Explosion Relief Panels for hazard reduction in gas compressor buildings and hydrogen refuelling stations

Robert Brewerton BSC C.Eng MICE

Dr. Christopher Norris BSc(Hons), PhD

Summary

The paper's objective is to give the reader information on how to optimise explosion relieving cladding and vent panels and blast resisting panels to reduce explosion hazard and consequence by design.

The paper is full of illustrations to help the reader understand how these objectives have been met on projects in the past. It then goes on to illustrate how the technology can be adapted to new hydrogen fuelling stations that may be installed in urban areas. An accident occurred in Oslo last summer in which hydrogen gas that leaked caught fire in the open air and this created a pressure wave. In order to minimise the consequences should such a leak and ignition occur within an enclosure, there is now foreseen a need for improved cladding concepts especially for relief of explosions. The overriding objective is to reduce societal risk, especially projectile formation.

The paper firstly shows how the oil and gas industry has applied explosion relief panels (ERPs) and explosion relief cladding to protection of onshore gas compressor buildings. Both authors have been involved in designing and delivering all the projects portrayed here, over a period of more than 20 years.

Methods for optimising explosion relief cladding systems for compressor buildings are explained with due regard to other technical and architectural requirements such as thermal insulation, sound reduction, fire resistance and resistance to external explosions.

Layout options for contained equipment are discussed with comments on reducing equipment congestion and hence peak explosion pressures internally and externally by optimisation of equipment layout.

A fast-opening panel concept has recently been developed for hydrogen refuelling stations, usually located on the roof and covering the whole roof or alternatively integrated into equipment doors. The objective is the reduction of peak explosion pressures and impulse durations within enclosures and to reduce risk of catastrophic fragmentation of the enclosure and escalation of explosion effects to nearby people and facilities. The types of ERP's advocated are all hinged panels.

In the paper concepts are presented together with basic design requirements, analytical and test methods and material characteristics. Reference is made to design for fire resistance and operational sound reduction. Explosion loading input requirements to design are also discussed.

The second part of the paper lists special hazards related to the use of hydrogen and how they impact on explosion relief panels for use in hydrogen refuelling and other facilities where hydrogen gas explosion is a potential risk. Candidate ERP designs are presented and adaptations for use in personnel and equipment doors which can also be particularly useful for retrofit situations.

Reference is made to results obtained in the pre-normative HySEA explosion research project 2017-18 (Refs 10 & 11) and the effects of speeding up panel opening time on peak realised explosion pressures are assessed.

Guidance on methods for determining loads applied to the support framing through the hinging zones of ERPs to the support structures is given.

External explosion pressures caused during venting and in external congested equipment zones are an important consideration as hydrogen stations will often be installed in urban areas and have users of the stations in close proximity to explosion risk areas. The paper refers to some blast resisting wall options, including perforated options which may have potential as heat shielding to attenuate fire effects from ignited hydrogen leaks.

The stainless steel concepts described herein were developed by Inoventech Limited and are a proprietary system covered by international patents and is licensed to Rhino Systems Limited of Wales.

The Covid 19 Pandemic of 2020 caused a postponement of the Hazards 30 Conference of 6 months. During this period, much advancement has taken place in the hydrogen industry. This paper has been updated to account for this and further developments of the presented concepts.

The main new elements that have arisen were:-

- The publication in March 2020 of the ISO standard 19880 part 1 "Hydrogen Refuelling Stations" (Ref 1)
- Preliminary reporting of DnV studies of distancing measures as a means of increasing inherent safety in hydrogen refuelling stations.
- Further design development and evaluation of the ultra-fast opening ERP concepts presented here.
- A series of webinars on hydrogen fire and explosion safety given by FABIG during May – July 2020.

Historic arrangements for explosion relief panels (ERPs) in gas compressor buildings, modules and gas-powered ships

Panels are normally supplied as complete prefabricated cassettes for spanning between main building columns (for walls) or main horizontal roof beams or purlins (for roofs).

The system can equally be supplied in the form of a kit of parts and can be applied to walls or roofs like conventional corrugated cladding. The concept can be applied to winterisation walls on offshore platforms where it may be supplied as perforated panels for weather protection with ventilation (eg for Barents Sea).

The concept of perforated panels (explosion relieving or not) is extensively applied for radiant heat shielding (flares and fires) on offshore platforms and may have an application to hydrogen refuelling stations.

For roof panels in areas prone to ice and snow they can be provided with trace heating cables between the insulation and the stainless steel panel or warm air internal heating for uninsulated panels.

Figure 1 and 2 show the system applied to a compressor building in France.

In these cases the system was required to provide relief of internal explosions, sound reduction (to reduce external noise) and a degree of resistance to internal fires.

Figure 1 Stainless steel explosion relief panels installed on a gas compressor building in France

Figure 2 Explosion Relief panels viewed from inside, note foil- covered high density mineral fibre insulation for sound reduction and fire resistance.

In the wall cassettes shown in Figures 1 and 2 the main longitudinal framing is external but internal for the roof cassettes. The framing is carbon steel and is designed to withstand forces due to explosion effects, which are significant as the relief panels are fully fixed at their mid-line to the support framing and designed to hinge in an explosion so that they do not blow off. The main load component is centrifugal force as the panels rotate. If not securely anchored at their hinging lines they would become projectiles with risk of injury to persons outside the building and damage to other nearby facilities, which might escalate the consequences of the original explosion. The hinge action is provided by bending the thin profile plate which is made of highly ductile stainless steel.

Figure 3 below shows a large gas compressor building in Norway. The hinged explosion relief panels are a composite design with an outer panel of Kevlar reinforced Glass Reinforced Plastic (GRP), an inner one of mild steel and mineral fibre in between but serve a similar purpose. In this case the whole external wall area (apart from the bottom 2m which is concrete) is covered with relief panels.

Figure 4 shows a Norwegian LNG powered ferry which has panels similar to those shown in Figures 1 and 2 installed to protect the engine rooms. Outside the ERPs there is a void space leading up to above the water-line and the top of this is vented through a secondary vent panel to atmosphere (painted black and not visible in Figure 4). The engine room panel is configured to be openable as an access hatch.

Figure 3 A gas compressor building where cladding provides explosion relief for internal explosion (hinged panels for projectile avoidance) and resistance to external explosions and 43dBA sound reduction

Figure 4 ERPs used in Norwegian LNG powered ferries to protect internal engine room

One of the reasons why the proportion of wall area covered by panels is much larger in Figure 3 than in Figure 1 is that the parameter for effective venting and provision of relief panels is the buildings Av/V ratio, where Av is the effective vent area and V is the volume of the building. As the buildings become bigger the percentage of wall coverage increases to maintain Av/V ratio. In the Figure 1 type building the Av/V ratio is typically 0.1 but was higher (about 0.25) in Figure 3 where almost all of the external walling comprised explosion relief cassettes.

