Gas Explosion Protection for Aerosol Filling Rooms – Full Scale Testing and Analytical Validation

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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). Aerosols are filled with propellants in dedicated unmanned buildings external to the main factory on a site. 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. There are a number of layers of protection to reduce the consequence of such an event such as hazardous area classification, gas detection, forced ventilation, unmanned operation and automatic shutdown. Despite this, there is the potential for these barriers to fail or for the release to be of such a size that a significant explosion could occur. In these instances, a demand is then placed on the venting provided on the building and the strength of the structure to withstand the blast.

This paper presents an overview of an experimental and analytical validation programme on aerosol gas houses that was conducted in 2017 for Unilever

Keywords Explosion Protection, Experimental, CFD

1.0 Introduction

The hazards associated with the ignition of aerosol cans is something that is very relatable, and many people have seen ignition of the flammable propellant first hand. During the filling of aerosol cans, the potential hazard is even more extreme due the rate at which can are being filled and the potential consequences are devastating as illustrated in Figure 1.

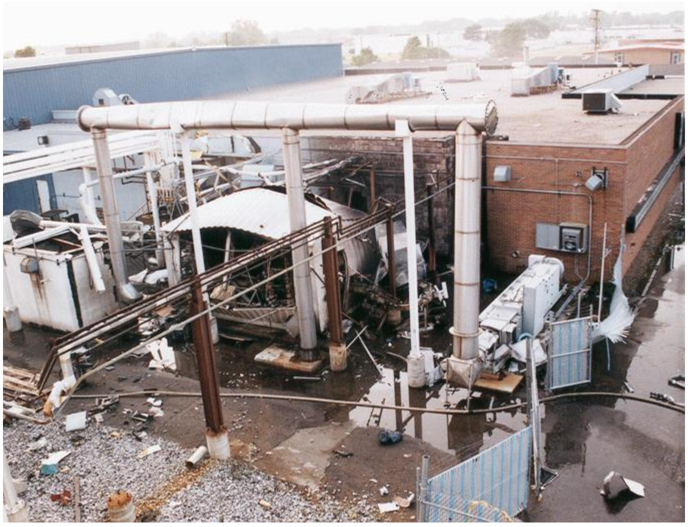

Figure 1: Example Aerosol Filling Accident (EPA , 2000)

In line with industry best practice, aerosol cans are filled with propellant in dedicated unmanned buildings external to the main factory on a site. Aerosol cans are delivered to the gas house via conveyor before returning to the factory, Figure 2 shows an example of a gas house. Should an ignition of the propellant occur, the explosion overpressures are relieved via a lifting roof which opens at a predefined pressure.

Unilever uses two standard designs for aerosol filling rooms (gas houses) - a rectangular design and a circular one. The primary advantage of the circular design is the better ventilation provided by under floor extraction with the disadvantage of a much larger volume due to the extraction subfloor.

The rectangular designed building has conventional lightweight vent panels, whereas the circular design employs a lifting roof with restraint chains to prevent the roof becoming an unconstrained missile.

A review of the two design types identified a potential issue with the explosion venting of the circular building.

