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Medium-scale Tests to Investigate the Possibility and Effects of BLEVEs of Storage Vessels Containing Liquified Hydrogen

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Experiments have been performed to determine the consequences of a storage vessel containing liquified hydrogen (LH2) is engulfed by a fire. The tests were performed at the Test Site Technical Safety of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Germany within a research cooperation between BAM and Gexcon as part of the SH2IFT program. Three tests were performed using double-walled vacuum insulated vessels of 1 m^3 volume varying the orientation of the vessel and the effect of the insulation material used (perlite or multi-layer insulation (MLI)). The degree of filling of the vessel was approximately 35 % in each of the tests performed. The fire load was provided by a propane fed burner positioned under the storage vessel and designed to give a homogeneous fire load. In one of the tests a rupture of the storage vessel occurred causing a blast, a fireball and fragments. Apart from measuring these consequences, the conditions in the vessel (e.g. temperatures and pressure) during the heating process were monitored in all three tests. The work described was undertaken as part of the project Safe Hydrogen fuel handling and Use for Efficient Implementation (SH2IFT).

1. Introduction

The consequences of a Boiling Liquid Expanding Vapour Explosions (BLEVE) can be devastating and as historical events show fatal due to both blast waves, fragment generation and if the contents of the vessel involved in the BLEVE are flammable, a strongly radiating fireball (Abbasi and Abbasi, 2007). BLEVEs of flammable liquids have been seen for a big range of fuels (Hemmatian et al, 2017) including liquefied natural gas (LNG) of which the effects of BLEVEs have recently been studied by Betteridge and Phillips (2015). The BLEVE phenomenon has been the topic of many investigations and reviews (see e.g. (CCPS, 2016).
There has also been confusion on the definition of a BLEVE as discussed by van den Berg et al. (2004) and van den Berg et al. (2006). These authors refer to a BLEVE as an explosive evaporation of a liquified gas as a consequence of the rupture of a pressure vessel containing this liquefied gas. The consequences are directly related to the evaporation rate of the liquified gas which implies the temperature of the liquid and the disintegration speed of the pressure vessel. Other authors define a BLEVE to be the rupture of a vessel containing a liquid above the superheat limit. For temperatures above the superheat limit the evaporation rate of the liquid can be described as instantaneous. Using different methods Ustolin et al. (2020) and Ustolin et al. (2019) estimated the superheat limit of hydrogen to be in the range of 26.2 – 32.4 K.
Hydrogen is one of the key energy resources in the future with a minimum of energy generated from fossil fuels. Liquefaction of hydrogen is considered as one of the most promising means for transportation and storage of hydrogen in large volumes in the light of its low density. A BLEVE of a vessel containing liquid hydrogen (LH_2) therefore is an accident scenario to consider (Rigas and Sklavounos, 2005). On the other hand, experimental investigation of LH_2 BLEVEs have hardly been performed. The only investigation performed and available in open literature is the work performed by Pehr (1996). Small LH2 tanks designed for automobiles containing 1.8 to 5.4 kg of LH2 were destroyed by means of cutting charges. The lack of experimental data is most probably

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related to the limited application of liquefaction. Perhaps also because a LH_2 BLEVE hazard was not viewed as a credible event thanks to its storage at cryogenic temperatures at relatively low pressure (Betteridge and Phillips, 2005). In fact, LH_2 is stored in double walled vacuum insulated vessels which will contribute to the reduction of the probability of BLEVEs as recently shown by an experiment where such a vessel (3 m^3) filled with LNG (filling degree 66 %) proved to be resistant against a realistic accident fire scenario for a period of at least 2 hours (the test was aborted after 2 hours) (Kamperveen et al, 2016). The current paper presents LH_2 experiments performed with medium-scale 1 m^3 storage vessels exposed to a fire load. The vessels were double-walled vacuum insulated vessels with a filling degree of approximately 35 % - 40 % (corresponding to approx. 25 kg – 30 kg of LH2).

2. Experimental set-up

The experiments were performed at the Test Site Technical Safety (TTS) of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, approximately 50 km south of Berlin. The Blast Area 2, which is especially used for safety related investigations on hydrogen, was used, a 400 m diameter flat circular area with a 80 m x 80 m concrete pad in the centre.

