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GAS EXPLOSION PROTECTION FOR AEROSOL FILLING ROOMS – FULL SCALE TESTING AND ANALYTICAL VALIDATION

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Abstract: *Almost all domestic aerosols are propelled by a liquefied compressed gas. Since CFCs were banned in the 1970's these are mainly flammable LPG propellants (propane/ butane blends). Aerosol cans are filled at a significant rate of up to 500 cans per minute (each with up to 200ml of LPG). Therefore, a significant explosion hazard exists should a leak and subsequent ignition occur. In the event of a release, demands are then placed on the provided venting and the strength of any enclosing structure to withstand the confined blast with tolerable consequences.*

This paper presents an overview of an analytical and experimental validation programme of the structural withstand and potential explosive loads on aerosol gas filling houses. A full-scale representation of the gas house was designed and constructed (including HVAC and vented roof systems) and subject to multiple internal explosions. The results of the experimental testing were used to justify the existing structural design accounting for congestion and turbulence. Numerical modelling was also performed using industry standard software, however comparison with the results from the experimental programme identified a number of discrepancies and limitations. These limitations are currently being investigated and indicate that care should be taken when numerically modelling uncongested vented structures.

Introduction

MMI Engineering (now MMI Thornton Tomasetti) have been working with a client in the consumer goods industry in relation to their aerosol products and the hazards involved in this area of their business. Filling of aerosol cans with LPG propellants is an extremely hazardous activity. In line with industry best practice, our client fills their aerosol cans in dedicated unmanned buildings, known as 'gas houses', external to the main factory on their production sites. As part of a wider process safety review the client had previously undertaken validation of the performance of their gas houses in the event of an explosion during aerosol filling. The basis of this validation exercise was to use numerical modelling to predict the potential overpressures that could develop from an ignition of a gas release inside the gas houses. The gas house structures were then assessed to determine their likely blast withstand capacity.

The validation process raised several concerns over the design of the client's round gas house design, shown in Figure 1. The main concern was over the predicted overpressure that could arise from a blast event inside one of these houses. The numerical modelling, conducted using FLACS CFD software, predicted extremely high overpressures well in excess of the expected capacity of the houses. The second issue highlighted during the review was with the design of the houses and their assumed performance during a blast event. The gas houses had been designed with a lightweight roof structure than was intended to lift off the structure during a blast event in order to provide blast relief and venting, this can be seen in Figure 1and Figure 2. To avoid the generation of hazardous flying debris, the roof is secured by long chains and is intended to return to its original position following venting of the explosion.

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Figure 1- Overview of Round Gas House

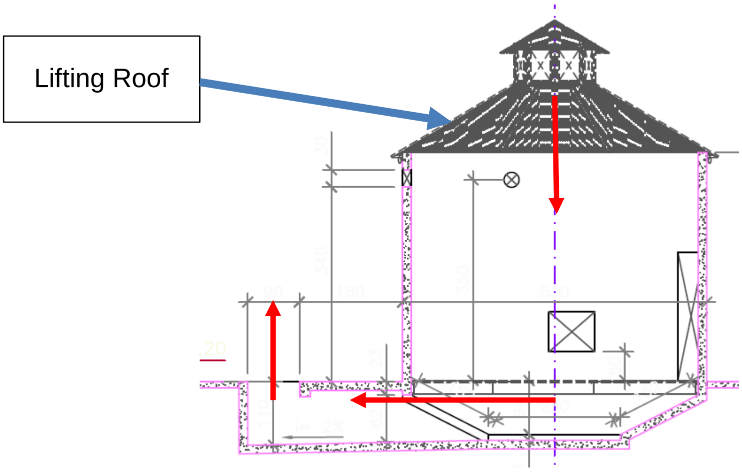

Figure 2 – Schematic of Round Gas House Ventilation

Based on significant experience of blast hazard modelling and blast resistant structures, MMI felt that it was very unlikely that the overpressures predicted by the numerical modelling could actually be achieved in practice, particularly given the relative lack of congestion within the gas houses. It was also considered extremely unlikely that the lightweight roof would perform as predicted during a blast event. It was considered much more likely that the roof would be significantly damaged during a blast and would likely break up forming missiles that would present hazards to personnel and equipment in the vicinity of the gas houses. It was therefore decided that testing program was required to (a) determine the likely achievable overpressures resulting from a release and subsequent ignition of LPG within the gas house and (b) understand the performance of the roof structure during a blast event.