It is important to maximise the Av/V ratio particularly where internal equipment congestion is high as this increases the rate of burn of the gas in a developing internal explosion (due to turbulence generation). The enhanced Av/V ratio allows combustion products (and unburnt gas mixture) to exit the building more quickly thus reducing the peak explosion pressure reached inside the building. This has all sorts of advantages not least of which is reducing the explosion pressure the building frame, roof and foundations have to be designed for. Furthermore, the ERP zones cause much less explosion force to be transferred to the structure even when hinged retained panels are used.

Later in the paper the roof-vented hydrogen examples will be described (Figures 13 and 14) and this has an Av/V ratio of 0.26. When the personnel doors are also equipped with vent panels (Figure 16) the Av/V ratio increases to 0.33. It is important that the vent panel characteristics for the door are similar to those for rest of the ERPs otherwise their vent areas cannot simply be added.

These values compare with a maximum Av/V ratio of 0.21 used in the HySEA explosion tests (Ref 10).

An important issue is the degree of equipment congestion inside the building as this dictates the rate of burning of the internal vapour cloud and the peak pressure reached in the building once the panels have opened. Figure 2 is a particularly good example as the equipment is configured so that the internal congestion is low so that developed explosion pressures inside the building are minimised.

Similarly for Figure 3, there was little congestion inside the buildings: the gas compressor drivers were electric, as was the case for the buildings shown in Figures 1 and 2. The congestion associated with gas cooling and Natural Gas Liquid (NGL) processing is external, naturally ventilated and set back from the clad buildings to minimise external pressures on the relief cladding for which the ERP cassette framing was structurally designed.

ERP Cassette designs

Figure 5 shows a transverse section through stainless steel relief panels shown in Figures 1 and 2. The cassette for the LNG powered ferries is generally similar except that the panel is configured as an openable equipment hatch.

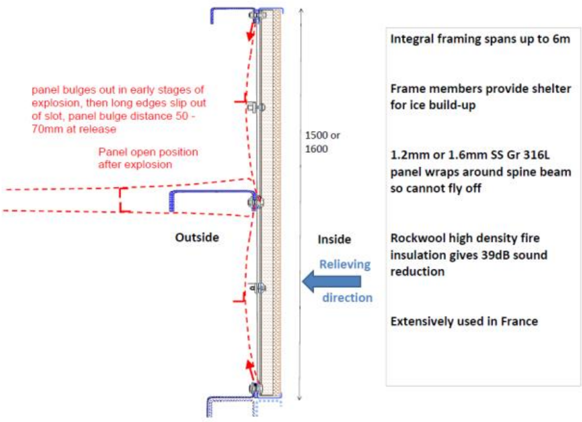


Figure 5 Section through ERP cassette used in Figures 1 and 2.

In Figure 5 the panel opening behaviour is shown in red dotted lines. Internal pressure rises in response to the developing explosion inside the building.

The panels are fixed strongly to the spine beams at their mid-line. The outer long edges of the panels are retained in a slot, which allows the panel edges to slip out when the panels bulge out about 50mm in response to rising explosion pressure from within the building.

The two small intermediate horizontal L stiffeners on the panels are supported off the vertical L members by proprietary duplex stainless steel release clips. They release at a predetermined pressure and then move out with the panels in an explosion. The panels then open like doors. Most of any mineral fibre insulation is then blown out.

It is important that hinged panels are configured to open back to back (Figure 5 & 6) or to open into non-venting zones, otherwise the panels will continue past their fully open position and close over the openings for adjacent panels. Avoidance of overshoot of panels is a potential problem for the ductile capacity of the hinging zone, which must be respected if the panels are not to become projectiles. Panel overshoot also increases the explosion impulse force given to the panel support frame because the duration of the peak centrifugal force applied to the framing is increased.

For the roof panel ERP cassettes the free span is typically 7.5m and cassettes are bolted into a 9m x 7.5m assembly which can be lifted off bodily to facilitate major maintenance on the gas compressor equipment inside the module.

Figure 6 shows a typical roof panel cross section, again with the panel opening behaviour shown in red, similar to Figure 5.

Both these cassette types were designed for sound reduction given by the noisy equipment in the building. They were also designed for a measure of fire resistance. The cassette form shown in section in Figure 6 is also supplied as a kit-form system as shown in Figure 7.

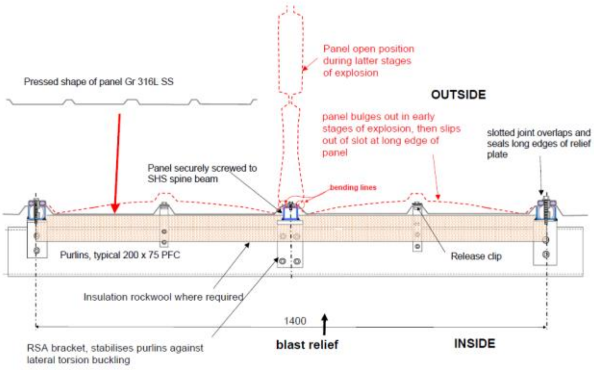


Figure 6 Typical roof panels and support framing.

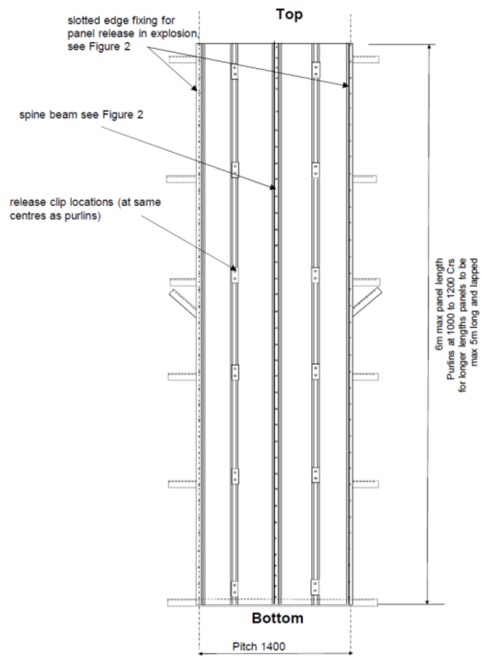
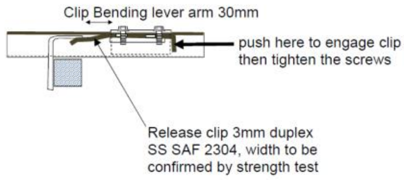


Figure 7 Kit-form cladding ERPs

Figure 7 applies both to wall cassettes and to sloping roof cassettes. The kit comprises: a) the pressed stainless steel relief panels, b) longitudinal spine beams with fixing L's welded to them, c) longitudinal open section pressed edge beams, also with fixing L's welded to them and d) various fixings and seals.

Figure 8 shows the proprietary release clip.

Figure 8 Proprietary release clip.



