NTNU
Norwegian University of Science and Technology

SH2IFT

Consequence Analysis of Liquid Hydrogen Tank Explosion

Green Hydrogen Webinar

Federico Ustolin

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Content

- Introduction on BLEVE and modelling activity
- Liquid CO_2 explosion experiments
- BMW safety tests on liquid hydrogen
- LH_2 BLEVE CFD analysis by using ADREA-HF
  - ADREA-HF code validation
  - Simulation of BMW bursting tank test
- Conclusions

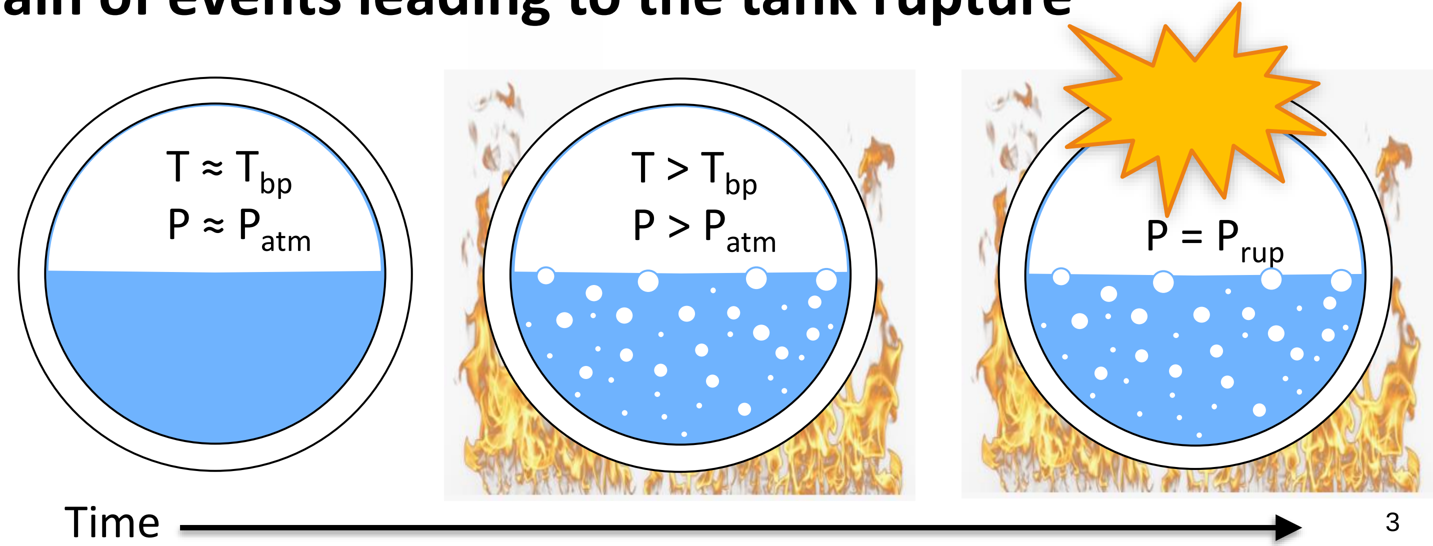
BLEVE

Boiling Liquid Expanding Vapour Explosion:

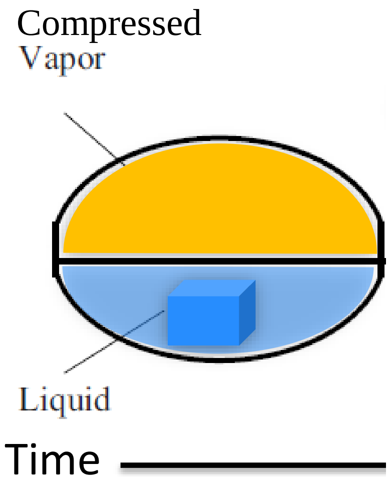
physical explosion might result from the catastrophic rupture of a tank containing a superheated liquid due to the rapid depressurization