MMI worked with the client to develop the test program for the gas houses. This paper discusses the testing program including design of the test rig and design and testing of possible remedial measures for the gas house.

Design of Test Rig

The overpressures generated during a deflagration event, like that of a vapour cloud explosion, are highly dependent on the level of congestion, degree of confinement/venting and geometry of the building. In order to determine the likely overpressures that would be generated during a vapour cloud explosion in the gas houses, the test conditions need to match the actual conditions inside the gas houses as accurately as possible. There were no existing test facilities that could replicate the gas house conditions accurately. Hence, it was decided to design a custom test rig that was as close a replica of the actual gas houses as possible.

The actual round gas house is constructed of reinforced concrete, however, for practical reasons it was decided to design a steel test rig that was a full-scale replica of the internal geometry of the gas houses. A steel design made the construction and installation quicker, easier and more cost effective than a concrete construction. Additionally the steel construction would more robust, allowing multiple tests to be carried out at overpressures which are at the extreme end of those to be expected from modelling.

Design Loads

The CFD modelling initially undertaken to quantify the explosion hazard suggested that in some scenarios a transition to detonation was possible in the vapour cloud, resulting in extremely high overpressures. Given the lack of congestion in the gas houses it was considered very unlikely that a transition to detonation was possible. These anomalous overpressures were therefore discounted when designing the test rig. Other modelling runs which showed deflagration events however still predicted significant overpressure, reaching approximately 1barg. A typical overpressure time history from the CFD modelling is shown in Figure 3.

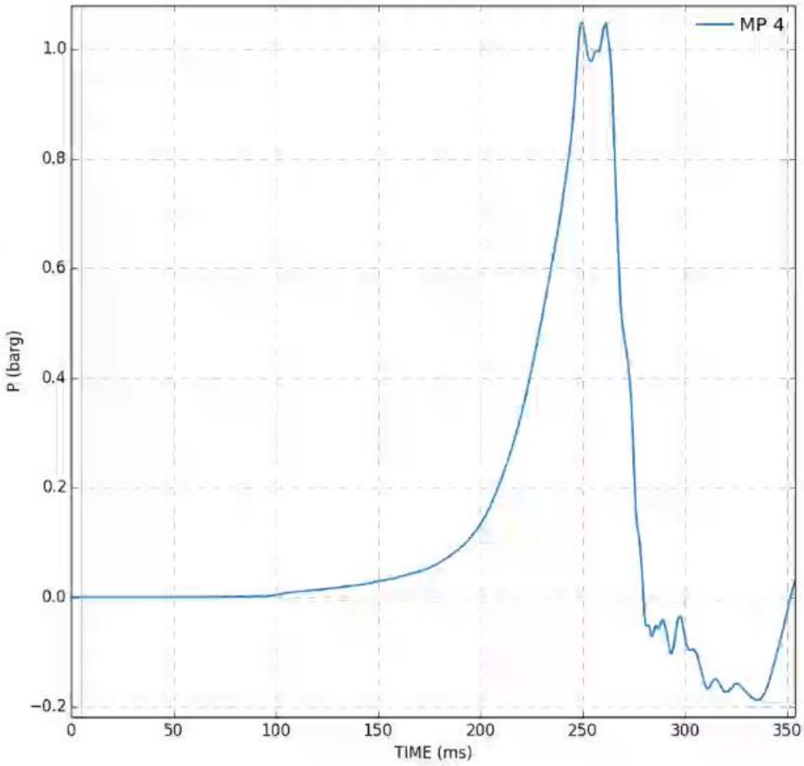

Figure 3 – CFD Modelling Overpressure Curve

As the multiple tests were planned it was necessary to design the rig to remain undamaged under the maximum predicted overpressures. Although the CFD-predicted pressures were considered to be unrealistic it could not be ruled out that they were accurate or even underestimated. It was therefore decided to take the maximum predicted overpressure of 1barg and apply a conservative safety factor of 2 to give a design overpressure of 2barg. The rig was designed to remain broadly elastic at this design overpressure.

Design of Steel Structure

The test rig was initially designed using the Cloud-based CAD program Onshape and the section sizes estimated using hand calculations. An initial concept for the design is shown in Figure 4.