The 1 m^3 storage vessels were purchased from and produced by INOXCVA in Vadodara, India. Three vessels were produced: two horizontal vessels where one vessel was provided with perlite as insulation material in between the outer and inner vessel, and one with MLI (multi-layer insulation), while one vessel placed in a vertical position where the insulation material was again perlite (see Figure 1). The outer and inner vessels were made of low temperature resistant stainless steel (X5 CrNi 18-10). The thickness of the shell of the inner vessel is 3 mm and that of the outer vessel 4 mm. The thickness of the heads is always 5 mm. The maximum allowable working pressure of the vessels was 9 barg. The vacuum insulation in the space between the two walls was a medium vacuum with a pressure of 0.3 mbar. The safety valve provided on each vessel, was deactivated during the experiments to force a pressure build-up and a possible vessel burst.

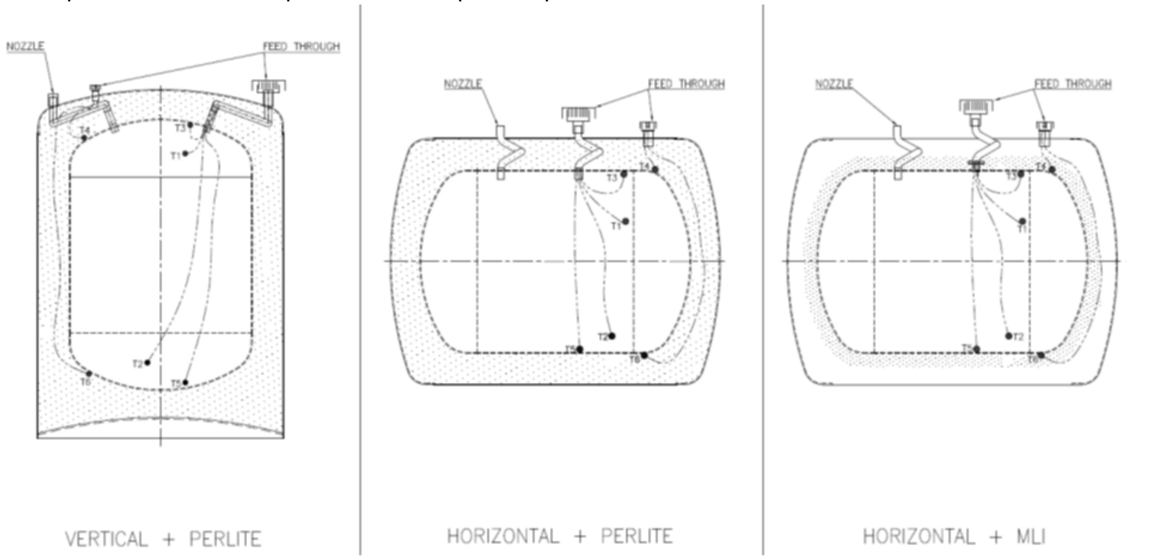


Figure 1: The layout of the three LH2 storage vessels used during the BLEVE experiments.

Measures were taken to protect vulnerable items from the propane flames, including thermocouple connections, flange gaskets and the piping in contact with flames. All these vulnerable items were insulated using glass wool. The thermocouples were led away from the vessel using scaffold (See Figure 2c).

The liquified hydrogen was transported to the test site by a trailer (sourced from Air Liquide). The vessels were directly filled from this trailer via a flexible double-walled vacuum insulated hose. Before filling the whole system was flushed with helium to avoid ignitable atmospheres within the filling system and the tank. During an initial phase the tanks had to be cooled down, which occurred by means of the flashing LH2 entering the tank.The filling was controlled by weight and pressure measurements. During the filling process the vessel was placed on load cells and the amount of filled hydrogen was additionally controlled by a differential pressure sensor, controlling the hydrostatic pressure built-up inside the tank.

The heat load applied to the vessels was provided by an array of 36 propane burners (See Figure 2b) located underneath the vessels providing a heat load of approximately 100-150 kW/m^2 (propane consumption rate 4.3 kg/min). Since the array of burners cannot withstand the load caused by a failing storage vessel three such burner arrays were prepared for each test. The propane was provided from a storage vessel at some distance from the vessel protected by a concrete wall (see Figure 2a). The burner has been designed to give a fire load of the storage vessel from all sides.