Chain of events leading to the tank rupture

Valid for cryogenic substances



BLEVE



$$P$$

$$T = T_s(P)$$

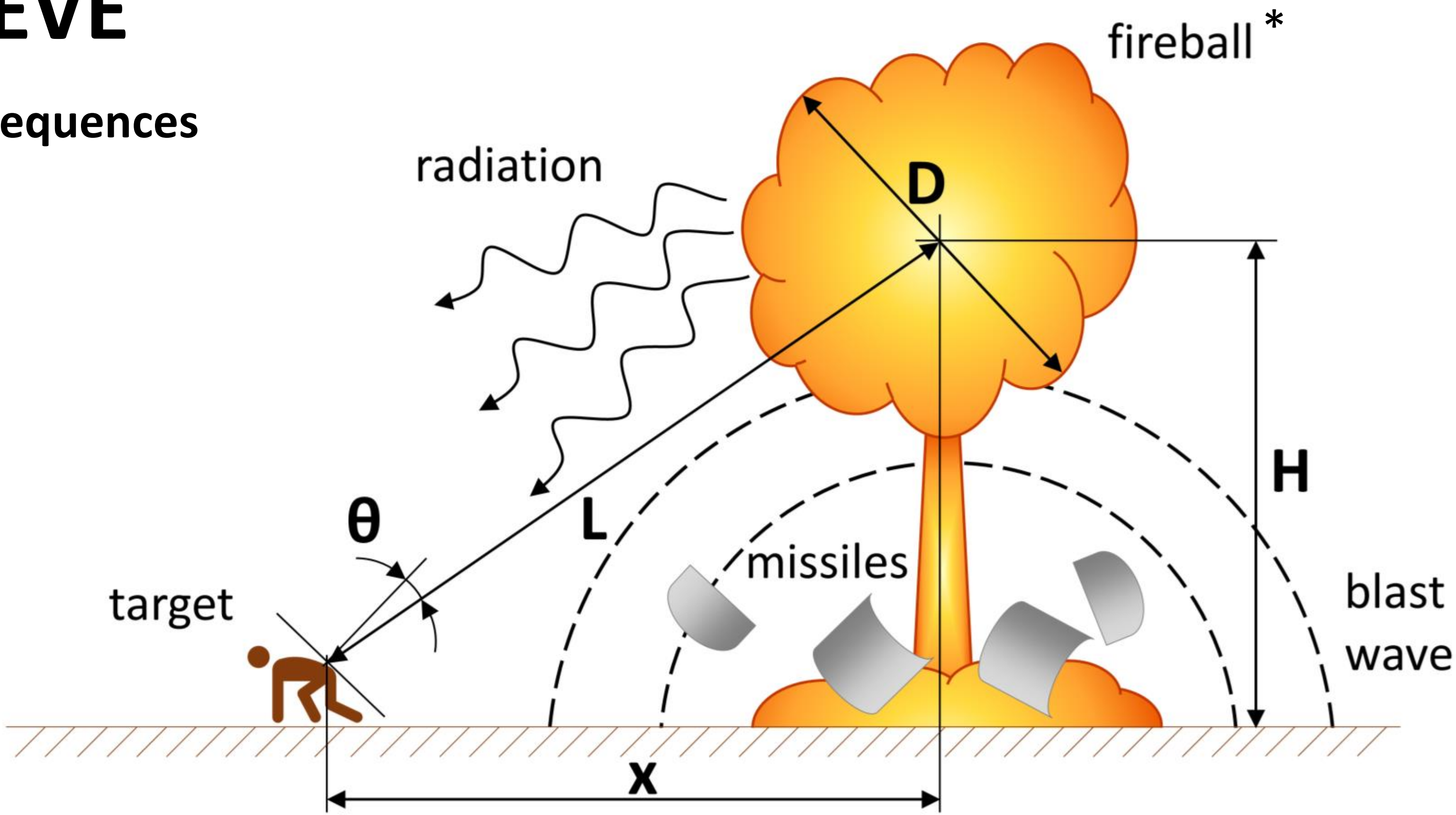
$$h_l = h_l(T)$$

$$h_g = h_g(T)$$

Hot liquid undergoing sudden depressurization in a tank
(adapted from [Casal, 2008])