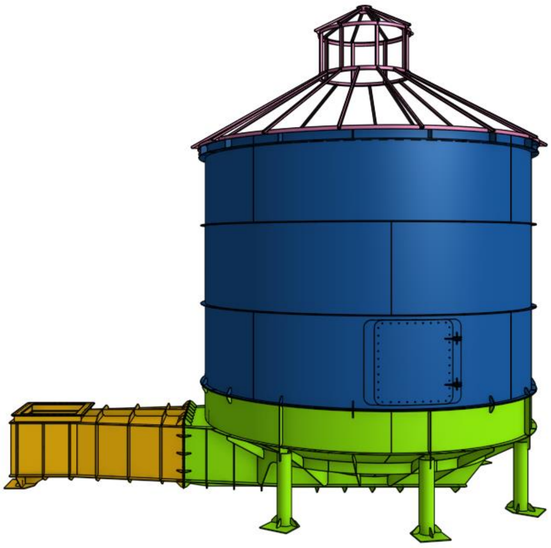

Figure 4 – Initial Concept Design

The response of the concept design to blast loading was then checked by dynamic finite element analysis using ABAQUS Explicit. The walls of the test rig form a large cylinder and therefore have good resistance to uniform internal pressure loads. However the base of the structure is a more complex shape and was more flexible under blast loading. The dynamic deflection of the base and vent module (coloured yellow) under blast loading actually caused the rig to lift off the ground as they rebounded. This movement could adversely affect the quality of data that could be recorded by pressure transducers, reducing the accuracy and repeatability of the tests. Figure 5 shows the displaced shape of the rig (note that displacements have been scaled by a factor of 10). The 'bellying' of the base of the rig also causes the cylindrical section to ovalise.

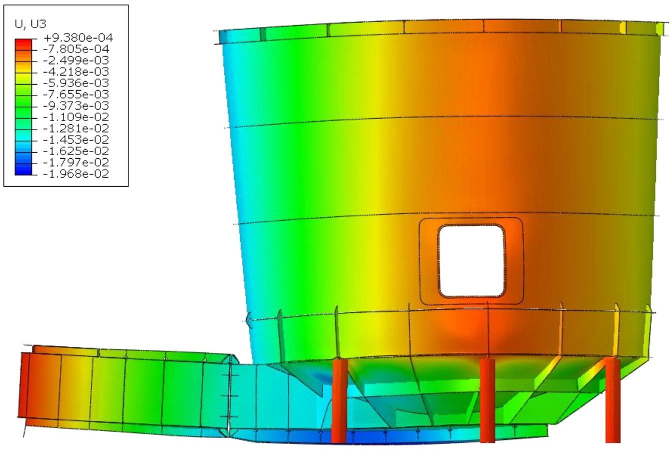

Figure 5 – Displacement of concept design

In order to prevent this dynamic response of the test rig, the base would need to be stiffened substantially, resulting in increased fabrication costs, and the legs would need to be anchored which would require drilling of the test pad and repair following testing. It was therefore decided that the design could be improved by encasing the base of the rig in concrete; this would provide stiffening to the base, significantly reducing the amount of welding required and would act as a gravity base to anchor the rig. In order to install the ballasted base a steel skirt was added to the base to act as shuttering with chutes left open to allow concrete to be poured into the void.

