Experiments to investigate the possibility and effects of BLEVEs of storage tanks containing liquified hydrogen

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BLEVE (Boiling Liquid Expanding Vapour Explosion)

“Definition”

Rupture of vessel containing a liquid at a temperature well above its boiling point at atmospheric temperature

Consequences: blast, fragments and in case of flammable liquid: radiating fireball

Discussion

Definition varies: consequences are directly related to the evaporation rate of the liquid which implies the temperature of the liquid and the disintegration speed of the pressure vessel (van den Berg, 2004)

Highest evaporation rate when liquid is above its superheat limit at moment of vessel rupture, condition which is often referred for definition of BLEVE. Superheat limit hydrogen is 29.7 K (depends on way this temperature is determined)

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BLEVE of storage vessels containing LH2

- Previous work: only investigation performed and available in open literature are performed in small tanks designed for automobiles containing 1.8 to 5.4 kg of LH2 opened by means of cutting charges (Pehr (1996))
- LH2 is stored in double walled vacuum insulated vessels which will contribute to the reduction of the probability of BLEVEs (demonstrated in experiment for double-walled vessel containing LNG (Kamperveen et al, 2016)).

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LH2 BLEVE experiments; vessels

- Three medium-scale double-walled vacuum insulated 1 m^3 storage vessels
- Vessels were produced by INOXCVA, Vadodara, India
- Two types of insulation were applied: perlite and MLI
- Vacuum pressure was 0.3 mbar
- Material outer and inner vessel: low temperature resistant stainless steel (X5 CrNi 18-10)
- Thickness of the shell of the inner vessel is 3 mm, outer vessel 4 mm, heads 5 mm
- Maximum allowable working pressure of the vessels was 9 barg.

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LH2 BLEVE experiments: vessels

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LH2 BLEVE experiments: programme of work

Test no	Degree of filling level [%]	Amount of LH2 (kg)	Vessel orientation	Insulation material
1	35-40	25-30	Horizontal	Perlite
2	35-40	25-30	Horizontal	MLI
3	35-40	25-30	Upright	Perlite

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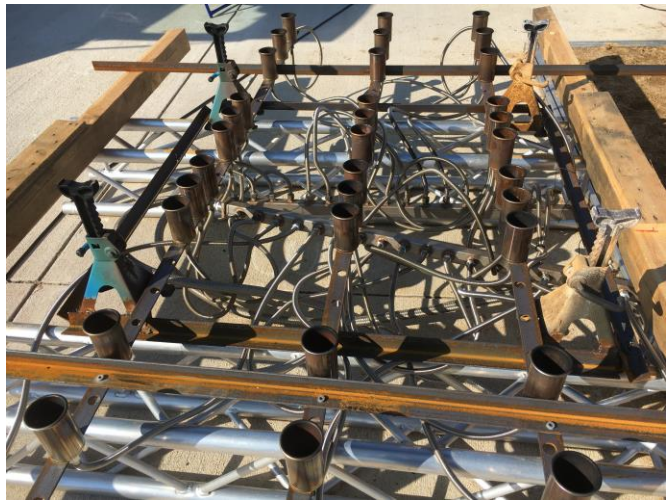
Experimental set-up

- 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, Germany
- 400 m diameter flat circular area with an 80 m x 80 m concrete pad in the centre
- An observation bunker at about 200 m distance from the centre of the test pad is used for controlling and monitoring the tests from a safe
- LH2 was supplied from a road tanker via a flexible double-walled vacuum-insulated hose.
- Vessels and flexible hose were inerted using helium before filling
- The amount of hydrogen in the vessels were monitored by load cells and a differential pressure sensor measuring the hydrostatic pressure built-up inside

Experimental set-up

Propane burner

- To provoke a BLEVE the vessels were heated by a propane fire
- An array of 36 propane burners was located underneath the vessels
- Heat load provided is approximately 100-150 kW/m^2 (mean propane consumption rate 4.3 kg/min)



Propane burner

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Measurements

Item/Sensor	Number	Description
Gas sensor for H2	4, on in each orientation	NEOHYSENSE NEO974A
Heat radiation sensor	each in 70 m, 90 m and 110 m	Medtherm, Model 64-XX-14
Inner pressure	2	1 absolute Keller PA-10 1 differential Keller PD-23
Thermocouple	14	Type K, 1.5 mm with Inconel mantle
UAV	1	DJI M300 RTK, optical and IR
IR-Camera	1	FLIR E 95
Load cells	4	MTS VC 3500
Blast sensors	Up to 3	Kistler Pencil Probe, type 6233A
Action cams	Up to 5	GoPro, 4K
Optical camera	1	Canon EOS 1DX