BLEVE

Consequences



*Fireball if substance is flammable and ignition source is present

Modelling activity

Collaboration with **PRESLHY** project partner National Centre for Scientific Research "Demokritos"

Aim of the work: provide critical indications on the BLEVE theory

- CFD analysis of BLEVE for liquid CO_2 (LCO_2) and liquid hydrogen (LH_2) tanks
- Study the dynamic of the blast wave (no combustion)

Liquid CO_2 explosion tests

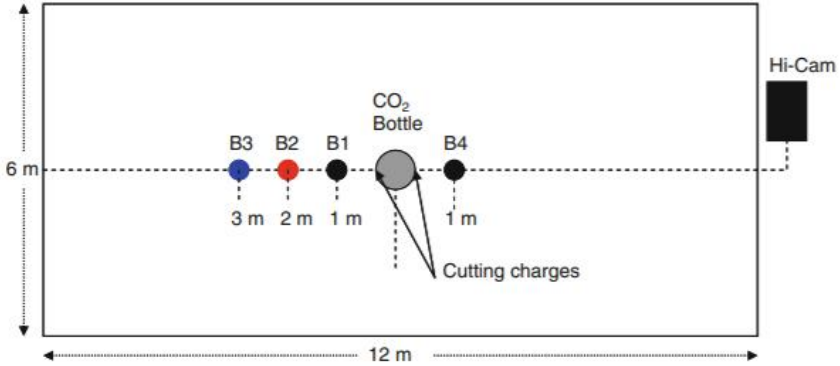
Laboratory for Ballistic Research (TNO Defence, Security and Safety)

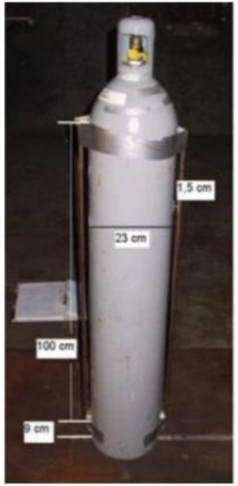
Bunker: 6 × 12 × 4 m

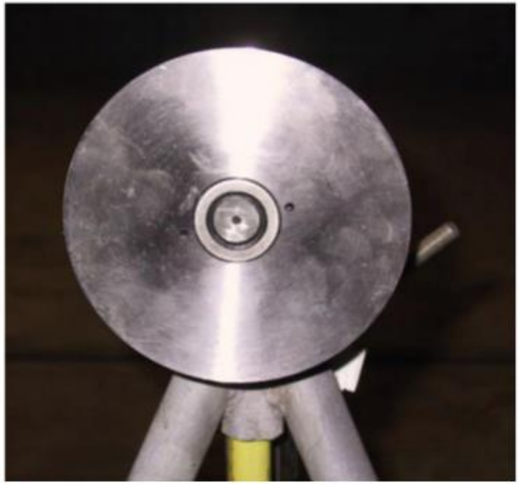
40-l LCO_2 bottle wrecked by explosive:

- D = 0.23 m
- h = 1.37 m
- fd = 95%
- T = 290 K
- P = 5.2 MPa

[van der Voort, M.M., van den Berg, A.C., Roekaerts, D.J.E.M. et al. Blast from explosive evaporation of carbon dioxide: experiment, modeling and physics. Shock Waves 22, 129–140 (2012)]