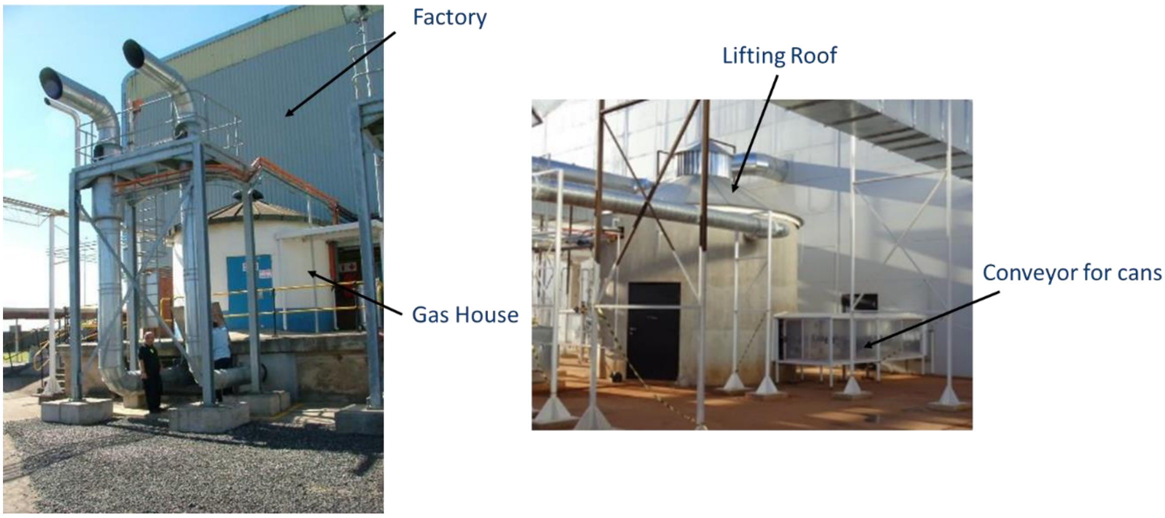

Figure 2: Example circular filling rooms

This paper presents an overview of work conducted during 2017 which started with a desktop review of the design of gas houses for Unilever and culminated in a full scale experimental and analytical validation programme.

2.0 Review of NFPA Design Standards

NFPA 30B - Code for the Manufacture and Storage of Aerosol Products (NFPA, 2015) covers the design of aerosol facilities and is used as the design basis by Unilever for it aerosol filling rooms. Following NFPA 30B: the minimum wall strength is specified at 100lb/ft^2 (0.048bar). NFPA 30B then specifies the use of the correlations in NFPA 68 - Standard on Explosion Protection by Deflagration Venting (NFPA, 2017) to specify the required venting area.

The methods defined in NFPA 68 calculate the pressure inside a weak walled enclosure as a function of:

- Gas type
- Vent area
- Relief pressure
- Internal surface areas

These methods are somewhat simplistic and there is uncertainty associated with the definition of certain parameters such as the internal surface area. The gas houses contain grated floors and it is not clear whether or not the total area of the grating, which is significant, should be included in the calculation of the internal surface area. Surface area is included as a variable in the calculation as geometric features act to increase the rate of combustion due to turbulence generation. Increased turbulence increases the mixing of hot products with unburnt fuel and accelerates the flame leading to higher overpressures.

The Unilever design is on the edge of the applicable range of the correlations in NFPA 68 due to the weight of the moving roof combined with the wall design. As a result, the review of the design standards showed that there may be a requirement to strengthen the gas house walls to ensure that they withstand the higher than expected overpressures following an explosion. Due to the substantial cost of this, and the uncertainty associated with the methods used to calculate the internal pressures, it was concluded that more sophisticated tools would be used to investigate the problem. The tool in question was Computational Fluid Dynamics (CFD), this is discussed further in the next section.

3.0 Initial CFD Analysis

The CFD analysis was conducted using FLACS. FLACS is a well-established CFD code that was designed to model explosions and has been used extensively in support of COMAH (Control of Major Accidents and Hazards) and Offshore Safety Cases, and has been the subject of several critiques by the Health & Safety Laboratory (Ledin, 2002) and (Hoyes & Gant, 2010). The conclusion of these critiques are that the code is more suited to explosion analysis than dispersion and has been developed based on a range of small, medium and large scale experiments, which is a strength, but certain numerical schemes that are applied can be considered somewhat outdated.

The advantage of using more complex analytical tools is that a wider range of parameters could be investigated, such as ignition location, and these tools offer a richer level of output data in terms of spatial and temporal resolution. Figure 3 shows an example output of one of the simulations showing the combustion products, overpressure generated and a pressure time-history.