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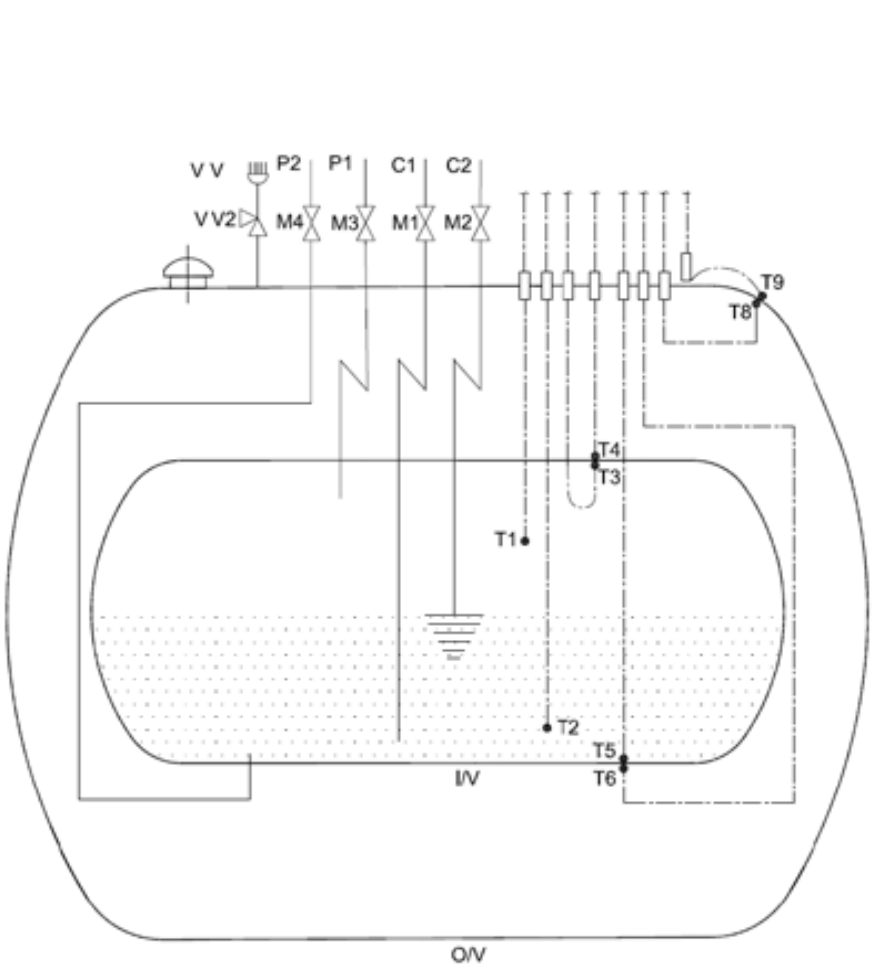
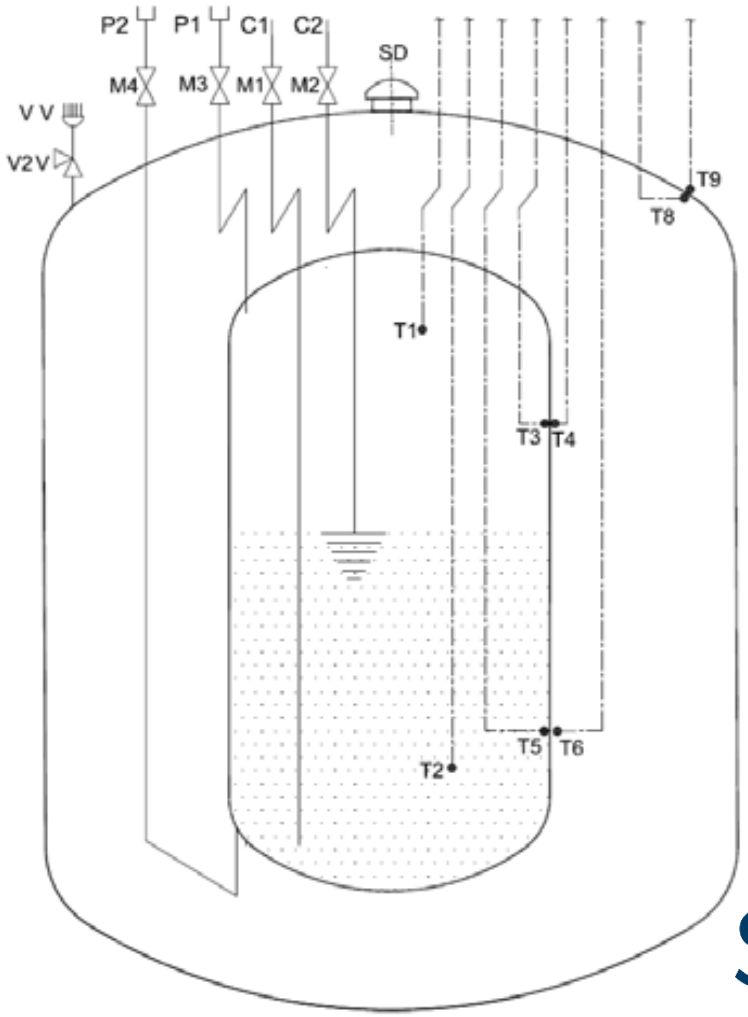
Measurements on vessel





Results test 1: horizontal vessel with perlite insulation

- Total test duration: 1 hour and 20 minutes,
- Outer shell imploded after approximately 50 minutes
- After approx. 1 hour 15 minutes leak via the seal of the blind flange connection at the filling valve on top of the vessel. Resulted in jet fire and pressure drop from 23.5 bar down to 10 bar within 300 s and down to 1 bar within 1000 s.

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Results test 2: horizontal vessel with MLI insulation

- This vessel was filled with about 27 kg of LH2
- Leak after approximately 40 minutes at cryogenic valve equipped with a pneumatic actuator, which opened at about 50 bar
- Vacuum pressure slightly increased up to 56 millibar
- Vessel failure after 68 minutes causing a fire ball, blast waves and fragments.