Controlling the release pressure and opening time

One of the most important performance parameters is the release pressure. The design release pressure for the systems proposed here is normally 40mbar (4kN/m^2), which gives a good safety factor against spurious release for areas with storm wind gust speed of up to 40m/s (suction effects). For offshore North Sea locations the release pressure needs to be higher due to higher wind speeds.

The release pressure is dictated by the plastic bending resistance of the release clips (see Figure 8) and these are sized and tested for the particular application.

Due to the flexibility of the panel the actual opening of the panel starts when its edge slips out of the slot, which is some milliseconds after clip release when the pressure is raised above the clip release pressure. The panel, by this time, is already moving outwards so that final opening time is largely unaffected. Ref 12 is a paper on the explosion behaviour of these panels and explains these effects and how the insulation affects opening time, an important issue. The insulation has to be blown out and its inertia affects the rate of increase of vent area, even though the insulation may have little structural resistance.

Opening time and the forces transmitted to the support frame via the hinging lines in the relief plate are covered by the methodology given in Ref 13. Alternatively, non-linear finite element packages LSDYNA or ABAQUS can be used. As with the opening time, these depend upon the nature of the explosion impulse at the panel location, in particular the rate of pressure rise during panel opening, a parameter which sets the limit for the ability of the panels to hinge open without becoming projectiles.

Typical opening time depends upon rate of development of explosion pressure, the panel unit mass and the panel width. For typical gas compressor applications where sound reduction insulation and some fire resistance is required the typical opening time is 40-50 milliseconds for a 0.5bar explosion, but for very reactive gasses the rate of pressure rise is high and a light-weight narrow panel as featured later in this paper can have its opening time down to 10-15milliseconds, depending upon impulse shape.

Simple pop-out panels individually can have similar opening time to hinged panels as they do not have to move far to open up vent area around their perimeter. But when pop-out panels are located in groups the group size lengthens the distance the panels have to move to open up their full vent area (Ref 13). This makes them much slower to fully open than hinged panels with consequences for the peak pressure reached within the space enclosed by the ERP set.

Explosion testing and certification

Venting performance of the stainless steel system designs described above is confirmed by full scale explosion tests performed at GexCon's facility in Norway. Full design and technical documentation to Ref 13 is provided.

The systems are covered by ATEX certification in accordance with Ref 5 and is applicable for onshore systems installed in Europe.

In the venting standard EN14797 (Ref 3) the venting efficiency definition is effectiveness compared to equivalent massless panel area, i.e. one which gives the same peak pressure in the protected enclosure. This is not compatible with FLACS Computational Fluid Dynamics (CFD) analysis which accounts directly for panel mass, width and gas type. The value in EN 14797 is different for different gas explosion scenarios. This makes it difficult to define ATEX performance which refers to EN14797 and needs extension in each certificate to cover analysis by CFD.

For the hydrogen applications, explosion analysis will invariably have to be accompanied by CFD analysis hence there is a current gap in guidance which will hopefully be plugged by planned revisions to the EN standard including the pre-normative test series for the HySEA project (Ref 10 and 11).

Many of the Gas compressor buildings described here were either designed or verified with CFD (FLACS) and some with NFPA 68 (Ref 8).

Figures 9 and 10 show explosion testing of the stainless steel panels detailed above in a congested explosion test module by GexCon near Bergen in Norway. The panels were fire and sound insulated with high density mineral fibre insulation. Peak pressure in the module for the tests was approximately 0.5bar.

Figure 9 Explosion Relief panel before explosion test

Figure 10 Explosion Relief panel after explosion test to 0.5bar.

Important issues confirmed were effective release pressure (in this case 75mbar), opening time, avoidance of harmful projectiles from the panels and the insulation. Insulation was retained by wire mesh which helped break it up into small pieces. The results of the tests were used to calibrate the time domain simulation of the panels to Ref 13 and to calibrate the software to calculate the internal forces and dynamic support reactions: see Ref 12.

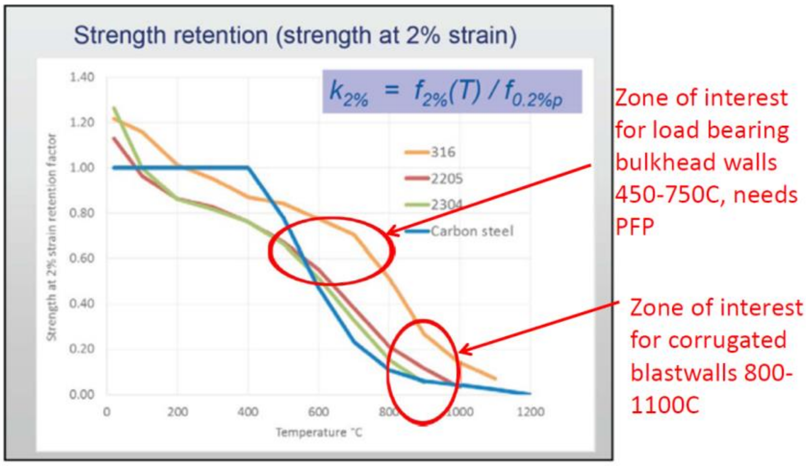
Fire resistance, material selection and avoidance of electrostatic spark risk

Explosion will usually be followed by a fire as the leak that led to the explosion continues to flow until all of the inventory behind it is exhausted.

While ERPs will not normally be specifically fire-resistant they can, if not first opened by an explosion, help with attenuating fire loading on the equipment situated behind them.

For this reason, the ERP's and screens, being of thin plate, are made of stainless steel (usually grade 316L stainless steel), with carbon steel support structures. Neither the panels nor the structure are subject to significant structural loads during fires and have high thermal resistance (800-1100ºC) as illustrated in Figure 11 below. Blast resisting cladding is often thicker and can be made of painted steel (providing the paint is spark resistant).

An advantage with 316L stainless steel for explosion applications is its ductility, with minimum elongation at break of 40%.



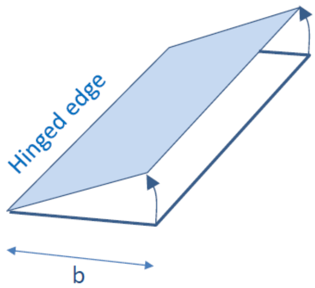
(Ref 3 Advances in the use of high strength carbon and stainless steels offshore, Fabig TM80 2014)

Figure 11 Fire resistances of carbon and stainless steels

Electrostatic spark resistance is an important issue with hydrogen as it has such a low ignition energy (0.02mJ) over a broad range of concentrations. For this reasons non-conductive materials are avoided or carefully applied (eg seals) to minimise ignition risk. This is part of the ATEX certification process. For more guidance on electrostatics see Ref 2.