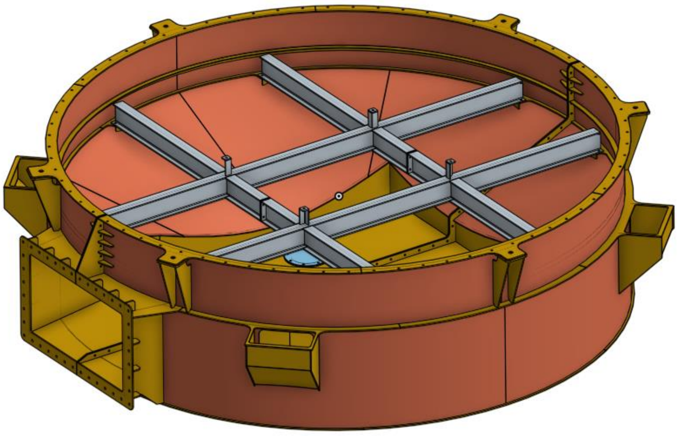

Figure 6 – Ballasted base of test rig

In order to facilitate transport to the test site the rig would need to be designed as a bolted assembly with pieces that could fit on a standard lorry trailer. This necessitated splitting the cylinder in half then dividing into three shorter cylinder sections, breaking the continuity of the cylinder and therefore its ability to resist pressure loading. The flanged connections therefore needed to be very robust in order to transfer load between the two halves. The half cylinder sections were arranged such that joints in the cylindrical sections did not align vertically at the various levels. An overview of the test rig structure along with filling and recirculation loop is shown in Figure 7.

Figure 7 – Overview of Test Rig

Design of Internals

In order for the test to provide as accurate a prediction as possible of the potential explosion overpressures inside the actual gas house, the geometry inside the test rig must reasonably represent the actual gas house geometry. While the rig itself provides a close replica of the gas house structure, the internal equipment inside the house needs to be approximately represented in order to provide the correct level of congestion. The aerosol filling equipment within the gas houses is extremely expensive so the internal congestion was provided by providing mocked up versions of the largest components using cheap construction materials. A mock gasser unit was constructed from a steel angle frame clad in plywood sheets with an empty oil drum to represent the main filler unit. The conveyor sections were represented using steel box section and HVAC ducting using large diameter sections of drainage pipe. See Figure 8and Figure 9.

Figure 8 – Mock Gasser Unit

Figure 9 – Model HVAC Ducting

Test Program

Phase 1 Testing

The test program was conducted in two phases with the initial phase investigating the effectiveness of the existing lifting roof structure at relieving blast overpressure. This was done by comparing the roof against a polythene sheet cover which would provide maximum possible venting. The phase 1 test were as follows:

- Test 1: Polythene sheet roof, ignition at bottom of gas house
- Test 2: Repeat of test 1
- Test 3: Actual roof, ignition at bottom of gas house
- Test 4: Repeat of test 3

A polythene sheet was used as this would give a theoretical lowest possible overpressure for ignition in the gas house. The withstand capacity of the walls of the houses was already understood so if the lowest possible overpressure exceeded this capacity then it would not be possible to design a retrofit roof to reduce the overpressures.

Ignition at the bottom of the gas house was used as the CFD analysis had indicated that this would provide the worst case overpressures. This location provides the longest distance from ignition point to vent location (roof) allowing maximum acceleration of the flame front and hence maximum overpressure. The same ignition point was used for all 4 tests to obtain comparable results.

Phase 1 Results

Tests 1 and 2 showed an average overpressure on the walls of 0.08barg with a maximum of 0.09barg. This defines a lower limit for the potential blast loading on the walls. With the roof on, overpressures increase to 0.1barg average and 0.14barg max. Images from the test 1 and test 3 are shown in Figure 10.

Figure 10 – Phase 1 Testing Results. Test 1 (Left), Test 3 (Middle & Right)

Although the specification for the circular gas house walls was for a minimum 0.048barg withstand capacity, a structural review of the design showed that the walls actually had strength beyond this minimum requirement and would be capable of withstanding the peak 0.14barg overpressure observed in phase 1 of the testing without suffering catastrophic failure.

While the first phase of testing showed that the gas house buildings would likely survive an explosion event, tests 3 and 4 showed that the response of the lifting roof was not as anticipated. As the roof lifted off during the explosion, it was abruptly brought to a stop by the restraint chains. This shock loading tore the restraints chains from the metal frame of the roof and caused significant damage to the roof structure.

Further testing was undertaken in phase 2 to investigate other factors affecting overpressure and to investigate alternative roof options.

Phase 2 Testing

As Tests 1 & 2 and Test 3 & 4 show good repeatability, only one test was performed for each configuration in phase 2. The test performed in the second phase were as follows:

- Test 5: Polythene sheet roof, ignition inside the 'gasser'.
- Test 6: Polythene sheet roof, ignition at bottom of gas house, pre-ignition turbulence.
- Test 7: Frangible roof, ignition at bottom of gas house
- Test 8: Polythene sheet, ignition at bottom of gas house, grated floor removed

Tests 5 & 6 both investigate factors which have the potential to increase the explosion overpressures. If there is an ignition in the gasser, there is the potential for gas to become compressed before the walls of the gasser enclosure fail leading to a secondary, more powerful, explosion as the hot combustion products ignite the gas in the rest of the gas house. Additionally, the phase 1 tests all considered quiescent conditions. Test 6 considered the addition of pre-ignition turbulence to represent the turbulence associated with the release itself and the forced ventilation system. This should increase overpressures as the transition to turbulent combustion is faster.