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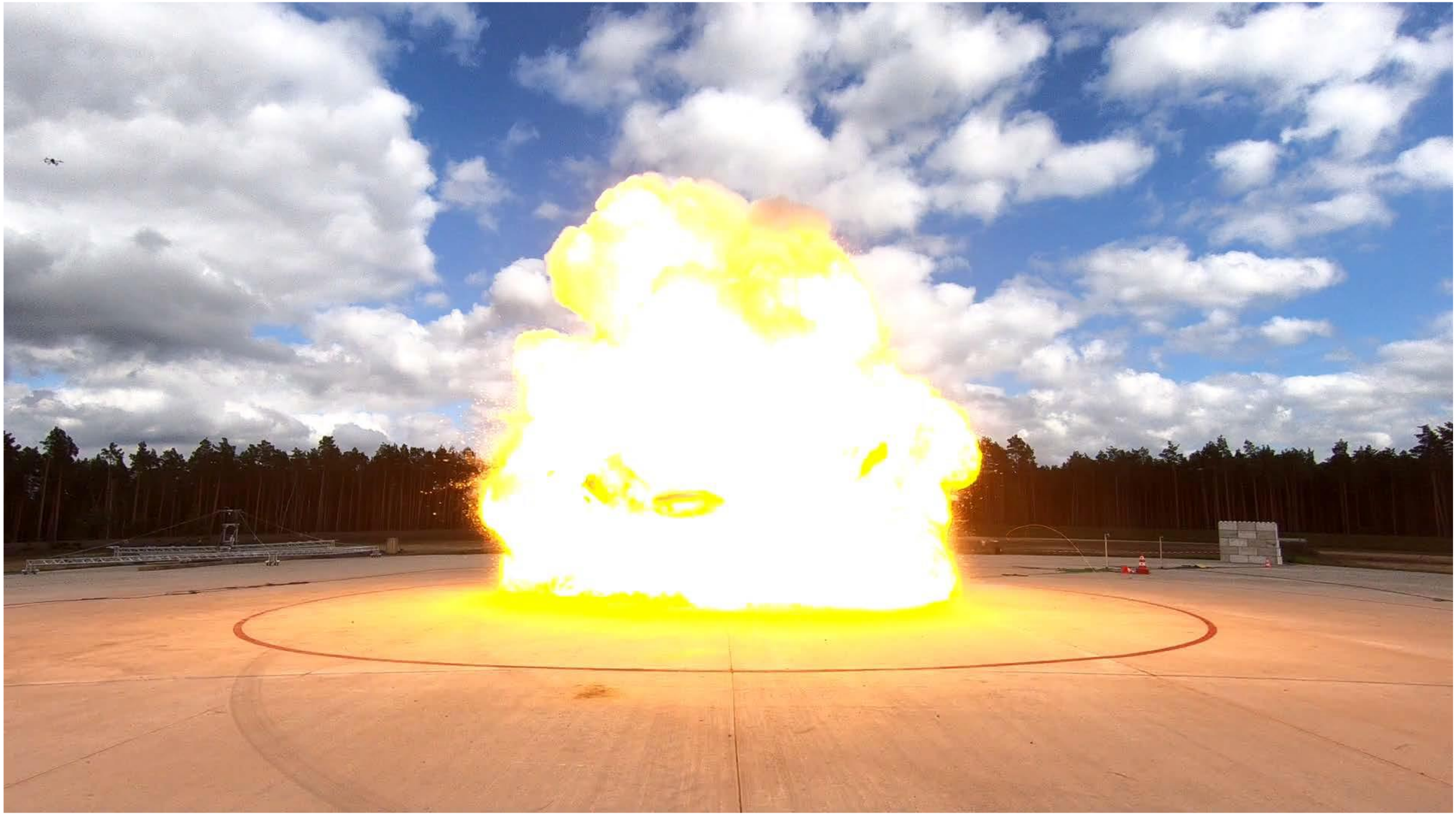