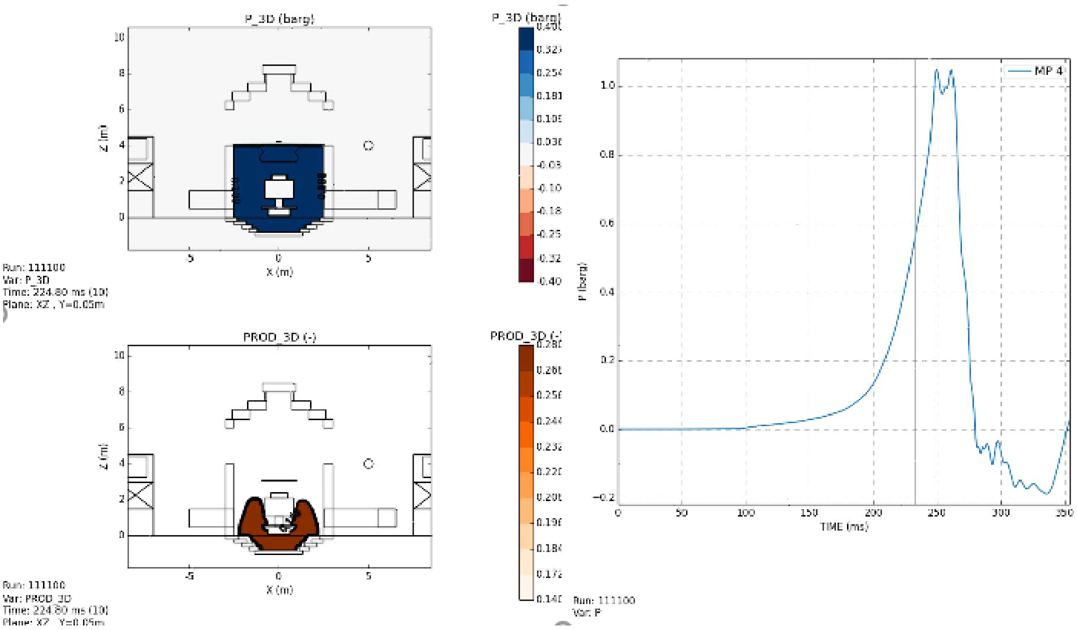

Figure 3: CFD Example Output

The CFD analysis calculated overpressures in the region of 1 barg. These pressures were higher than those predicted using the NFPA 68 methods and would lead to catastrophic failure of the gas house walls. If the CFD analysis was assumed correct, then it would not be possible to strengthen the walls and the gas houses would have to be rebuilt at a cost of millions of Euros. Although CFD methods are more rigorous than those employed in NFPA 68, there are still simplifications that have to be made due to the complexity of the explosion in question. Some of the simplifications made are listed below:

- FLACS is unable to resolve curved surfaces directly therefore they are represented by the porous sub model. This is illustrated in Figure 4 which shows how the geometry becomes faceted when resolved by the computational grid.
- The roof itself is a ‘top hat’ arrangement with slanted sides. Again, these cannot be resolved by the grid in the CFD model.
- FLACS simplifies the modelling of pressure relief panels as a ‘moving’ mesh cannot be employed to represent the lifting roof design.

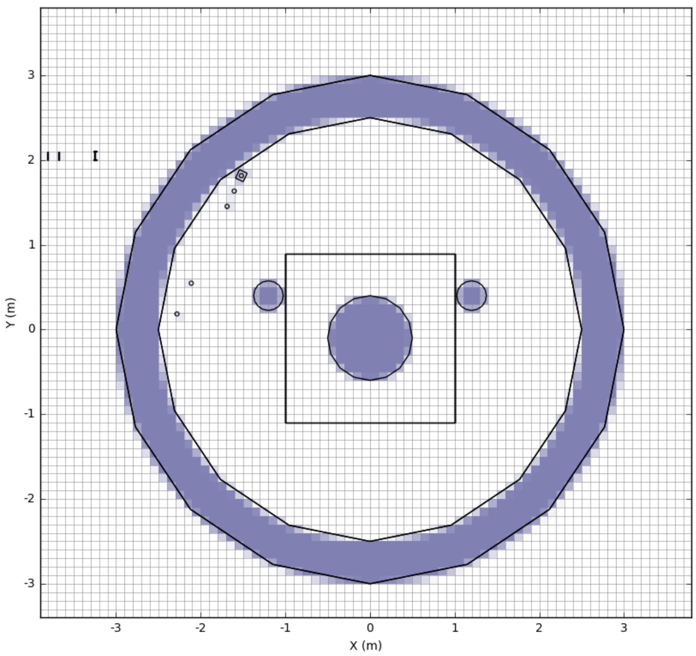

Figure 4: Geometrical Representation of Cylindrical Geometry

The conclusion of this stage of the project was that, based on engineering judgement, it was felt that the overpressures were overpredicted using CFD. Therefore, due to the costs associated with rebuilding the gas houses, it was decided to embark on a full scale experimental test programme using a $100m^3$ test vessel.