Summary of parameters for explosion relief panels

- Hinging or pop-out (pop-out = projectiles).
- Verified release pressure.
- Panel unit mass w kg/m2.
- Panel dimension b.
- Vent area to module volume ratio Av/V.
- Max. allowable rate of pressure rise dP/dT (higher values needed for H2).
- Design wind gust speed and ventilation overpressure.
- Standard EN 14797 applies
- Explosion pressure impulse and drag forces determined by CFD (FLACS).
- Response analysis to FABIG TN2 and TN4 or ABAQUS/LYDYNA
- Full scale explosion testing required.



Explosion loading input requirements for design of ERP systems and their framing

To ensure that ERPs do not open spuriously, design meteorological gust wind speed is required and any constant ventilation over/under pressure. Normal load factors are applicable to the environmental load conditions as in Eurocode 3 (Ref 4) for example.

A design accident load specification (DAL spec) needs to be compiled from the hazard and explosion analysis which includes not only the peak pressure reached in the enclosed space but the impulse duration and rate of pressure rise and the follow on drag pressure when the panels are open (drag acts on the frame members). For situations where external explosion pressure is to be resisted, this will also need to be defined.

The concept of the DAL spec comes from offshore standard ISO 19903 and needs to condense down a large number of hazard scenarios into one or a small number of impulse curves (pressure time histories) as indicated as type 1 or 2 in Figure 12 below.

If the explosion is a deflagration (i.e. does not detonate) the impulse shape will be as (1) or (2). In the explosion response simulation in Figure 15 below impulse type (2) was applied as it was best fit to the explosion impulse measured in the full-scale test and is the most common shape.

All the gas compression modules and buildings described here have been designed for deflagration not detonation.

It is important to lay out the equipment (congestion and flame acceleration length) so that the risk of detonation impulse type 3 or 4 is minimised. Transition to detonation can occur with strong explosions. It is difficult to predict and needs careful consideration of the characteristics of the developing explosion by specialists to identify when it is likely to occur.

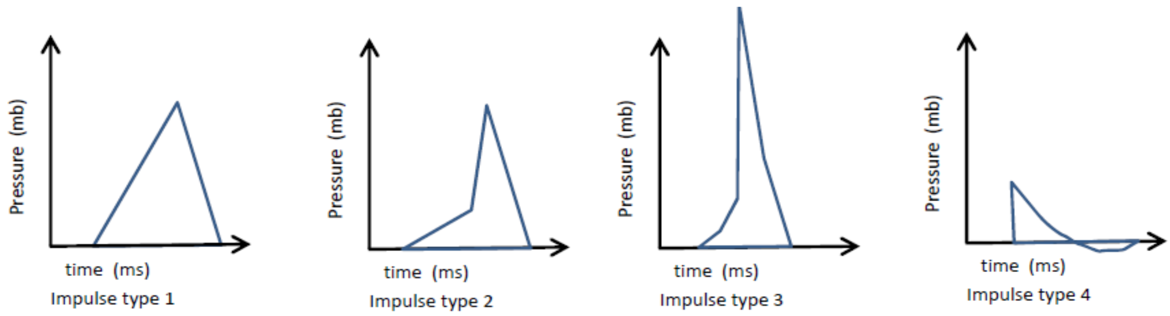


Figure 12, Impulse shapes for ERP and cladding design

If the gas mixture detonates inside a container the pressure rise will start gradually for some milliseconds and then rise instantaneously to a high value, possibly 20 bar before falling back rapidly: impulse (3).

This is a situation that must be avoided as it will lead to the container disintegrating, causing projectiles and blast damage to the surroundings. Avoidance by design is essential and can possibly be by careful equipment and facilities layout. Alternatively, an option is to inert the container with nitrogen or maintain high ventilation to keep hydrogen gas concentration suitably low.

If the receiving object is far away from the exploding cloud the impulse (4) will attenuate rapidly with distance and lengthen in time. An impulse starting as type 1 or 2 will eventually "shock-up" in the far-field to an impulse shape 4 but with the peak value attenuating with distance (not exceeding its starting impulse type 1 or 2 peak).This is a common feature for design and assessment of objects at some distance from the initial explosion, e.g. external loads on the ERPs.

The first 3 diagrams in Figure 12 do not show the negative pressure phase of the explosion. It is however known to occur and needs to be allowed for especially where resistance to external explosions on ERPs are considered, e.g. fire-rated ERPs.

Special hazards related to the use of hydrogen

Hydrogen is a much more reactive gas (higher flame speed) with 10 times lower ignition energy and can transit to detonation with much greater ease than hydrocarbons, i.e. over a shorter flame acceleration distance. It also burns at a higher temperature – with a blue or transparent flame, which affects fire protection requirements when engulfing (impinging) flames are applicable. Its characteristics are significantly different from hydrocarbon vapours: much can be learnt from Ref 7.

Currently hydrogen is destined for use in the transport industries as fuel for vehicles, trains and ships. In many cases hydrogen fuelling stations will be close to persons using the facilities and habitations, thereby entailing societal risk. This is an issue that has historically been avoided with chemical plant and compressed gas handling installations which are fenced off from the public, and habitations are located at some distance from the hazardous equipment.

Hydrogen refuelling stations have dispensing compressor modules that pump up the gas to 700bar, for cars, and 350bar for buses and lorries. These are the last compressor stage before the refuelling nozzle that is connected to the vehicle.

A significant effect that has only come to light since CFD program FLACS has been properly verified for hydrogen explosion simulation (2019/20) has been that the ignition turbulence caused by the very high pressure leak greatly increases rate of burn and peak explosion pressures.

Detonation risk is a function of local flame speed and overpressure: too high local values and the whole mixture will detonate. The broad detonable range of hydrogen adds to the problem and makes detonation a real risk to be avoided. With methane it is difficult to detonate a gas-air mixture.

Fire is an issue with hydrogen: a fire from a high-pressure leak will produce a long narrow jet of gas which slows down near the end to a turbulent mixing zone. Igniting the gas leads to the flame following the jet and when it arrives at the turbulent zone at the end it causes an explosion at that point which can produce significant explosion pressures. This is an added source of explosion loading in hydrogen refuelling stations.

The heat radiation from a hydrogen flame is weaker than from hydrocarbon jets but the burn temperature and radiation from the turbulent mixing zone at the end is strong. Despite the buoyancy of hydrogen high pressure jets can run a long way horizontally before rising.

With hydrogen flames one needs to make the distinction between impinging and non-impinging flames and distancing measures at hydrogen fuelling stations need to account for this. Blast / fire walls can divert the flame and if suitably configured could prevent impinging flames reaching nearby facilities and according to Ref 1 can allow reduction in safety distances.

It is to be noted too that high-pressure jets sometimes will auto-ignite without the need for an ignition source. This has been verified by experiments

On the positive side hydrogen applications have certain safety advantages over hydrocarbons:

- Hydrogen is very buoyant and this can be capitalised on to vent hydrogen leaks upwards and away from congestion (but be careful of nearby trees: see Ref 9 and below).
- Hydrogen fuelling stations inherently have much smaller inventories and flow rates than conventional hydrocarbon plant.
- The equipment packages are naturally small so that shorter flame acceleration lengths are naturally achievable, thereby reducing peak pressures and Deflagration Detonation Transition (DDT) risk.