Test 7 considered an alternative design for the gas house roof in which, rather than the whole roof lifting off, the roof is clad with lightweight frangible panels which would break up into small, light pieces under the explosion loading (Figure 11). This removes the potential for the whole roof to become a missile hazard.

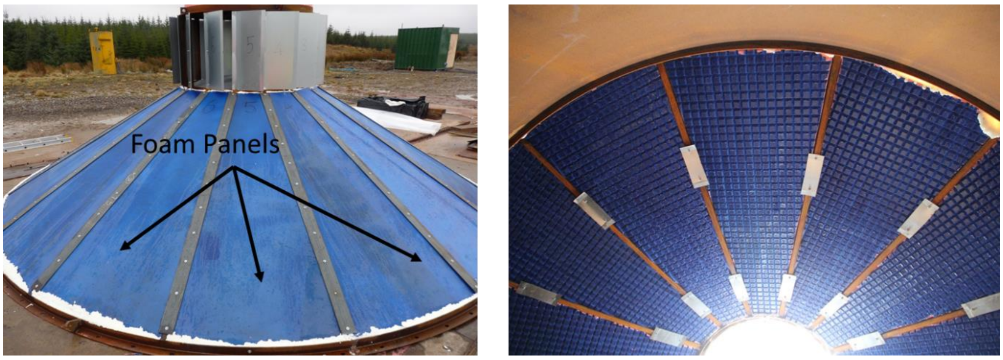

Figure 11 – Alternative roof with frangible foam panels

Test 8 addressed an uncertainty within calculations based on NFPA 68 - Standard on Explosion Protection by Deflagration Venting (NFPA, 2017). The NFPA 68 calculations use surface area as a measure of congestion within a building and the inclusions of the surface area of the grated floor in the calculation results in significantly higher overpressures. There was uncertainty as to whether the grated floor could actually produce such an affect.

Phase 2 Results

Results from the second phase of tests were as follows:

- Test 5 – Ignition in the gasser led to overpressures increasing from 0.08 to 0.25 barg – 220% increase.
- Test 6 – The addition of pre-ignition turbulence increased overpressures from 0.08 to 0.15 barg - 88% increase.
- Test 7 – The removal of the grating led to reduced overpressures from 0.08 to 0.07 barg - 15% reduction.
- Test 8 – the frangible roof increases overpressures from 0.08 to 0.28 barg (250%) compared to the polythene roof test. Compared to the steel roof, overpressures were increased from 0.14 to 0.28 barg (200%).

Although some of the phase 2 tests show a significant increase in overpressure, the maximum overpressure observed (0.28barg) is still significantly lower than the overpressure predicted using the FLACS analysis (1barg). These results confirm the assumption that the FLACS analysis was over-predicting the overpressures for this scenario. Further work was conducted to refine the FLACS analysis in order to more accurately match the experimental results, however the analysis was still found to over-predict the overpressures.

The alternative roof design behaved as expected during the explosion, breaking into many small lightweight pieces as shown in Figure 12. The size of fragments ranged significantly and were distributed over a large area, exacerbated by wind. However, none of the pieces would have caused serious damage or injury to equipment and personnel as the very light material and high drag result in low velocities.

Figure 12 – Response of frangible panels

Although the frangible panels behaved broadly as expected, this alternative roof design resulted in a significant increase in overpressure compared with the original roof (200%). There are several reasons for this. The increase in overpressure is largely due to a reduction in vent area compared to the original roof due to a) the steel roof frame remaining in place throughout the event and b) sections of frangible panel remaining in place during the explosion. The panels are of uniform thickness yet the triangular shape means that the span of the panel reduces further up the roof. This reduces the stress in the tops of the panels and means that failure does not occur uniformly. This can be seen in Figure 13 which shows that the panels fail first along the bottom edge and shows the remaining sections of panel in the roof following the explosion event.