4.0 Experimental Program

The experimental program consisted of 8 tests conducted over two phases. The 3D model and experimental test rig are shown in Figure 5.

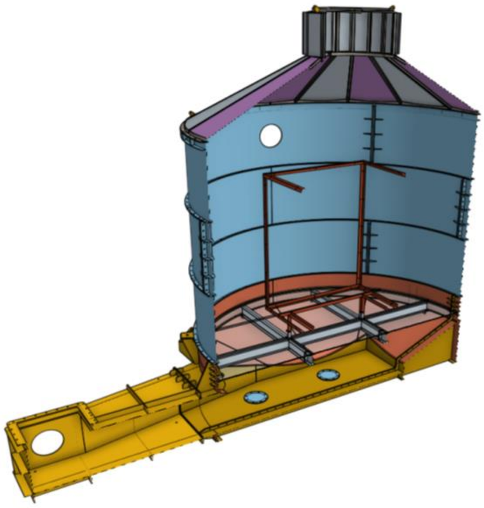

Figure 5: Test Rig with Representative Roof

Phase 1 consisted of two types of test; the first set with a gas house with a polythene roof and the second set with a roof representative of those fitted on the gas houses. The phase 1 tests are described below:

- 1: Polythene sheet roof, ignition at bottom of gas house
- 2: Same as 1, ignition at bottom of gas house
- 3: Same as 1 with actual roof, ignition at bottom of gas house
- 4: Same as 3, ignition at bottom of gas house

A polythene roof was used to understand the theoretical lowest overpressure that could be achieved as the polythene relieved at negligible overpressure and had minimal inertia. Any retrofit option of the roof would not be able to achieve a lower overpressure than a polythene roof. Hence, if this test gave overpressures higher than the withstand of the walls, there would be no requirement for considering further tests. The polythene also offers a cheaper alternative when considering sensitivity analysis compared to building new roofs for every test.

For all four tests, the ignition location was close to the bottom of the gas house as the CFD analysis had shown that this gave the worst case results. This results in the worst case overpressure as there is a long flame path that allows flame acceleration before the roof lifts and relieves pressure. An ignition at this level is seen as a realistic scenario as there is the potential for either static or a spark from a tool being dropped to be a source of ignition at this elevation. Each type of test (1/2 and 3/4) was carried out twice to ensure repeatability in the experimental set-up.

Overpressures within the gas house were monitored using eight pressure transducers for each test. The locations are shown in Figure 6. These were sampled at 500kHz with a 1ms moving average applied to remove noise.