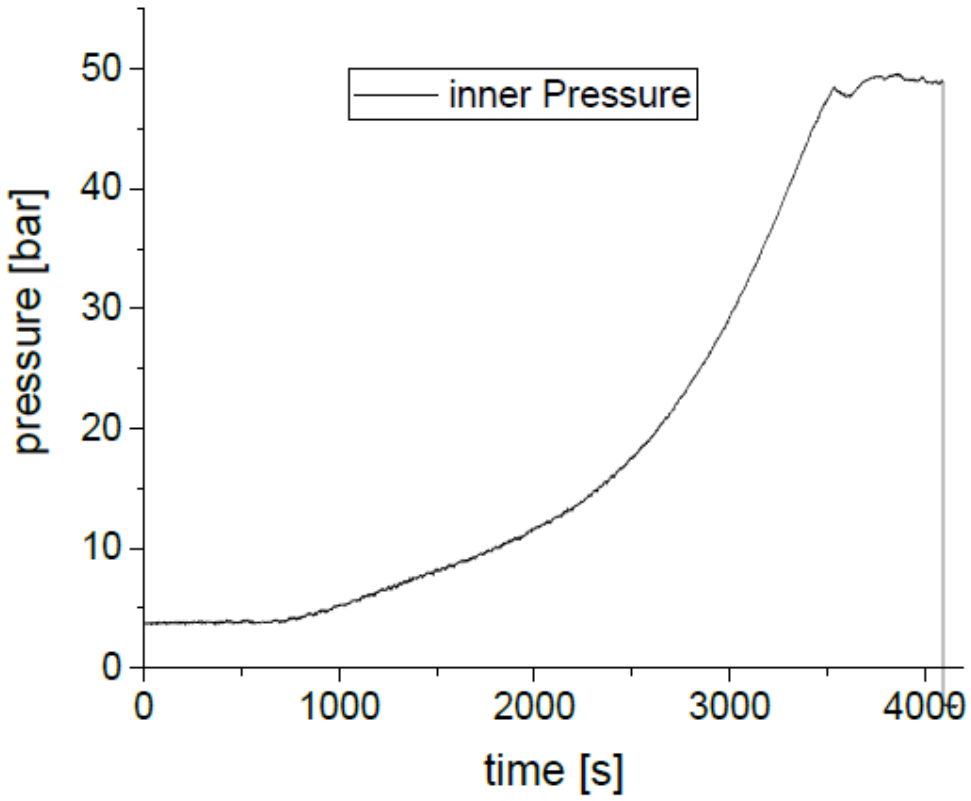
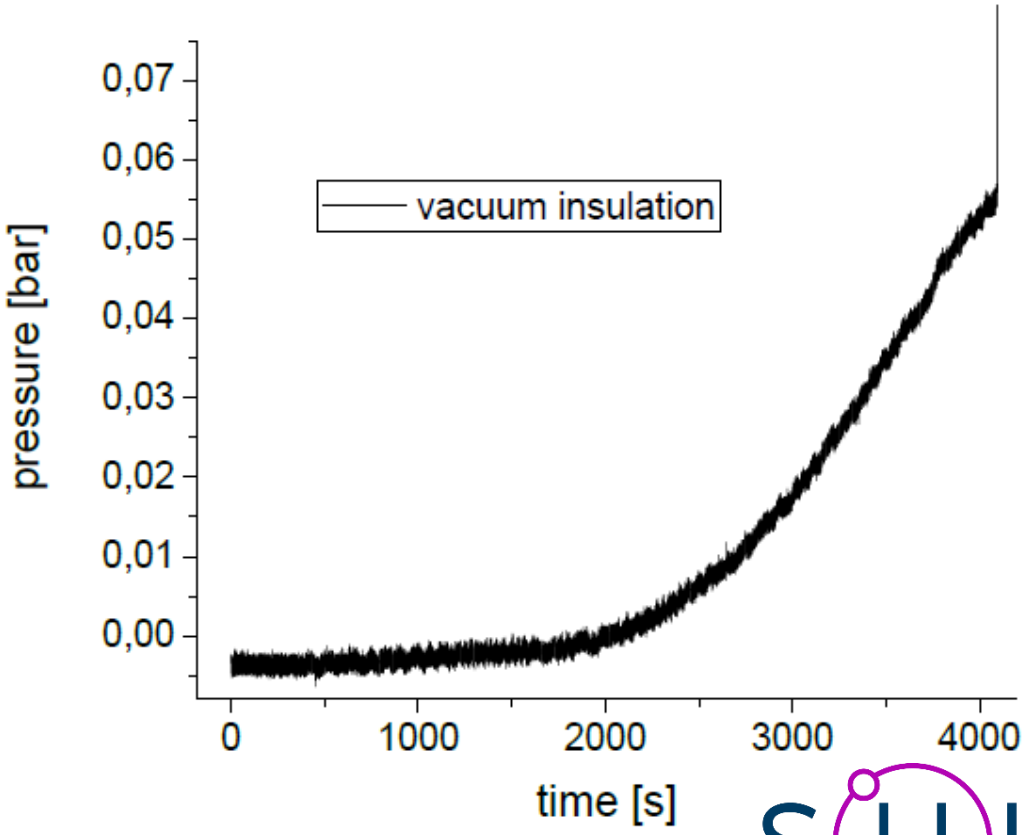