One note of care: hydrogen gas is buoyant and will rise above the leak. If there is foliage or branches above, especially pine trees and the gas mixture becomes entrained in them is in flammable or detonable concentration range, ignition would cause a major explosion or detonation with significant effects in the far field (Ref 9).

Societal risk is of particular significance in safety regulations as the target return probability for installations were this is not involved is 10^{-4} whereas it can be down to 10^{-7} where major societal risk is involved. This depends upon the sites' safety classification under UK HSE COMAH regulations (Ref 6).

ISO 19880 (Ref 1) advocates risk reduction by imposing minimum safety distances between process elements on the site and from process elements to the public. The currently applied values mentioned in Ref 1 are however under review by DnV and are likely to have to increase substantially with impacts for planning of hydrogen fuelling stations.

The implications for design of explosion relief panels for hydrogen applications are:

The increased reactivity of hydrogen means that faster opening relief panels are required.

- The low ignition energy means that GRP and other non-conductive materials should be avoided or controlled.
- Where hazardous equipment is protected by ERPs from explosions in other nearby hazardous equipment the ERPs may require resistance to external explosion.
- Boundaries of enclosures not designated as explosion relieving need to be explosion resistant.
- Given the importance of free ventilation to reduce the incidence of cloud formation louvered panels or perforated panels may be considered in some circumstances.
- Canopies and screens need sometimes to be specifically explosion relieving so as to provide a means of projectile prevention for reduced risk to persons and reduced design loads for supporting structure.
- Design against terrorism and malicious damage is now a fact of life for new infrastructure and enclosing to prevent entry with malicious intent can conflict with safety aspects.

The effectiveness of the site arrangements needs to be evaluated by a comprehensive hazard identification and analysis and risk analysis, as part of a multi-barrier loss prevention philosophy, which includes provision of suitable gas detection and operating methodologies: Ref 1 advocates this.

Blast relieving and resisting applications for hydrogen refuelling stations

The applications listed below are

1. Roof ERP cassettes for small modules containing hazardous equipment.
2. Explosion relief cladding for walls and roofs of buildings.
3. Explosion relief roofs for canopies and protection screens where projectile formation due to nearby blast is to be avoided and imposed forces on their support structures is to be reduced.
4. Explosion relieving doors. As advocated in Ref 1.
5. Fire and blast resistant walling for modules and protection screens for hydrogen storage containers and for personnel protection.
6. Perforated options.

Transportability is part of the design requirements for these products:- often they are configured to be transported in or as ISO shipping containers. In the case of 1) above the whole module can be configured to the geometric constraints of ISO shipping containers, but not necessarily the strength constraints, as ISO shipping containers will rarely be strong enough.

Ref 1 advocates lightweight panels, hatches and doors fixed with suitable release bolts for relief of explosions. Ref 1 omits to mention that the opening time is the key parameter. The cladding will blow off as one large zone but still acts as a barrier to gas expansion until it has moved far enough to open up vent area around the perimeter (see Ref 13, Ch5). Small hinged panels open much faster as they rotate and only have to move a short distance to be out of the way. Panel width is a key parameter..

Another problem with blow off (pop-out) panels is that they form harmful projectiles. Hydrogen explosions have fast pressure rise times (dP/dt), typically 100+bar/sec. A typical explosion would accelerate the pop-out panels to over 100m/sec in the first 1 metre following release, forming energetic projectiles with a range of dozens of metres. This is not currently accounted for in the safety distances in Ref 1: in which the issue of relief panel risk is dealt with in clauses 5.3.6.3 and 7.11.6.

It is for the above reasons that practice has historically been to use hinged - retained panels.

Hydrogen refuelling stations will have a number of separate equipment packages distanced from each other but connected by underground piping. The typical units are:

1. Hydrogen storage which might be a parked mobile tube truck.
2. An electrolyser for making hydrogen from mains electricity.
3. Multi-stage compressor to increase the pressure to storage pressure, perhaps 200bar.
4. A dispensing compressor in which the gas is pumped up to 700 bar, for cars and 350bar for buses and lorries.
5. Integral with the dispensing compressor module is a cooler to reduce gas temperature to -40°C for loading into the vehicle via the dispensing nozzle.
6. Protection of station customers and their vehicle occupants from accidental blast and fire effects.

Items 2, 3, 5 are often contained in enclosures that require explosion relief.

Fast explosion relief panel cassettes for roofs

Here the whole roof is supplied as a prefabricated cassette which can be fitted to the open roof of the container /module in one piece. The transverse beams integral to the cassette are designed also to stabilise the top of the side walls of the container.

For servicing of equipment in the container the roof can be lifted off bodily, Figures 13 and 14 show the arrangement.

Heating of vent air is possible to melt ice or snow on the roof. It is understood that in practice Hydrogen Fuelling Station equipment is usually exothermic anyway. For insulated roof panels one would have to use trace heating.