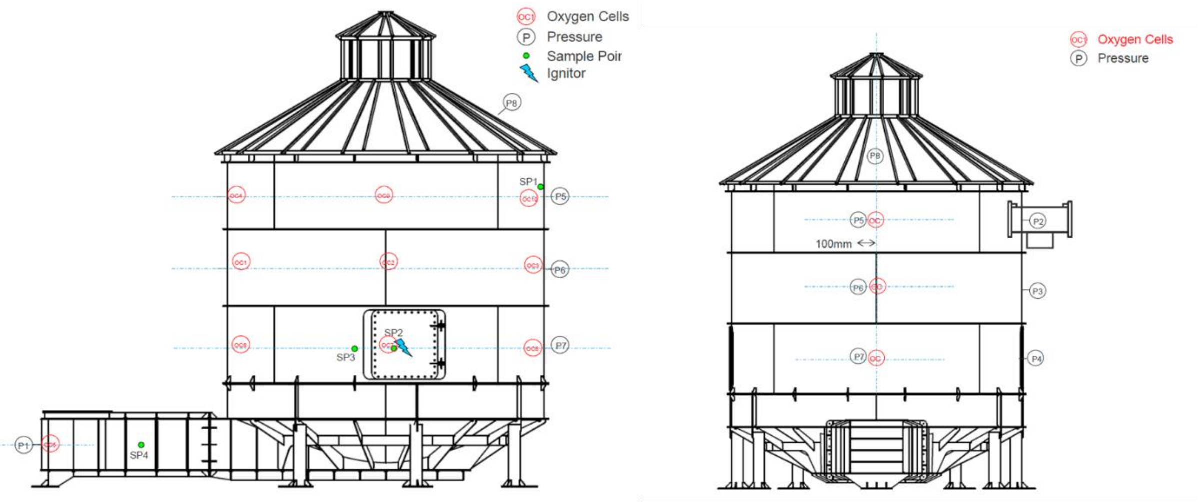

Figure 6: Gas House Instrumentation Locations

Example results for test 1 and 3 are shown in Figure 7. In test 3, the roof lifted as expected but the restraining chains sheared from the roof ring due to the shock load. The roof rose vertically and came back down, landing within the gas house as shown in the right-hand picture of Figure 7.

Figure 7: Phase 1 Experimental Results. Test 1 (left), Test 3 (middle and right)

The conclusions of the phase 1 tests were as follows:

- Tests 1 and 2 defined a lower limit for the design pressure for the walls.
    - Average pressure on the walls was 0.08 barg with a peak of 0.09 barg.
- With the roof, overpressures increased to 0.1 barg average and 0.14 barg max.
- Good repeatability between tests (1/2 and 3/4). Therefore, it was decided that multiple test would not be considered in Phase 2.

A detailed structural review of the existing circular gas houses showed that although their specifications were a minimum of 0.048 bar wall strength, the actual as built designs (due to seismic and wind constraints) were all capable of surviving the 0.14 bar maximum pressure seen in the tests without catastrophic failure. Therefore, it was concluded that the worst case rebuild costs would not be seen. However, the roof as a missile still caused significant risk to the sites.

Despite the phase 1 tests yielding positive results, only a limited number of parameters were considered. Therefore, a second phase was commissioned looking at sensitivities and potential design solutions. These are described below:

- 5: Polythene sheet roof, ignition inside the 'gasser'

  The gasser (see Figure 8) is the enclosure in which the cans are filled. 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.

- 6: Polythene sheet roof, ignition at bottom of gas house, pre-ignition turbulence

The phase 1 tests all considered quiescent conditions. This test considered the addition of pre-ignition turbulence to represent the turbulence associated with the release itself and the forced ventilation system. It was expected that pre-ignition turbulence would increase overpressures as the transition to turbulent combustion is faster.

- 7: Frangible roof, ignition at bottom of gas house

  This test considered an alternative design solution whereby the frame of the roof was fixed to the gas house and the fixed panels were replaced with frangible panels of negligible mass that broke at a predefined overpressure. This solution was investigated as it removed the potential for the roof to become a missile hazard following the explosion if the chains were to shear during an event like seen in test 3. The roof is illustrated in Figure 9.

- 8: Polythene sheet, ignition at bottom of gas house, grated floor removed

  This was an area of uncertainty when conducting the NFPA calculations as the inclusion of the surface area associated with the grated floor led to significantly higher overpressures. This test was conducted to address this uncertainty.