(a) (b) (c)

Figure 2: (a) propane tank, (b) propane burners and (c) one of the storage vessels (horizontal with MLI) before a BLEVE test showing the insulation used to protect valves and thermocouples on top of the vessel led away via scaffold.

Three tests would be performed varying the following parameters:

- Orientation of the vessel
- Insulation material (Perlite or MLI)

The test program, therefore, is as shown in Table 1:

Table 1: Test program

Degree of filling of vessel	Orientation of vessel	Insulation
35-40%	Horizontal	Perlite
35-40%	Horizontal	MLI
35-40%	Upright	Perlite

3. Instrumentation

For each test, similar instrumentation was used to record temperatures, pressures, heat radiation and video.
All vessels were equipped with K-type thermocouples at several locations: inside the inner vessel in the gas phase and the liquid phase, on the inner and outer side of the inner vessel and on the inner and outer side of the outer vessel. The pressure inside the inner vessel (both in liquid, as a level indicator, and gaseous phase), and in the space between the inner and outer vessels (vacuum pressure) was measured.
Bolometers were used to measure the heat radiation generated by both the propane fire and that generated by a possible fireball/BLEVE. To measure blast generated by the vessel burst/BLEVEs blast pencils were positioned at three locations in two directions. Weather conditions were monitored at two weather stations. Further several cameras were used to monitor the events: normal cameras, infrared (IR)-cameras, high-speed cameras also on board of a drone.

4. Results

4.1 General

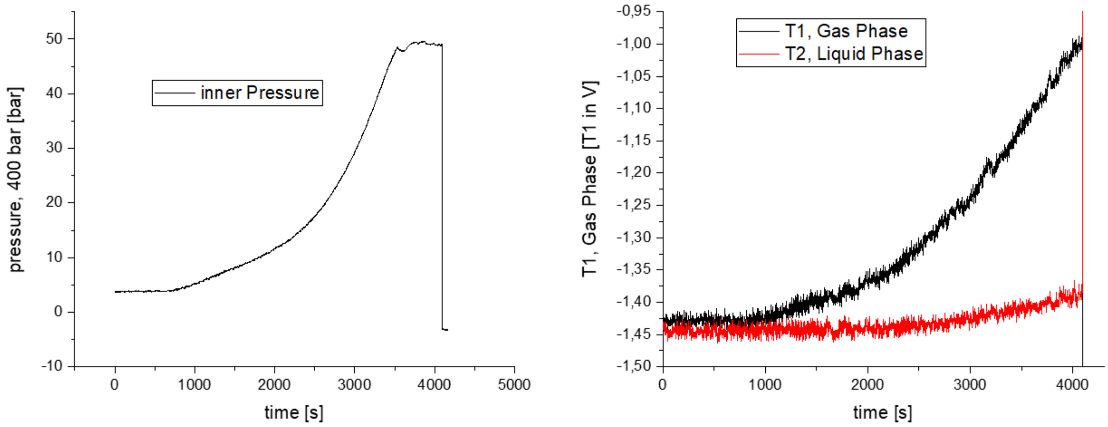
The first test was performed with the perlite insulated vessel positioned horizontally. The vessel withstood the fire during a period of 1 hour and 20 minutes upon which the test was aborted. After approximately 50 minutes the outer vessel imploded partly probably due to weakening provoked by the exposure to high temperatures and the vacuum in the space between outer and inner wall. The vessel started leaking via the seal of one of the valves on top of the vessel after approx. 1 hour 15 minutes. This resulted in a hydrogen jet fire visible on the IR cameras and also by regular video due to the propane fire underneath the vessel. Upon abortion of the test by shutting down the propane supply and extinguishing the propane fire, the hydrogen jet fire continued but invisible to the eye, detectable only with the IR-camera systems on site. The leakage caused the pressure inside the vessel to decrease considerably (from a maximum of 23.5 bar down to 10 bar within 300 s and down to 1 bar within 1000 s). This finally leading to the decision to abort the test, as the inner vessel pressure decreased so considerably that a vessel burst was impossible to achieve.