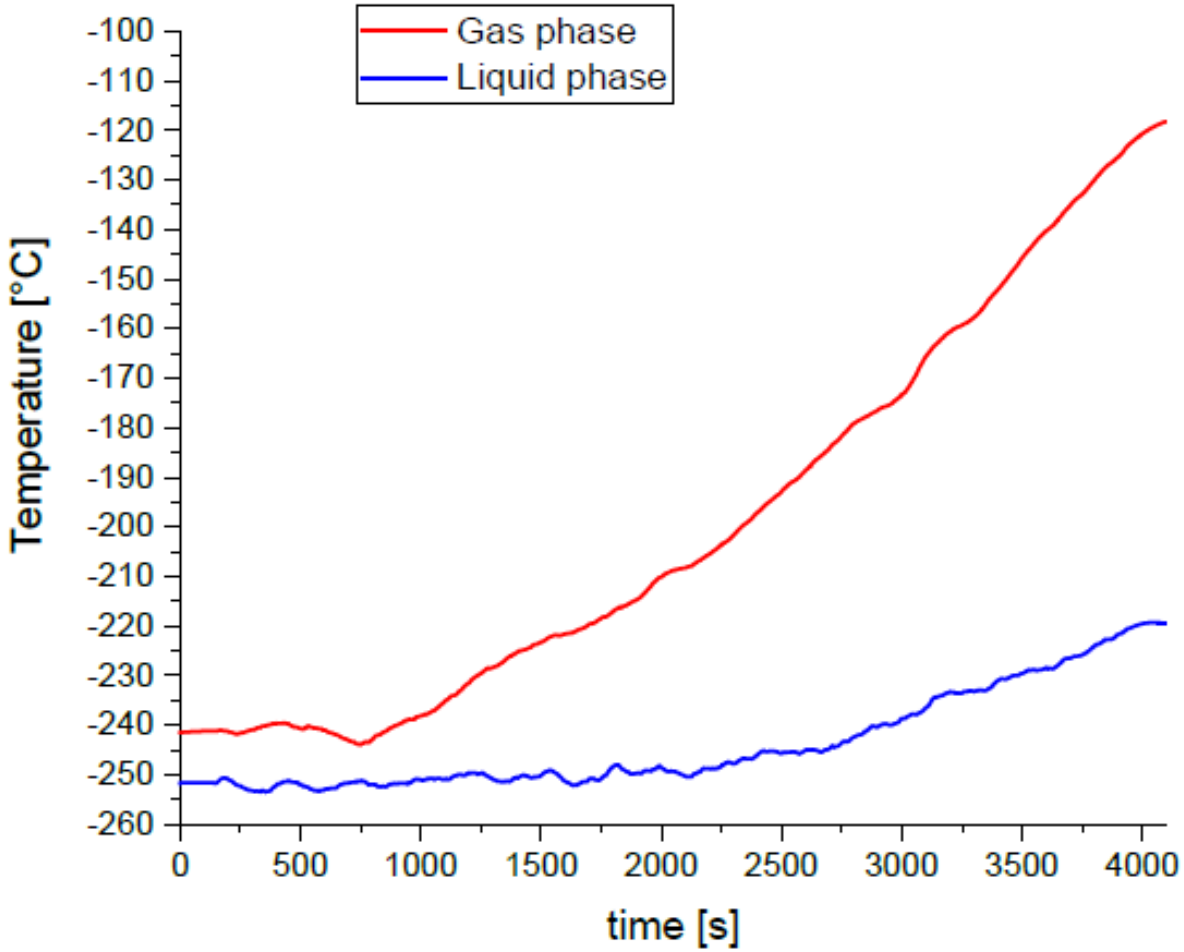
Pressure in gas phase in inner vessel and vacuum pressure in between walls