Figure 8: Test 5A - Gasser

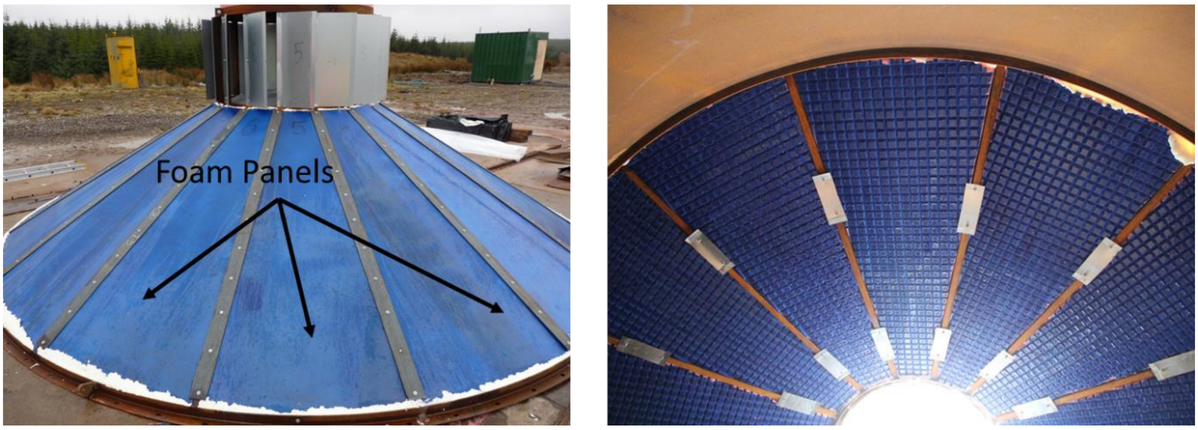

Figure 9: Test 7 – Frangible Roof

The conclusions of the phase 2 tests are shown below, with a comparison between the different tests included in Figure 10:

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

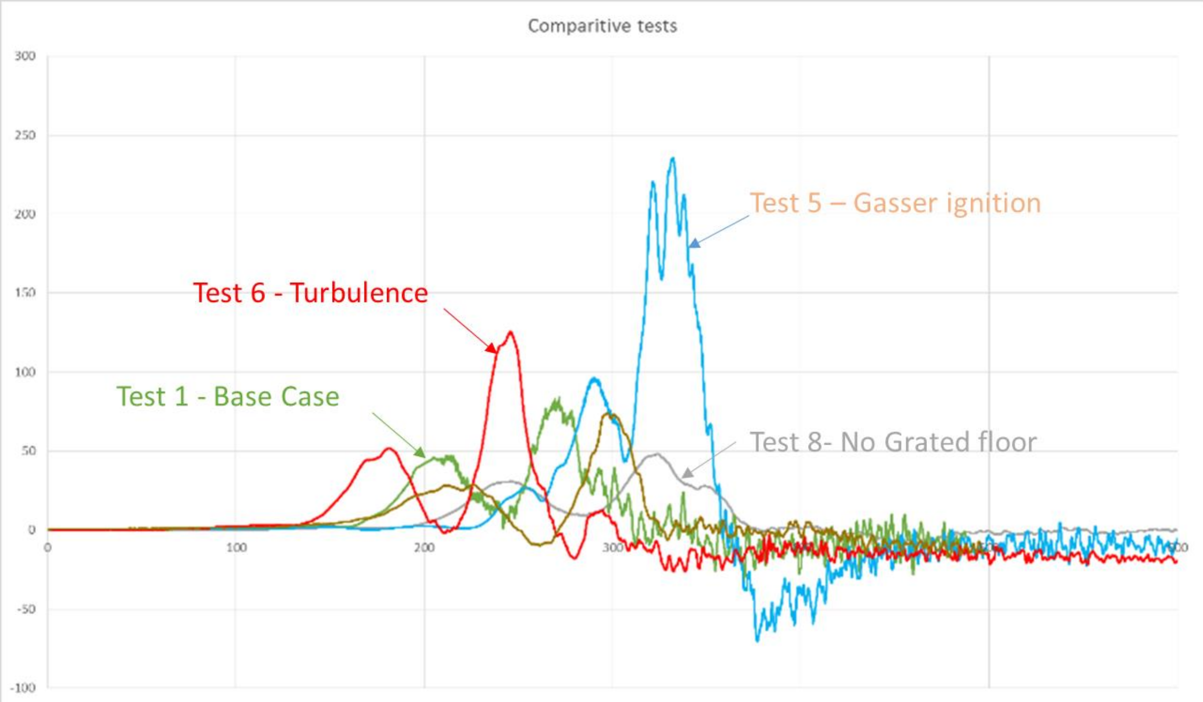

Figure 10: Test Comparison

Figure 11 shows the results of the frangible roof test. It can be seen from this image that the roof panels have disintegrated into many pieces of a range of sizes and are distributed over a large area. This confirms that the panels are not dislodged in single pieces, although the range of sizes produced is marked, from ~50mm cubed to pieces around 500mm long/wide. It is unlikely that any of the pieces observed would cause more than minor injury or damage to due to the large drag and lightweight material of the panels.

Figure 11: Test 7 – Frangible Roof Test

For test 8, there were three reasons for the increase in overpressures between this and the steel roof test (3 and 4).