The second test was performed with the MLI insulated vessel. This vessel also started leaking after approximately 40 minutes. Although in this case the leakage occurred at a different position, so that this time no jet flame was observed at the vessel, as the released hydrogen was vented through a blow-off line exiting far away from the fire. The leakage led to a stop of the increase of the inner pressure in the vessel, which then stayed constant at nearly 50 bar. After slightly longer than 1 hour the vessel failed to cause a fire ball, blast waves and fragments. Details of this test are presented below.

The third test was performed with the perlite-insulated vessel positioned vertically. The vessel was exposed to the propane fire during 4 hours without critical failure. The test had to be aborted because of the lack of propane feeding the fire underneath the vessel. At the moment the test was aborted the pressure inside the vessel was 60 bar. As for the horizontal perlite tank, this vessel's outer shell also imploded after a relatively short period into during the test.

4.2 Results of test where a full rupture of the test vessel was observed

In the second test, the vessel (an MLI-insulated vessel positioned horizontally containing 27 kg of LH2) failed after 68 minutes of exposure to the described fire load. Shortly before the failure the vessel started leaking through a valve causing the pressure to stop increasing but staying more or less constant at a value of about 50 bar (See Figure 3a).



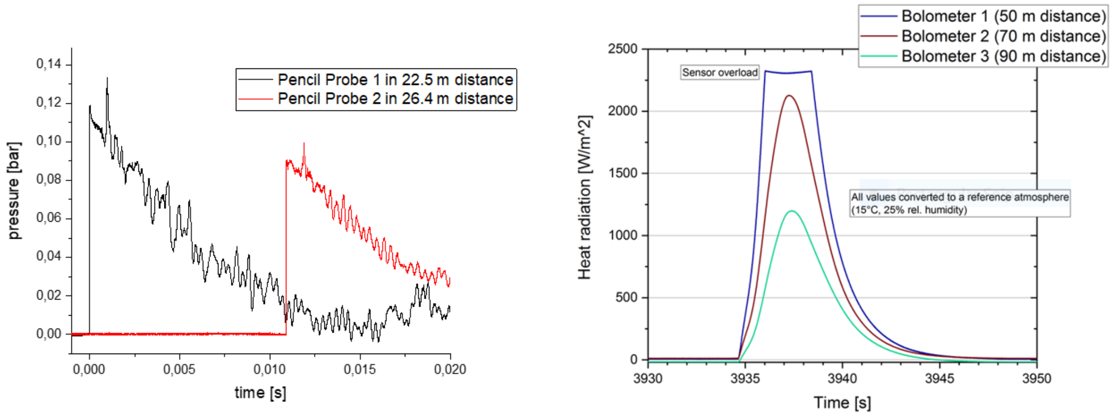
(a) (b)

Figure 3: (a) Pressure inside the gas phase and (b) temperatures measured in the gas and liquid phases of the MLI-insulated vessel positioned horizontally measured during the whole test duration. The temperatures at the moment of the rupture are estimated to be -245°C for the liquid phase and -180°C for the gas phase. At the moment of start of the experiment these temperatures were -253°C and -250°C respectively.

The temperature readings are to be confirmed; calibration of the thermocouples at these low temperatures appears very difficult and is still ongoing. The pressure inside the vessel is higher than expected on the basis of the estimated temperature of the liquid (using the Antoine equation given in (NIST, 2021)) indicating a non-equilibrium condition. The estimated temperature of the liquid hydrogen at the moment of failure of the vessel was within the superheat limit range of hydrogen (26.2 – 32.4 K) estimated with different methods (Ustolin et al., 2020) and below the critical temperature of hydrogen. Hence the explosion could have been a supercritical BLEVE (Ustolin et al. (2020). To be able to confirm this, a more detailed data analysis is ongoing.

During the test, the vacuum in between the two vessels slowly decreased. Just before the failure of the vessel the pressure in the space between the inner and outer vessels had increased up to 56 mbar. A few milliseconds before the failure of the inner vessel, the vacuum suddenly was completely lost. This leads to the assumption, that the vessel failure might be closely linked to the loss of vacuum. The latter supposedly caused by the failure of an O-ring at the filling opening for the perlite, causing a sucking in of hot gases from the surrounding fire.

The failure of the vessel resulted in fragmentation of the vessel, a fireball and a blast wave. Fragments were thrown up to about 200 m from the original position of the vessel. Larger parts (6) of the vessel were found at distances between 6 m and 35 m from the original position. Blast waves show at least two peaks occurring shortly after one another as can be seen in Figure 4a. At 22.5 m from the tank a maximum pressure of 133 mbar was measured and at 26.4 m 99 mbar.