Figure 13 – Frangible panels during and after explosion event

The design of the panels was limited by wind loading; these gas houses are installed all around the world with some located in regions with extreme environmental conditions. However it may be possible to improve the explosion response of the panels by tapering the thickness off towards the top point of the triangular panel. The FE analysis of the panels under wind loading (Figure 14) show that the stress over the panel is non uniform with the wider span at the base experiencing higher stress. The thickness of the panel could be adjusted to optimise the blast response while giving sufficient strength against wind loading as shown in the right hand image of Figure 14.

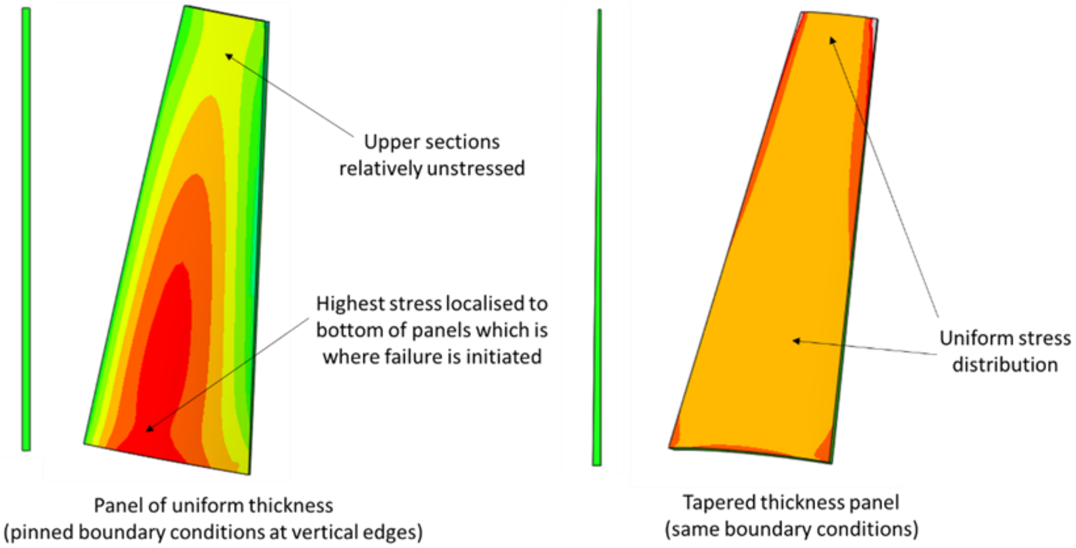

Figure 14 – Stress response of panels against wind loading

Retrofit Solution

The frangible panels provide a potential solution for the gas house roofs in terms of reducing the potential missile hazard posed by the current roof. However more work would be required to develop the concept in order to reduce the overpressures from an explosion as far as possible. Additionally it may be difficult from a practical point of view to design a weather-proof solution using this concept without further reducing the ability to vent an explosion.

Work is ongoing with the client to find a solution to improve the response of the current roof constructions with minimal disruption to the gas houses and minimal cost. From tests 3 and 4 it is clear that the current roof performs reasonably well as a method of pressure relief with the main problem being the potential missile hazard. It may be possible to retain the current roof constructions but reduce the risk of the roof or parts of it from becoming missile hazards.

Conclusions

This testing program has shown that for these gas houses, the numerical modelling performed in FLACS significantly overestimates the overpressures from vapour cloud explosions within the building. Although this project resulted in a positive outcome for the client in that they did not need to rebuild or significantly strengthen the structures of the gas houses, the issue remains that the CFD results were not accurate. Further development of the numerical modelling methods for confined gas explosions in non-rectilinear geometries are required to ensure that future problems of this kind can be modelled accurately and the results are reliable. It is not practical or cost effective to perform full scale testing for all such problems.

The testing also revealed that the lifting roof vent design did not respond as predicted. Although the roof provided a good level of venting it created an additional hazard as it was extensively damaged in the blast and could very easily have landed in the area surrounding the gas house. This highlights the importance of properly engineered blast relief systems. While significant modifications to the roof were not practical for this project it is the authors' opinion that a superior roof could be developed using specialised bespoke blast relief panels with well-defined relief responses.

References

NFPA, 2017. *NFPA 68 - Standard on Explosion Protection by Deflagration Venting.* [Online] Available at: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=68
[Accessed May 2019]