- Residual blockage of the fixed roof structure.
- Sections of the panels remaining in-place following the explosion.

  This is due to the panels being of uniform thickness despite the unsupported width decreasing towards the apex of the roof. The decreasing unsupported length leads to the panels being stronger towards the top of the roof which means they potentially failed at higher than intended pressures. This can be seen in Figure 12 which shows part of the panel remaining attached to the roof structure following the blast. There is the potential to reduce the overpressures seen within the gas house by optimising the panel design and varying the panel thickness along its length. This would provide a uniform failure load along the panel length and cause the whole panel to fail at the same time, allowing greater area for venting; the point is illustrated in Figure 13.
- The panel strength being limited by design wind speeds. These gas houses are installed around the world in some quite extreme environmental conditions; it was not possible to reduce the overpressure at which the panels failed without compromising their performance under wind loading.

Figure 12: Test 7A – Frangible Roof Following Test

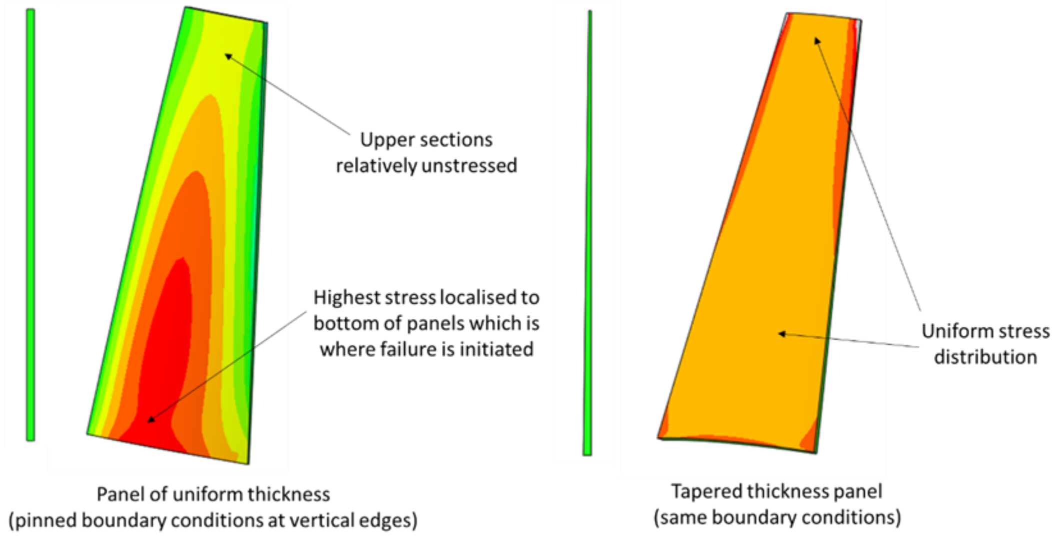

Figure 13: Test 7 – Panel Loading

5.0 Comparison of CFD and Experimental Data

The results of the experimental work showed that the CFD analysis had overpredicted the explosion overpressures by a factor of approximately three. Therefore, following the experimental program, the CFD analysis was revisited. Test 1 was considered as this was the 'simplest' experiment as it did not include the lifting roof structure and the polythene roof could be neglected in the analysis as it had negligible strength or inertia. The computational model used in the analysis is shown in Figure 14.