(a) (b)

Figure 4: (a) Blast waves measured at distances of 22.5 m and 26.4 m and incident heat radiation measured at distance of 50 m, 70 m and 90 m from an MLI-insulated vessel positioned horizontally upon failure of the vessel after a 1 hour and 6 minutes exposure to a propane fire.

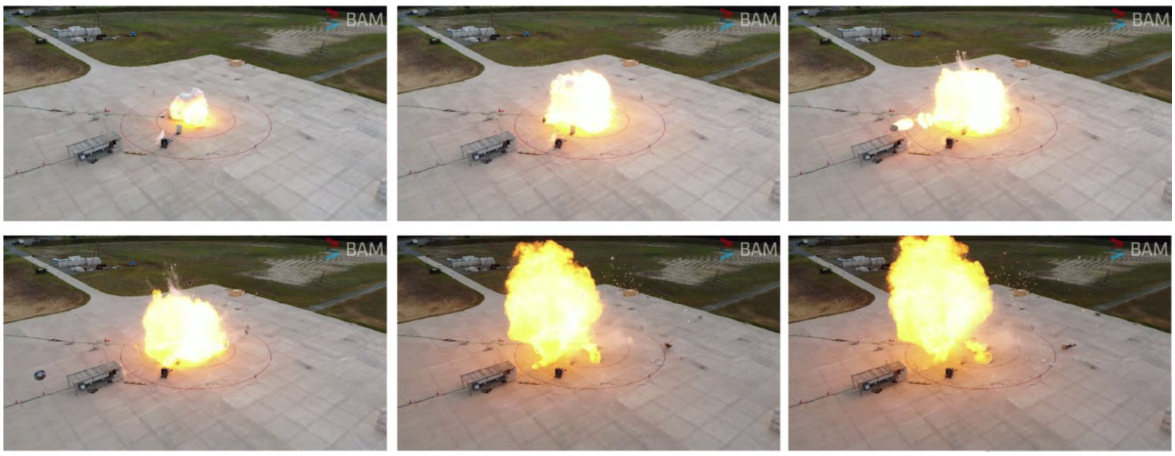


Figure 5: Fireball development after the failure of an MLI-insulated vessel positioned horizontally filled with liquified hydrogen a seen from a drone flying over the test pad.

The fireball development is shown in Figure 5 (recording taken from a drone).
The maximum fireball diameter is about 20 m. The total duration of the fire ball is about 5 s with lift-off occurring after 2s. Maximum incident heat radiation levels of 2.1 kW/m^2 at 70 m and 1.2 kW/m^2 at 90 m (the bolometer measurement results are presented in Figure 4b) were reached. The Bolometer at 50 m distance was in overload mode with incident heat radiation exceeding 2.4 kW/m². The bolometer distances are measured from the vessel centre point. With a fireball of approx. 20 m diameter the distances between radiating surface and bolometer have to be decreased by approx. 10 m.

5. Conclusions

Three double-vacuum insulated pressure vessels containing liquified hydrogen were exposed to a propane fire. Two of these vessels, a horizontal and a vertical vessel both insulated with perlite withstood the fire loading during 1 hour 20 minutes and 4 hours respectively without failing. A horizontal vessel insulated with MLI failed after 1 hour and 6 minutes resulting in a fireball, fragments and blast waves. In the test where the vessel burst occurred a maximum fireball diameter of about 20 m was seen. The total duration of the fireball was about 5 s with lift-off occurring after 2 s. Maximum incident heat radiation levels of 2.1 kW/m^2 at 70 m and 1.2 kW/m^2 at 90 m were measured. Fragments were thrown up to about 200 m from the original position of the vessel. Larger parts (6) of the vessel were found at distances between 6 m and 35 m from the original position. The resulting blast waves show at least two peaks occurring shortly after one another with maximum pressures of 133 mbar at 22.5 m from the vessel and 99 mbar at 26.4 m. An assessment made on the basis of the preliminary results of internal pressure and temperature measurements at the moment of failure indicate that the liquid hydrogen inside the vessel was above the most conservative value of superheat limit of hydrogen at that moment.

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