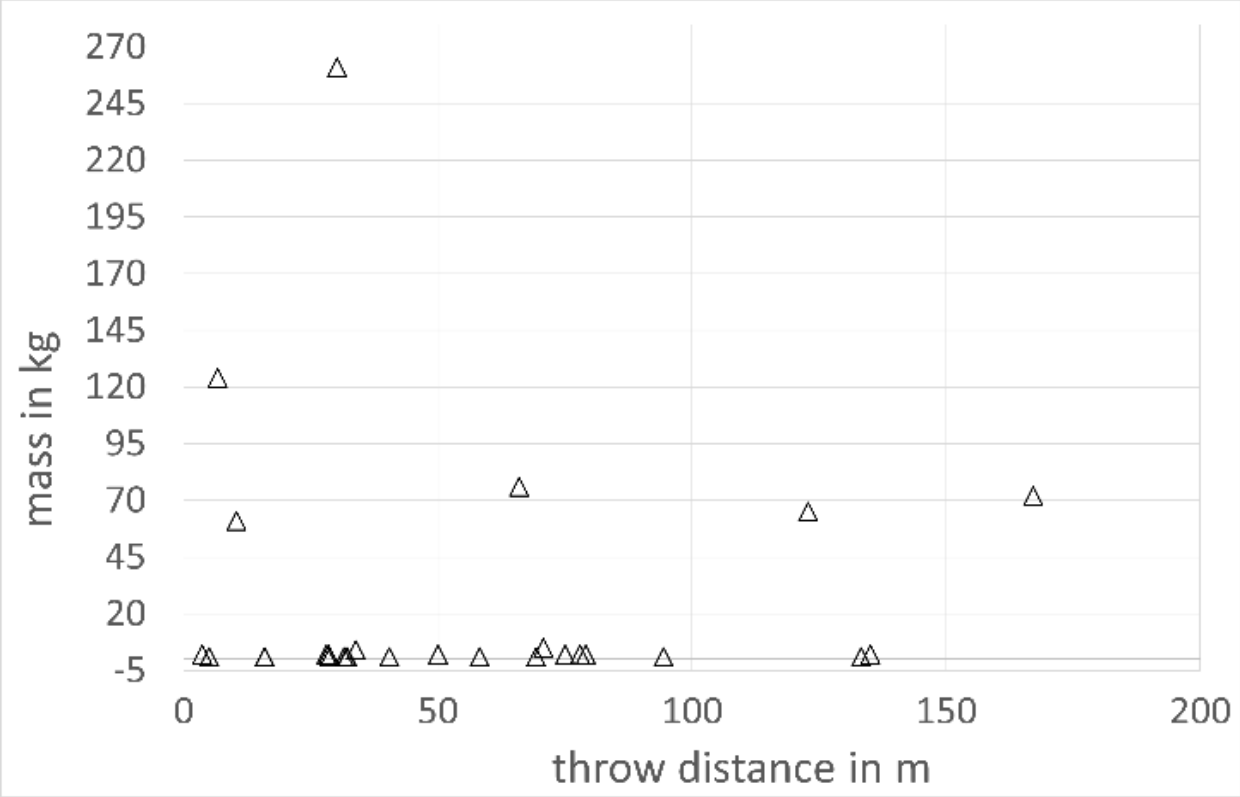


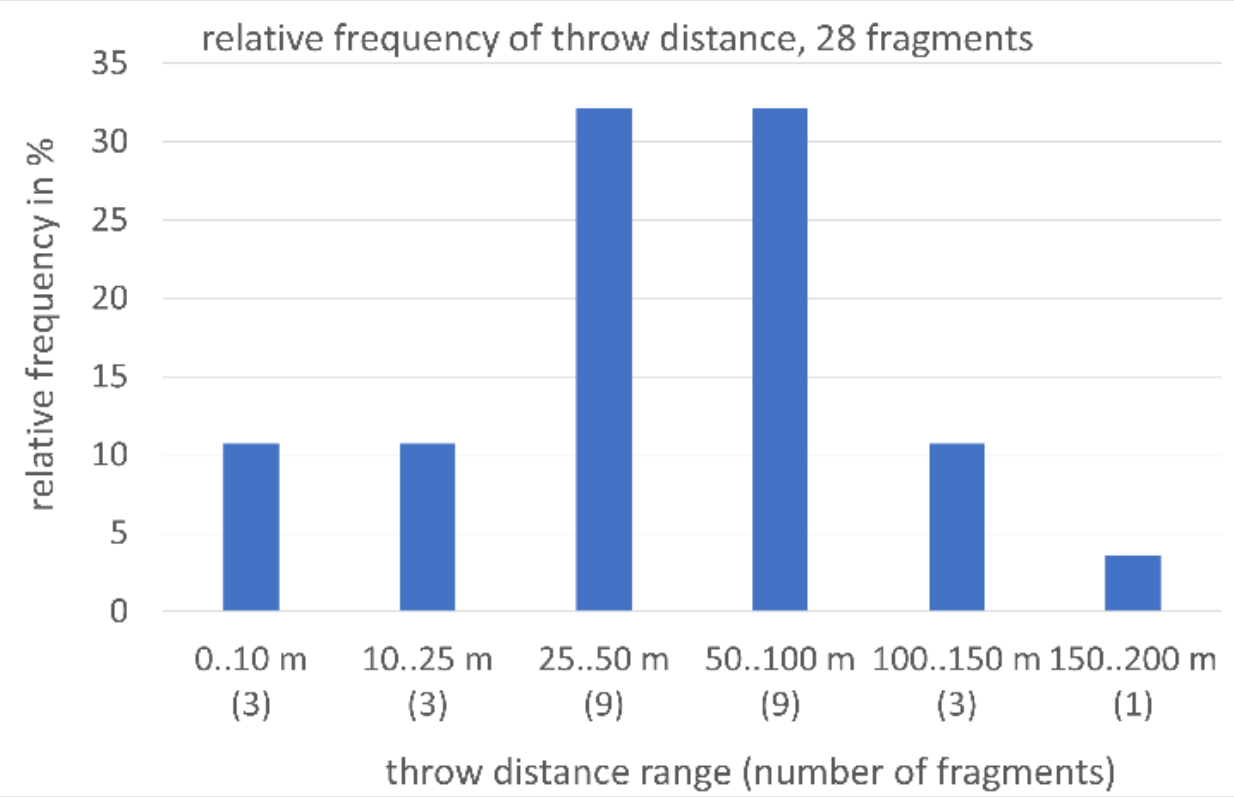
Temperatures in gas phase and liquid phase in inner vessel

Pressure in vessel is higher than expected on the basis of liquid temperature indicating a non-equilibrium condition



Fragments





28 fragments

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Fireball

- Fireball has irregular shape with maximum dimensions of about 24.2 m x 31.2 m
- Average maximum diameter 25.8 m
- Total duration about 5 s
- Lift-off after 2 s

