that pressure-impulse loci can take on such features in systems which are more complex than typical single degree of freedom (SDOF) treatments would allow.

With this definition of predicted panel response developed, full-scale explosion testing proceeded as discussed below.

5 Full-scale explosion testing of Rhino HySafe Vertex explosion relief panels

The full-scale explosion tests were performed in 2022 at the DNV Spadeadam test site, in Cumbria, UK, using their 26 m^3 chamber. A number of calibration tests were performed, reflecting discussions with the panel design team on the range of overpressure and impulse of most relevance to substantiating the performance of the panels. In due course, eight production tests were performed, with peak overpressures immediately upstream of the panels ranging from 21 mbarg to 850 mbarg. The level of control achieved over the test conditions is reflected in the test overpressure range running from the value of P_{stat} to a value usefully above the upper limit of intended application of the panels.

5.1 Explosion testing methodology & apparatus

As noted above, the full-scale explosion tests were performed in a 26 m^3 test chamber. However, the volume of flammable clouds established within the chamber was limited to 11 m^3, thus ensuring all test cases were partial fill, to approximately 40% of the chamber volume. The filled volume was located at the far end of the chamber, opposite the vented end, with an intervening zone of ambient air. A number of advantages attach to the use of a partial fill, including:

- The maximum safe overpressure rating of the chamber can be respected, which is of particular importance given the deflagration characteristics of hydrogen,
- Peak overpressures can be limited to the value deemed experimentally appropriate for the maximum intended service conditions of the panels,
- Higher, more reactive concentrations of hydrogen may be used, producing more rapid rates of pressure rise, and,
- Partial volumes may be considered more reflective of "real world" accident scenarios, under which transient, pressurised releases produce inhomogeneous clouds, which may ignite rapidly, and remotely, from relief vent locations.

The perimeter frame supporting the panels under test was robustly bolted to the open end of the test chamber, acting as an interface between the panels and the supporting structure of the chamber, whilst also permitting the response of the perimeter frame itself to be observed during test explosions.

At the opposite end of the chamber, light plastic sheeting was used to partition off the 11 m³ volume within which the flammable cloud was established using a recirculated fill approach in order to achieve acceptable homogeneity. Hydrogen concentration within the partitioned cloud was indirectly measured by way of oxygen depletion, from which it was possible to infer hydrogen concentration. Three VIAMED R-22AVG oxygen sensors were deployed in each test, being replaced as necessary if damaged, and located centrally within the flammable cloud at mid-height, and adjacent to both roof and floor. Additional oxygen sensors were placed in the ambient zone between the flammable cloud and the vent panels in order to detect any escape of hydrogen from the partitioned region. In all experiments, no such leakage was detected. Ignition of the partitioned cloud was achieved by way of a centrally located electric fusehead.

Overpressures were measured using five PCB Piezotronics 113B26 dynamic pressure transducers. These devices provide a relatively rapid response to overpressure, such that when exposed to a step change in pressure, 99.3% of the true value of pressure is registered and output in less than 5 μs. In view of the timescales relevant to the deflagrations which were under study, this speed of response is well suited. The mounting of the transducers, and their protection from short-term exposure to heat, were based on methods successfully deployed at the Spadeadam test site over several decades. All five transducers were mounted at floor level, with four located adjacent to the panels under test, and one below the point of ignition within the flammable cloud.