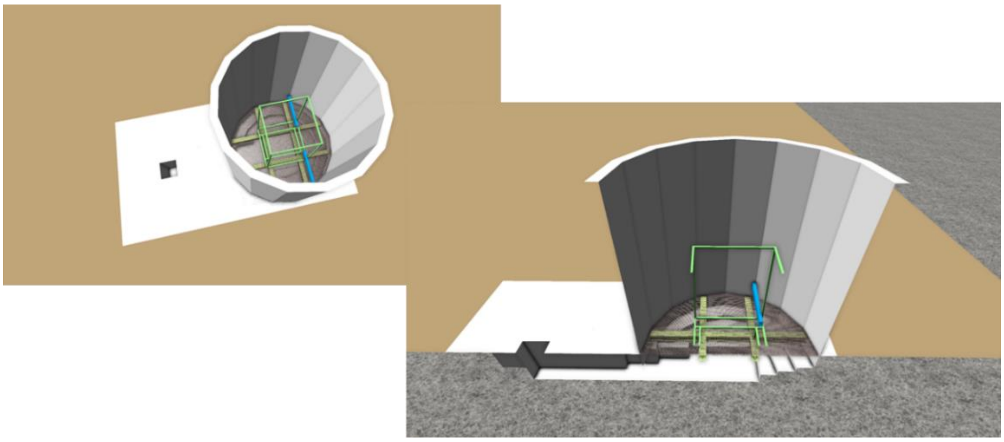

Figure 14: Computational Model used for Test 1

Figure 15 shows the results of the initial CFD analysis and overpressures in the region of 0.3bar were calculated which were approximately a factor of three higher than the experimental results. A number of parameters were investigated further including removing the gasser walls and slight modifications to the ignition locations to understand how sensitive results were to these parameters. The results of these test showed that if the gasser walls were removed, the overpressures went down, which is to be expected as these are a source of turbulence generation, but the results were still higher than those seen in the experiments. The changes in ignition locations also led to lower overpressures with a change of 0.5m leading to overpressures falling by 40%, but still much higher than those seen in the experiments.

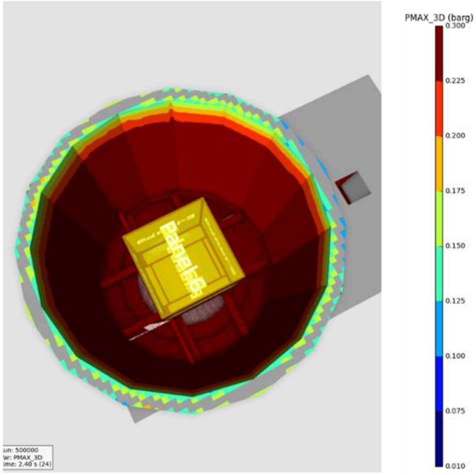

Figure 15: Test 1A CFD Results

The conclusion of this stage of the work were similar to the initial analysis in that FLACS was overpredicting overpressure, the capabilities of the commercial version of FLACS had been exhausted and that further investigation was required into the fundamental combustion models to understand the reason for the discrepancy.

6.0 Design Solution

Unilever has now rolled out a design solution to the gas houses as a result of this work. Despite the frangible roof test showing positive results in terms of functionality, the overpressures inside the gas house were higher than expected. In addition, to retrofit this solution to the existing gas houses would be difficult in terms of weather proofing and drainage. Therefore, due to test 3 and 4 giving favourable results in terms of overpressure, it was decided to remove the potential missile hazard of the roof becoming detached by re-engineering the restraining chains for the existing gas houses at a cost of less than two thousand euros per building.

Based on analysis of the high speed video after 100ms, the 530kg roof was accelerating at just over 6g when it reaches the end of the chain requiring a restraining force of 32kN to slow and stop its movement. Therefore, the number of chains installed to restrain the roof as a missile has been doubled to eight and the chains have been enhanced by the use of Osculati mooring springs with safety chains (see Figure 16) to reduce shock load and keep the roof attached to the structure.

Figure 16: Shock Absorbing Spring

7.0 Future Analytical Methods and Conclusions

Despite the project yielding positive results for the client, there is still a requirement to develop the analytical capabilities for this kind of problem further as at present the only way that designs can be validated is by conducting full scale testing which is expensive.

This work has shown that the commercial version of FLACS significantly overpredicts overpressures for these kinds of problems. FLACS was developed for the offshore industry for congested geometry and this work has shown that it is less suited to more open geometries of this nature and care should be taken when using it outside its sphere of validation. In addition, the non-orthogonal nature of geometries of this kind has also highlighted deficiencies and uncertainty within the code. Gexcon (the authors of FLACS) are currently developing a new version of the combustion solver and this experimental case will be used to potentially extend the range of applicability of FLACS and provide a better match to the data in the future. In addition, MMI and the client are also working with Cambridge University to understand if any of their codes have the capabilities to better match these experiments. It is hoped that this work may be presented at future Hazards conferences.

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