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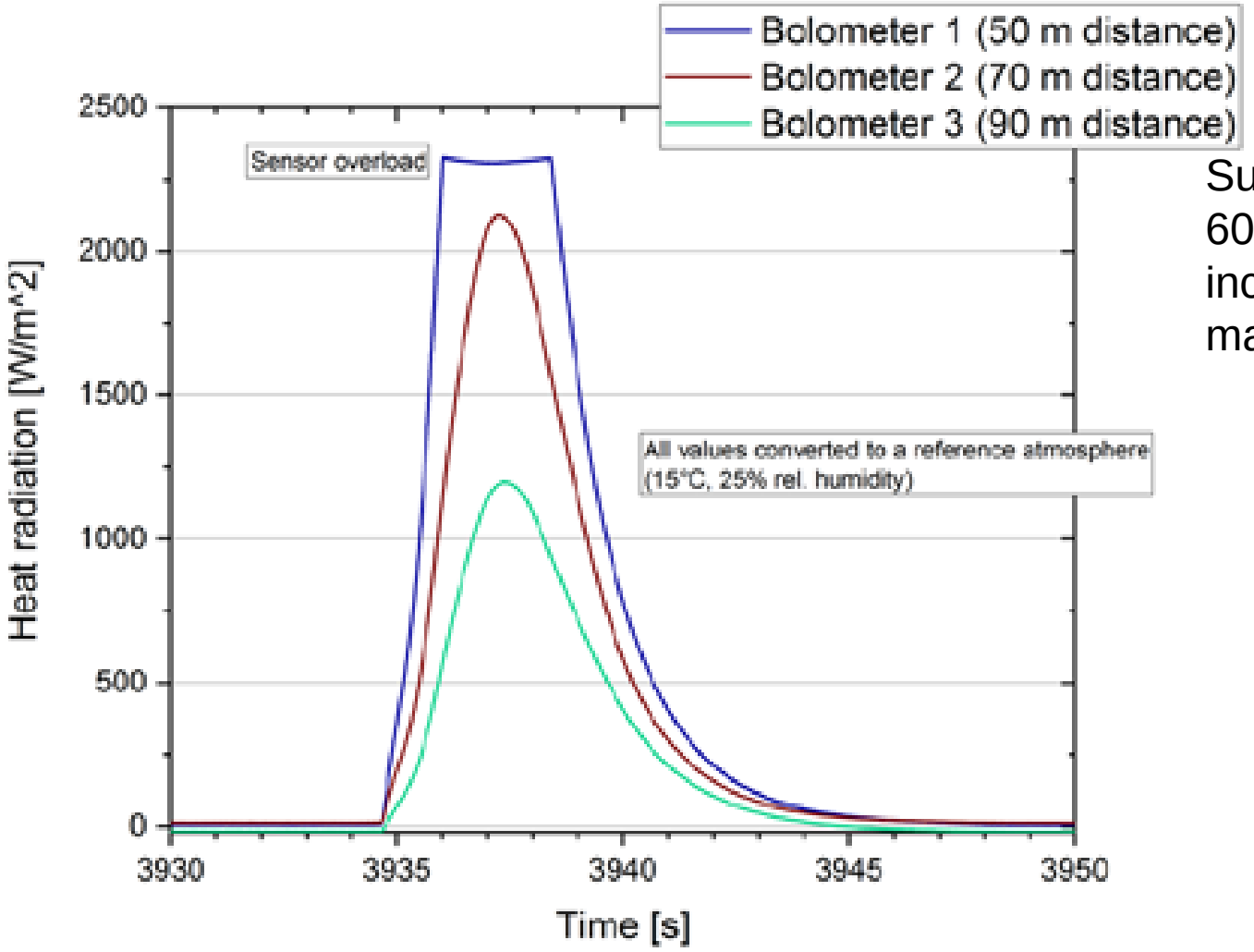
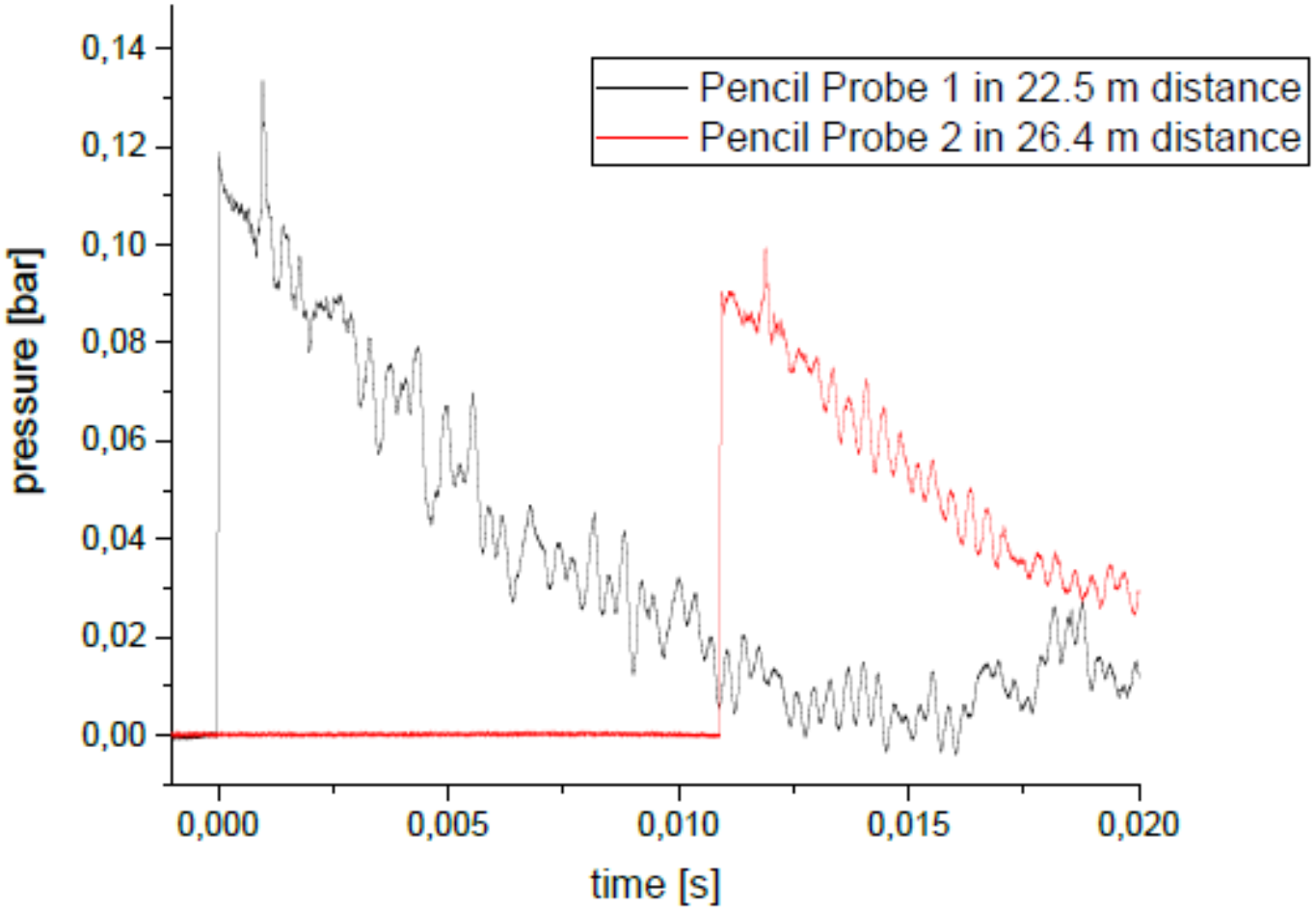
Radiation