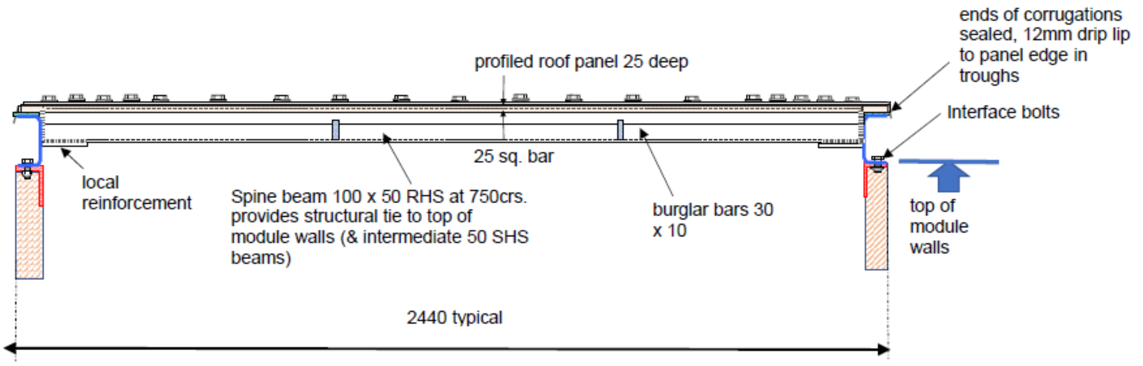


Figure 13 Explosion relief panels for small ISO container sized modules: section

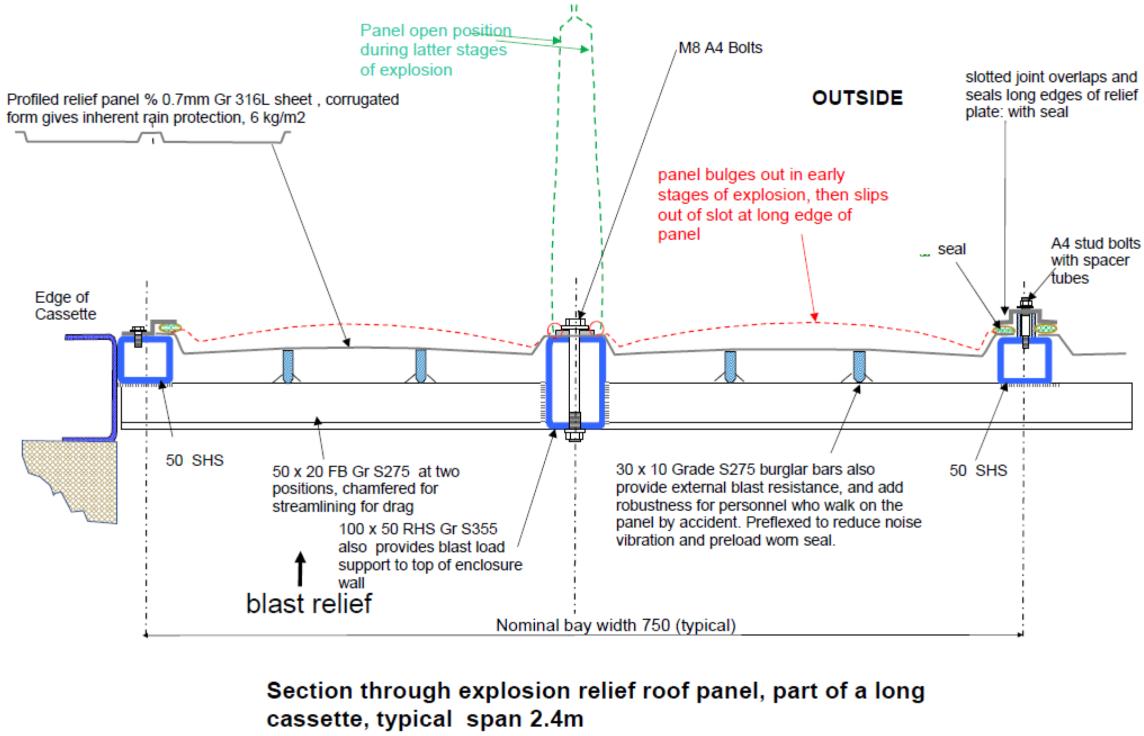


Figure 14 transverse section through panels

The fast opening roof cassette shown in Figures 13 and 14 provides 9.2m^2 nett vent area on a 6.1m x 2.44m wide module (Av/V = 0.26), 25% more than competing systems (once burglar bars are included). Opening time is reduced by having lightweight narrow panels with 50mb release pressure, less than competing designs and reduced opening times to typically 10-13ms. The cassette can support the top of the container walls and incorporate diagonal bracing.

A potentially useful option would be incorporation of corner column supports to make the module compatible with direct transportation as a stackable shipping container, albeit with some temporary roof protection.

The advantages of roof location are:

1. Flame acceleration paths are shortened as they tend to be directed upwards to the roof.
2. The explosion pulse and external flame is high above the ground giving more chance for protection of people nearby.
3. The reaction force to the foundation is less and does not cause significant lateral movement of the container which could shear off connecting pipes to other facilities. This is important as pipes linking such containers to other equipment are underground.

Figure 15 illustrates how the reduction of release pressure and speeding up of opening time (reduced mass, narrow panels) can improve venting performance: the conventional ERPs on the left are shown from Ref 10 (HySEA) tests No 59, 21% concentration of hydrogen, and demonstrate that the panels are not fully open until the peak pressure has passed, whereas the Rhino fast panels start opening earlier and are fully open before the pressure peak, with the same impulse and provides more vent area as well.

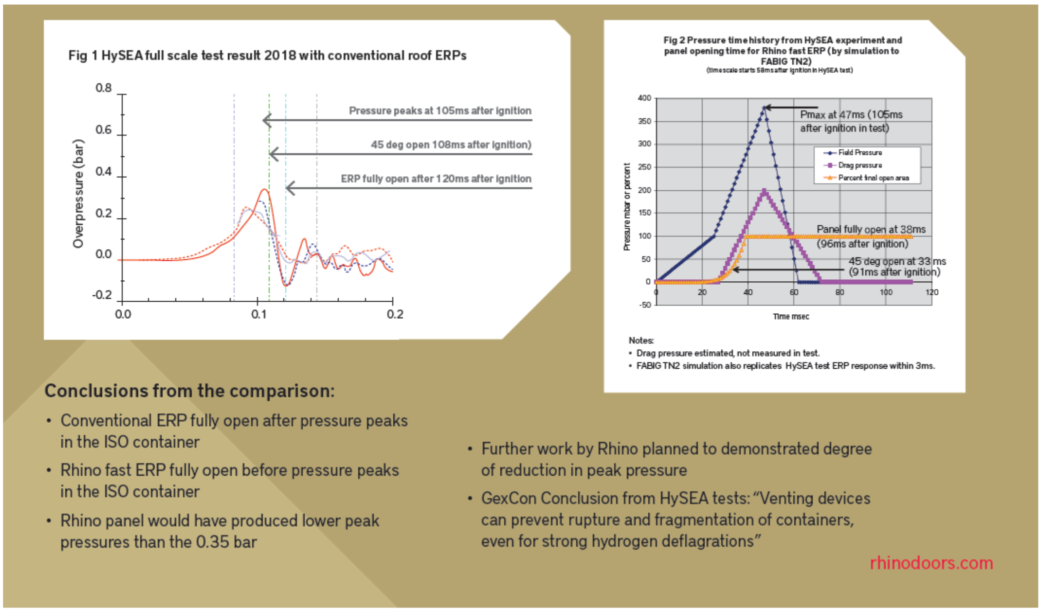


*Figure 15 Comparison of venting performance of Rhino fast panel and conventional ERP*s

The panels are normally backed up by security bars to prevent malicious entry or maintenance workers falling through the roof.

Further work in 2020 with example FLACS simulations for high pressure leak inside a realistically congested 2.5m x 2.5m x 3m enclosure showed that peak pressures were reduced by 50% when using the lightweight narrow panels of the type shown in Figures 14 or 16 below: opening time was 10-12ms..

Explosion relieving doors and fire rated doors

Explosion relieving doors can be a) manufactured as an open barred security gate with the fast relief panel(s) similar to Figure 14 bolted on to the framework (as shown below in Figure 16) or b) as a suitably reinforced lightweight hinged door. The problem with b) is that the added size and weight of the door will make it open much more slowly than the lightweight ERP door in Figure 16. Equally important to the panel unit weight is the flap width. Furthermore, the centrifugal force on the hinge and door frame will be high, which creates structural problems for the door and hinges and support structure.