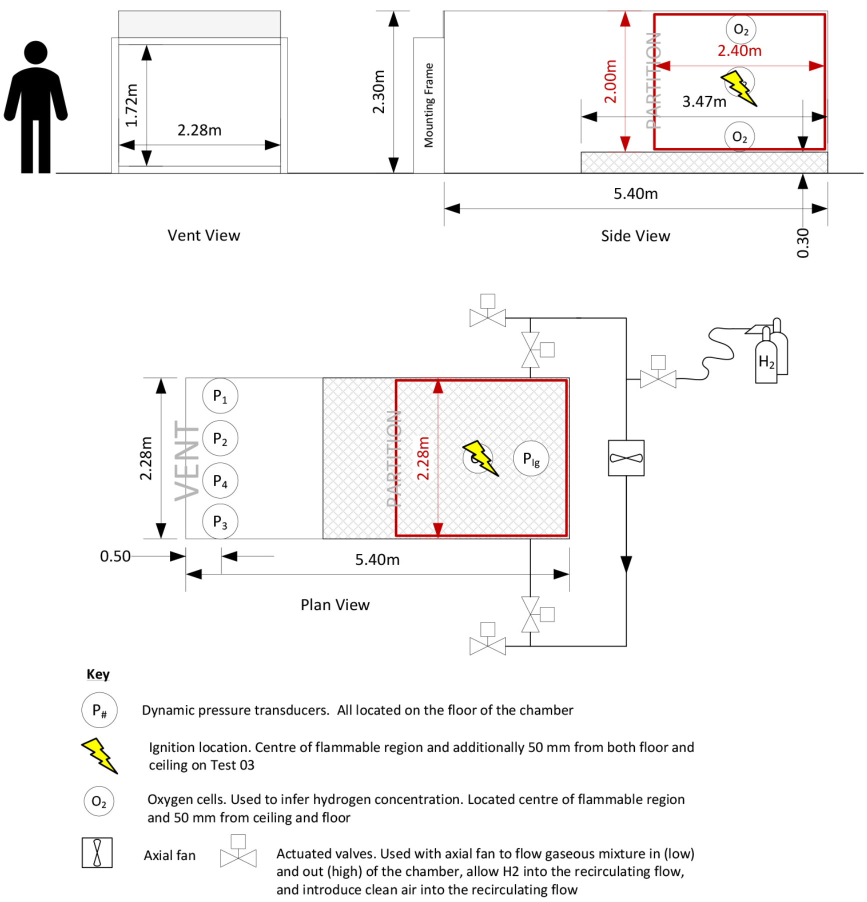

Figure 13 Schematic overview of explosion chamber & test configuration

Figure 14 Typical sequence of still images taken from one of two high-speed cameras during test

Data from pressure transducers, along with fusehead activation time, were acquired on a HBM Gen7t high-speed acquisition system, with sampling on individual channels carried out at 200 kHz. Gas concentrations were recorded on an IMC SPARTAN data acquisition system at a sampling frequency of 2 Hz. Both systems were subject to annual, traceable calibration processes.

Video was captured from PHANTOM high-speed cameras, placed at two vantage points, operating at approximately 3,000 frames per second, depending on ambient conditions.

Figure 13 shows a schematic overview of the explosion test chamber and test configuration.

5.2 General response of panels during testing

Qualitatively, the high-speed video footage gathered during each test was of particular value in demonstrating consistency between the predicted mode of panel leaf response and actual response under the varied overpressure and impulse conditions achieved in the apparatus.

Figure 14 shows a typical sequence of stills from one of the two high-speed cameras trained on the panels under test. Frame by frame examination of such footage from each test confirmed the flexural, catenary and rotational behaviour of panel leaves was in close agreement with the response predicted by the ABAQUS/Explicit model. It was established that agreement was particularly close in the activation phase, and up to the point where angular momentum becomes more dominant in the leaves, as they rotate. Beyond that point, it was found that the ABAQUS model tended to overpredict the speed of the leaves before they collide along the mid-plane of the vent. It was speculated that the absence of any treatment of resistance due to drag in the simulation may contribute to this deviation. However, the overall correspondence between modelling and experimental response was found to be reliable, and suitable for use in exploring other, future loading scenarios in support of client projects.

As noted above, the issue of debris and missile formation was of central concern to the design team. Notwithstanding the fact that any significant, vented deflagration within an equipment container will produce its own debris, the prevention of missile formation from vent panels themselves is a stipulation of the relevant codes and standards. In the early tests, it was apparent that panel leaf retention on the central spine was successful, however, the flashings were detaching and becoming entrained in the exhausting flow field. This was remedied in later tests by altering the riveting details used to retain the flashings on the panel leaves. Subsequently, even during the most arduous tests, no detachment of panel leaves or flashing occurred.

A further qualitative observation was that in all tests, the panels had activated and substantially commenced opening before the arrival of the flame front. It was observed that the panel leaves tended to converge along the mid-plane ahead of the high velocity outflow of combustion products, as shown in Figure 15. In general, this high velocity outflow resulted in strong, whipping oscillations of the leaves. It was speculated that these actions were likely the dominant source of loading on the fixings securing the panel leaves to the central spine. In all cases, even with limited failure of fixings at the outer edges of the fixed portion of the panel, the panel leaves remained securely attached to the central spine.

Figure 15 Example of complete panel activation & leaf merging before flame front arrival

5.3 Use of experimental data to substantiate panel performance & characterisation

Clearly, the prime objective of the full-scale tests was to substantiate the panel design, with regard to reliability and speed of activation, accuracy of the ABAQUS/Explicit analysis/design model, and, prevention of debris and missile formation. Furthermore, as the iso-opening curve was intended to be published as a tool to assist specifiers in their selection of Rhino Vertex panels, it was important to determine its accuracy and suitability for that purpose.