Surface emissive power of hydrogen fire ball 60 kW/m^2 at a maximum based on incident radiation at 70 m and 90 m and maximum fireball diameter of 25.8 m

Blast

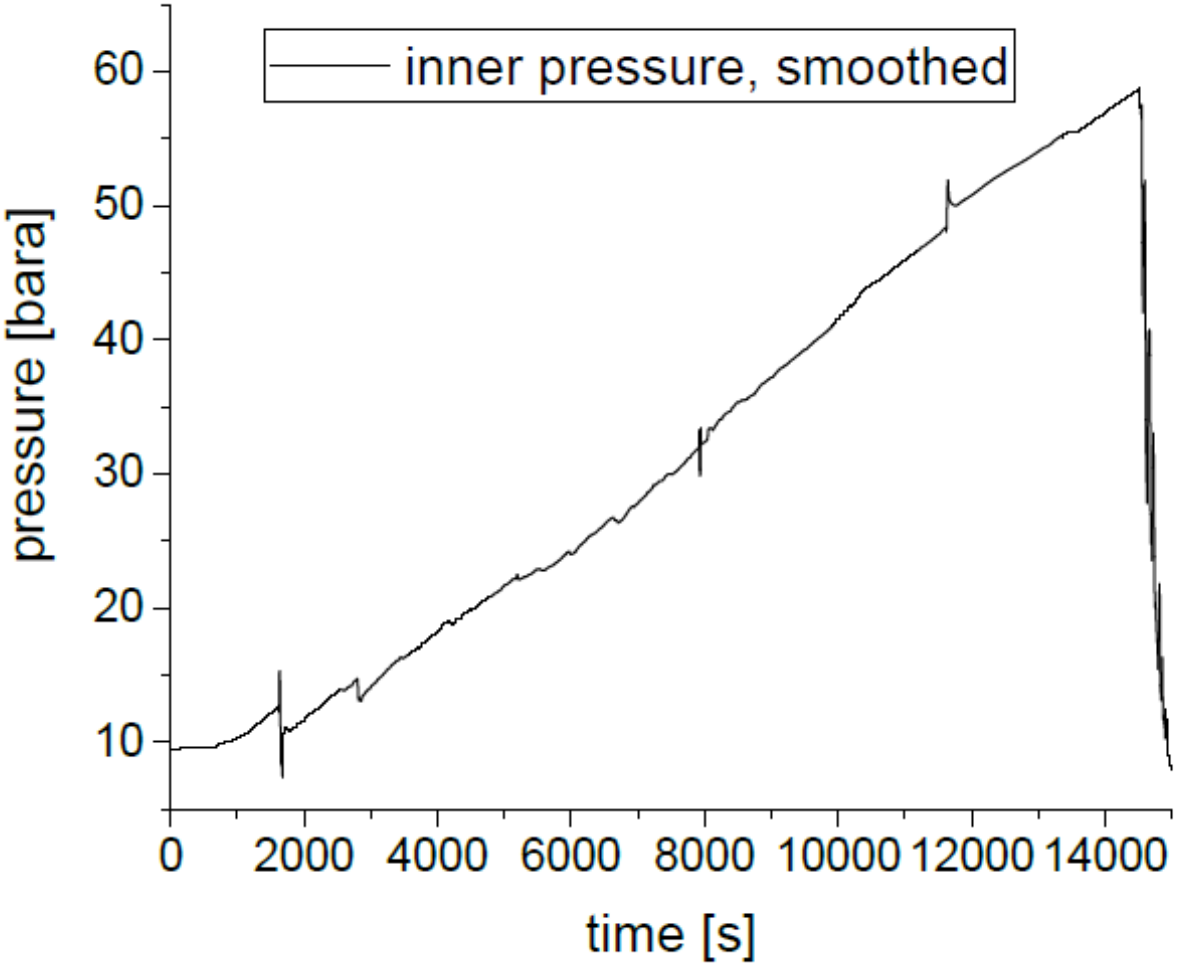


Three peaks: gas expansion,
liquid evaporation,
combustion

Test 3: upright vessel with perlite insulation

- Total test duration: 4 hours
- Outer shell imploded after relatively short period
- No leakage occurred
- Steady increase of internal pressure up to 60 bar

Steady increase of internal pressure up to 60 bar



Conclusions

- Three 1 m^3 double-walled, vacuum insulated pressure vessels containing liquid hydrogen (25-30 kg) were exposed to a propane fire.
- Two of these cryo-vessels, a horizontal and an upright one, both insulated with perlite, withstood the engulfing fire for 1 hour 20 minutes and 4 hours respectively without a catastrophic failing of the vessel but strong deformations of the outer shell.
- The horizontal vessel insulated with MLI failed after 1 hour and 6 minutes resulting in a fireball, fragmentation of the vessel and blast waves.
- A fireball with a maximum equivalent diameter of about 25.8 m and a maximum emissive power of 60 kW/m^2 was formed. The total duration of the fire ball was about 5 s with lift-off occurring after 2s
- The resulting blast waves show at least three peaks occurring shortly one after another with a maximum pressures of 133 mbar at 22.5 m

Acknowledgement

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Thank you!

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