It should be noted that, in Europe, if a door is to be relied upon for explosion venting it will need to de built and assessed in accordance with EN14797 "Explosion Venting Devices".

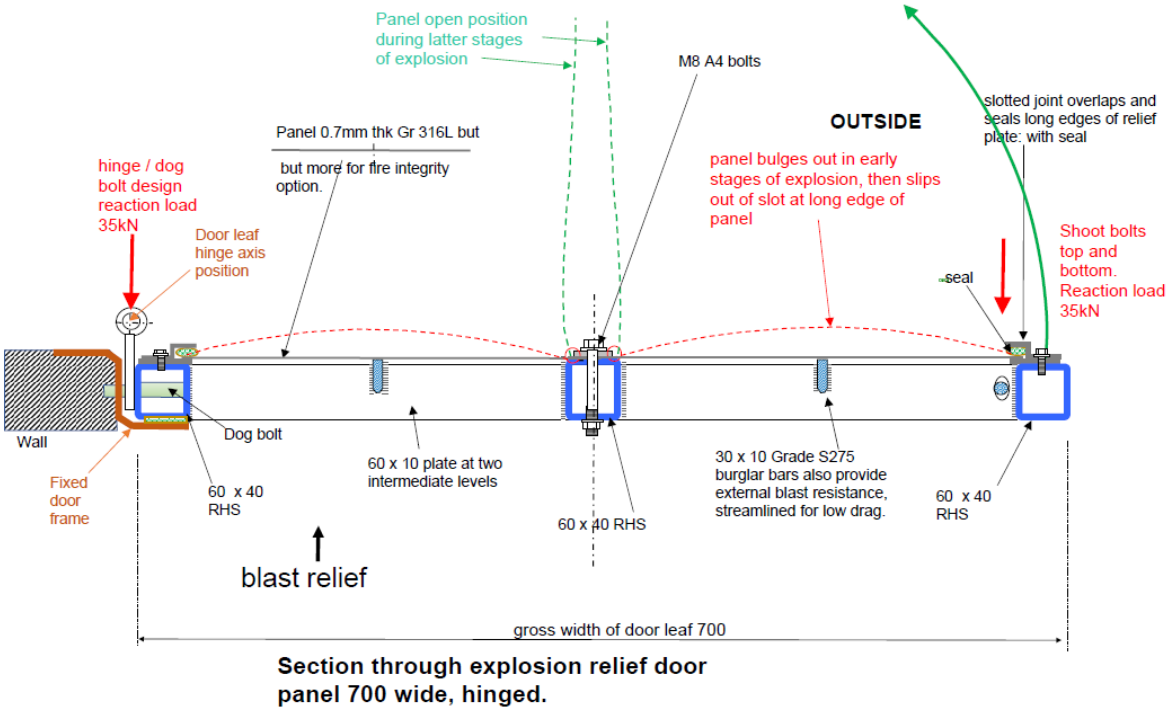


Figure 16 Door incorporating explosion relief panels (can be half of a double door)

The adoption of ERP rated doors and equipment access hatches can be a first step in mitigating designs where venting is inadequate. For small enclosures an adequate value of Av/V (see Section 2 above) may be obtained by this measure alone.

Figure 16 shows one leaf of a double door. This door is designed to be flat against the wall behind the door when open in case an explosion occurs while the door is open. A dynamic back-stop can be provided on the hinge side for the case where it is not possible to fold the door back against the wall behind the door. The fast opening door ERP produce a very short duration impulse which means that if the door is closed but not latched the opening leaf frame will not subject the hinges and door frame to as much centrifugal force as it would if the whole door leaf was the opening panel.

Standardised door leaves are a convenient way of providing explosion venting: they are easy to fit using shoot bolts and hinge pins and easy to remove and replace in the event of damage - without special expertise. Door leaves are interchangeable and refurbishment of a damaged door leaf and re-certification can take place at the originating factory before being returned to the station site.

Quite often fire design requirements or prescriptive regulations can demand that the door be fire rated and if this involves insulation as well the door is likely to be significantly slower to open and less effective as a vent panel. A major potential problem here with impinging hydrogen fires is that they burn much hotter than hydrocarbon fires, typically 2000-2400ºC which is above the melting point for stainless steel and carbon steel (see Figure 11).

It is therefore important to configure the layout of Hydrogen Fuelling Stations so that fires from hazardous modules do not impinge directly on explosion relief panels.

Current fire tests are based on cellulosic or hydrocarbon fires which are up to 1100ºC hence current fire certificates are not valid and this is a major problem for the hydrogen industry. The fear here is that there is currently no general test for hydrogen fire loading nor any tests houses capable of doing the tests in large enough scale. Some form of jump in technology is required for the industry.

Historically fire design in petrochemical plant relies on distancing between hazardous equipment plots or modules as mentioned in Section 2 above. In this way fires in one plot or module will not impinge directly on adjacent units or places where people could be present. Applying this approach to hydrogen fuelling stations may enlarge the required site surface area for the facility but is necessary. An added problem with hydrogen fuelling stations is that customers will inevitably be located close to hydrogen containing equipment. Addressing this means minimising inventories in those locations and, where possible, providing separation barriers between people and plant.

Solutions should be possible if fire durations are brought down to 10 minutes or less, which should be realistic with good process design providing on-site hydrogen storage inventories are kept down.

An added approach is to implement a two-barrier approach in the site arrangements where the first barrier nearest the flame is a perforated heat shielding barrier in high temperature resistant stainless steel. This solution has been adopted for stair-towers offshore (see section 15 below).

As regards the relief panels themselves, options with fire resistance are also developed as single plate fire integrity (similar to units used previously in the hydrocarbon industry in larger scale). Options with fire insulation (sandwich panels) are in development but are slower opening as vent panels leading to higher explosion pressures than single skin panels.

An intermediate option that largely preserves the short opening time of single skin panels is to provide water sprays inboard of the vent panels. After all, the doors might be open when the fire event occurs.

Explosion resisting walls and confined explosions

In situations where explosions are confined or semi-confined (vented modules) blast resisting boundaries are required, usually walls, as the venting will often be at roof level to keep the fire away from nearby facilities and people.

Whether the modules are converted ISO shipping containers or bespoke structures the blast-resisting cladding is usually corrugated steel. 20 ft ISO shipping containers are the lightest form of construction with shallowly corrugated (36mm) walls in 1.6mm and 2mm thick mild steel (Corten A weathering steel). They resist loads mostly by membrane action but to do so, gross deformations of the module occur and the ultimate bursting strength has been found to be a very variable parameter as seen from the HySEA test results (see Ref 10 & 11) with failure of the doors and the seam at the bottom of the walls being common failure modes at relatively low pressures (0.3bar). To combat this allowable plastic deflections and strains in blast resisting boundaries need to be limited.

It could be cost-effective to make the walls of ISO shaped modules out of stronger corrugated sections, perhaps 70mm deep and thicker steel material.