Accordingly, for each test, the time-synchronised overpressure transients and high-speed video footage were used to determine the time taken from the start of overpressure impingement on the inside of the panel until the completion of activation (i.e. full unlatching from the retaining strips). A conservative approach was taken when examining the video footage to establish the moment of complete unlatching of the panel leaf free edges. In each case, the actual overpressure transient – or more precisely, the average of the five transients recorded – was used to calculate the overpressure and impulse at the moment of activation. These data points were then plotted in the pressure-impulse space alongside the refined iso-opening curve. By definition, these points should lie close to the locus of the iso-opening curve, were it to have been accurately predicted by the ABAQUS/Explicit model. Figure 16 shows the results of this exercise.

It can be seen that across the experimental range of overpressures and impulses, there is a satisfactory alignment between the calculated iso-opening curve and the discrete combinations of

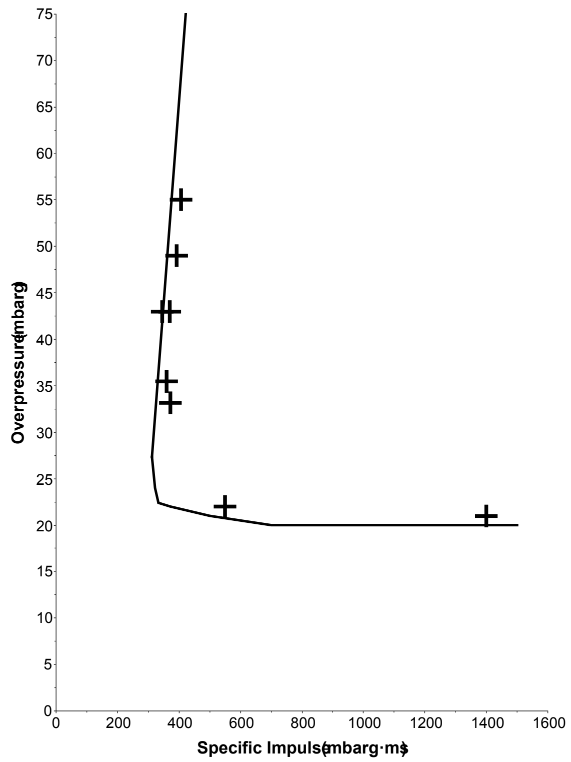

Figure 16 Vertex iso-opening curve with experimentally measured activation points

pressure and impulse found to activate the panels during testing. It was concluded, therefore, that the refined iso-opening curve could usefully be provided to specifiers to give them an acceptably accurate pressure-impulse threshold for panel activation, under a wide range of pressure and impulse.

Notably, the confirmation of P_{stat} was a particularly valuable experimental outcome, especially from tests at the lowest end of deflagration intensity which could practicably be achieved. Table 2 provides a summary of the experimentally measured activation overpressure, impulse and corresponding average hydrogen concentration associated with each test.

AVERAGE HYDROGEN CONCENTRATION (VOL. %)	OVERPRESSURE (mbar)	IMPULSE (mbarg ms)
21.0	36	360
22.4	43	370
19.3	33	372
24.8	55	406
23.8	49	392
22.8	43	345
11.4	21	1400
15.2	22	550

Table 2 Summary of experimentally measured activation conditions

6 Conclusions

The Rhino Engineering Group has developed and patented a new low inertia, rapid acting explosion relief vent for applications in the hydrogen economy, battery energy storage systems and other related sectors in which protection from deflagration hazards is a critical requirement.

Based on the Group's extensive design, fabrication and installation experience the new HySafe Vertex vent panel has been developed and tested to demonstrate its reliable and rapid activation, and assured prevention of debris and missile hazards. A design process using outline analytical methods, simplified preliminary testing, before proceeding to extensive explicit dynamics FEA was undertaken ahead of full-scale hydrogen deflagration testing.

The output of the design activity, substantiated by the full-scale testing, has been used to provide designers and specifiers with a transparent and convenient pressure-impulse nomograph indicating the full loading envelope for panel activation. This performance information is also well suited for use within more sophisticated computation fluid dynamics explosion consequence modelling, or within coupled fluid-structure interaction models.

The robust validation of the HySafe Vertex vent panel P_{stat} overpressure of 20 mbarg is of particular value when using established deflagration venting standards, such as NFPA 68 [8]. Having based the panel design and testing programme on the relatively challenging hazard of hydrogen deflagrations, the system is shown to be well suited to other deflagration hazards, including other flammable gases, combustible dusts and combustible off-gases associated with lithium-ion battery thermal runaway.

The overall design and testing programme also confirmed the satisfactory performance of the HySafe Vertex vent panel perimeter framing, central spine and associated fixings to the primary structure. It was estimated that under the most arduous explosion tests, outflow velocities through the opened vents may have approached 1,000 m/s.

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For further information, please contact:

Dr Chris Norris
Rhino Engineering Group Ltd
T: +44 (0)1639 888 119
E: chris.norris@rhino-eng-group.com
W: rhino-eng-group.com