Figure 17 shows a bespoke form of construction with stiffened plate floor and corrugated walls and given the right corner post configuration, is ideal for transport by road or sea as an ISO shipping container. The form of construction indicated in Figure 17 owes its origins to a number of external escape corridors installed on North Sea offshore platforms and have been designed for blast pressures on the wall of up to 3bar.

Figure 18 shows the form of corrugated construction commonly applied. The profile section is often trapezoidal as shown in Figure 18 top. Design pressures up to 3bar on 8m span walls have been routinely achieved using arch profile sections or stiffened arch profile sections as shown in Figure 18. These are proprietary patented solutions but widely used in the North Sea, seas off Australia and the Caspian Sea. These have ductile bending capacity which is more difficult to achieve economically with trapezoidal sections and the lower stiffened one has much more web crushing resistance. Design guidance can be obtained by use of Ref 14: though this is explicitly for stainless steel blastwalls it can be used for carbon steel blastwalls as it is based on to Eurocode 3 part 1.3 and 1.4. Normally ductile bending resistance will be confirmed in design by Non-Linear Finite Element Analysis (NLFEA).

For enclosures in hydrogen fuelling stations two issues are particularly important and if accounted for can greatly improve the economy of the enclosures.

The first is that membrane action has a large part to play in mobilising blast resistance, especially to internal explosions. For this reason, analysis should address the whole container structure in a very detailed non-linear explicit type NLFEA programme such as LSDYNA or ABAQUS. It is necessary to refine the mesh to pick up the local failure modes that trigger the collapse of the container.

The second point is that impulse durations for hydrogen explosions are very short, typically 5 to 30ms. These provoke a dynamic response in the blast resisting structure which, if accounted for, will lead to much structural economy.

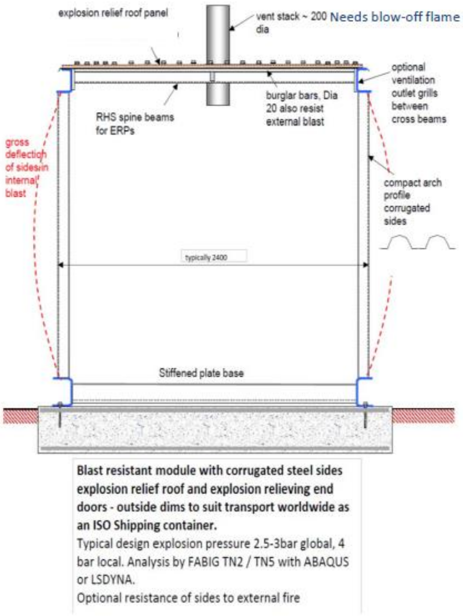


Figure 17 A steel blast and fire resisting enclosure for a hydrogen refuelling station.

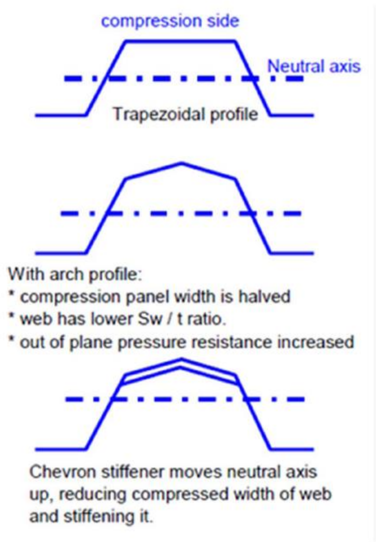


Figure 18 Conventional and proprietary corrugation profile: evolution for maximum ductile bending capacity (Arch profile much used offshore)

The enclosure in Figure 17 has an explosion relief roof but works equally well with explosion relieving doors.

There is a vent chimney on the top for venting gas leaks that do not ignite. This has to be less than 200mm in diameter otherwise a hydrogen air mixture in it can detonate and detonate the rest of the gas mixture as well. The chimney may have a flame cap and be tall enough to vent gas leaks to a safe area as advocated in Ref 1. If one 200mm diameter chimney is insufficient it is necessary to have more than one chimney.

Alternatively, high level venting can be via louvres in the top corner C profiles of the walls.

One aspect of ISO container shaped modules is that they can have a blast resistant and gas tight mid-line dividing wall. Then the non-hazardous electrical and utility equipment can be on one side of the wall and the hazardous hydrogen containing equipment in the other compartment. The advantages here are removal of much of the congestion out of the explosion risk area (as adopted historically for gas compressor buildings) and this reduces the number of ignition risk points in the hazardous compartment.

Another aspect is that, by careful selection of vent panel location, e.g. roof panels or solid roof with vent doors on one side of the module, one can give the explosion and subsequent jet fire some directionality to protect nearby facilities or occupied areas.

Hydrogen explosions within rooms of buildings

For hydrogen explosions in rooms of buildings it will be rare for uniform gas mixtures to fill a room. Good process and room design can prevent it but in order to prove it, feasible explodable cloud compositions and distributions need to be investigated by comprehensive CFD analysis, preferably with a tool that can go on to simulate the explosions as well (e.g. FLACS hydrogen). The response of the building will need to be assessed by NLFEA, in particular ABAQUS or LSDYNA, by a specialist.

An explosion in a building is likely to blow through into adjacent rooms and up or down, hence structural design and analysis will have to address explosion loading. Ultimately the explosion pressure will have to go out of the building from a perimeter boundary. If this is made of explosion relief cladding as shown in Figure 6 & 7 and is extensive enough in area then developed pressures in the building can be minimised, especially in rooms located adjacent to an external wall.

Part of the objective in the design will be to minimise projectile formation which can result in co-lateral damage and injury / fatalities. Use of the kit-form type ERP as shown in Figure 7 can be practical in such situations so long as the building frame can withstand the hinging forces in the panels of cladding.

Ref 1 calls for sufficient natural or forced ventilation to keep gas concentrations to below 25% of the lower explosion limit. The problem often is that it is impractical to have a natural forced ventilation throughput large enough to allow this criterion to be met.

Perforated options

Perforated versions can help to reduce explosion risk by improving natural ventilation of enclosed spaces. External perforated barriers can reduce heat flux on adjacent areas but require fire testing in large scale.

If the panel a perforated relief plate the relieving function is supplemented by natural ventilation for reduced explosion risk. Perforation levels from 25-35% are feasible, but not more as this would weaken the panel too much.

For explosion relief doors one can have the top part of the relief panel perforated to enhance ventilation of the module. This option is often followed for electrolysing modules, though historically the ventilation takes place through louvre panels which would act as pop-out panels in an explosion.

It is equally possible to apply perforation to corrugated blast resisting applications, though percentage hole area will be less.

On offshore platforms thin perforated stainless steel cladding is used as heat shielding for persons in stair towers and on walkways. Application of this form of construction and its ability to reduce heat flux from fires would be worth investigating as part of a two barrier fire protection system and as a means of reducing heat flux on modules and in places where people may be located.

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