BMW safety tests

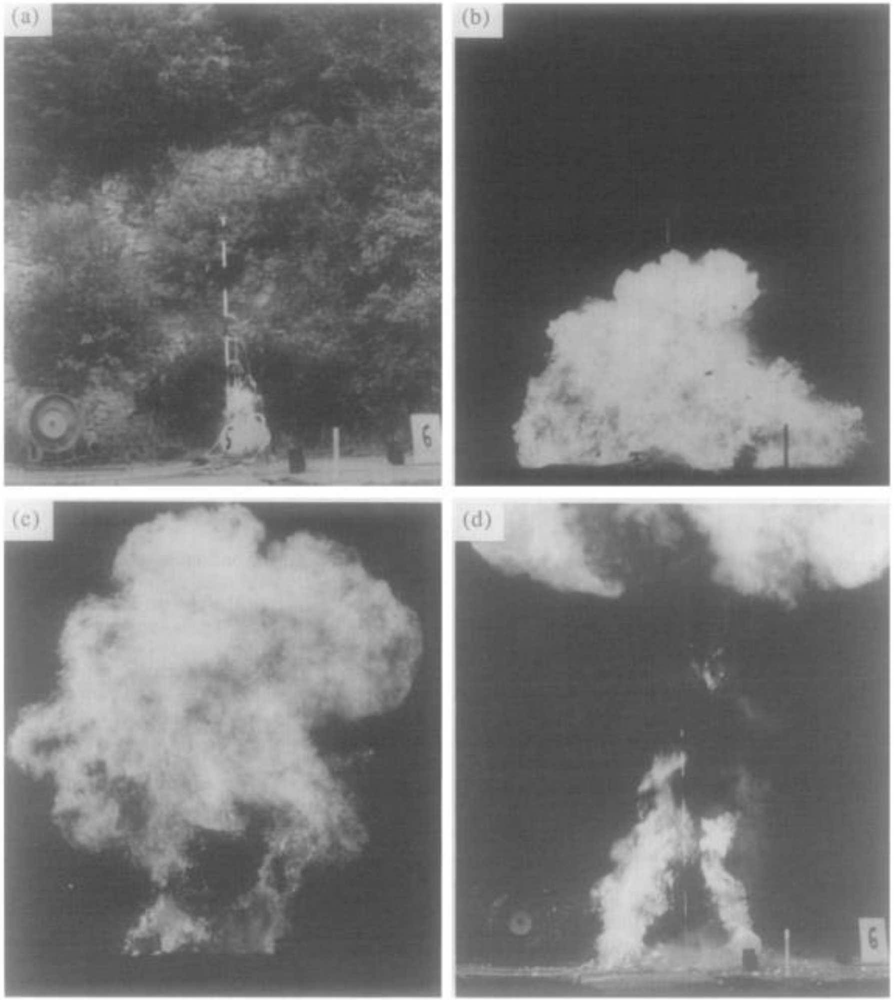
Bursting tank scenario test

Ten single wall vessels insulated with foam and ruptured with explosives:

- V = 120-l
- P = 0.2 ÷ 1.5 MPa
- m_{LH2} = 1.8 ÷ 5.4 kg

Many uncertainties (e.g. filling level, initial temperature, tank dimensions)

[Pehr, K., 1996. Aspects of safety and acceptance of LH2 tank systems in passenger cars. Int. J. Hydrogen Energy 21, 387–395]



g. 3. Development of a fireball. (a) Ignition; (b) 250 ms after ignition; (c) 1250 ms after ignition; and (d) 1800 ms after ignition.

CFD analysis methodology

- CFD code: ADREA-HF
- Homogeneous Equilibrium Model (HEM)
- Raoult's law for ideal mixture
- k-epsilon turbulence model with wall function
- Peng-Robinson and Redlich-Kwong-Mathias-Copeman EoS were tested

The code was validated with the LCO_2 experiments and then employed for the simulation of the LH_2 BMW explosion tests.

CFD analysis methodology

The Navier-Stokes equations, continuity equation, energy equation of the mixture and conservation equation of species. The Favre-averaged equations are (Einstein summation convention is used):

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i}{\partial x_i} = 0,$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)\right) + \bar{\rho}g_i,$$

$$\frac{\partial \bar{\rho}\tilde{H}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{H}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{Pr_t}\frac{\partial \tilde{H}}{\partial x_j}\right) + \frac{D\bar{p}}{Dt},$$

$$\frac{\partial \bar{\rho}\tilde{q}_k}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{q}_k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{Sc_t}\frac{\partial \tilde{q}_k}{\partial x_j}\right) + \bar{R}_k, \quad k = 1, \dots, N_{subs},$$

Assumption: instantaneous and uniform rupture of tanks in all directions

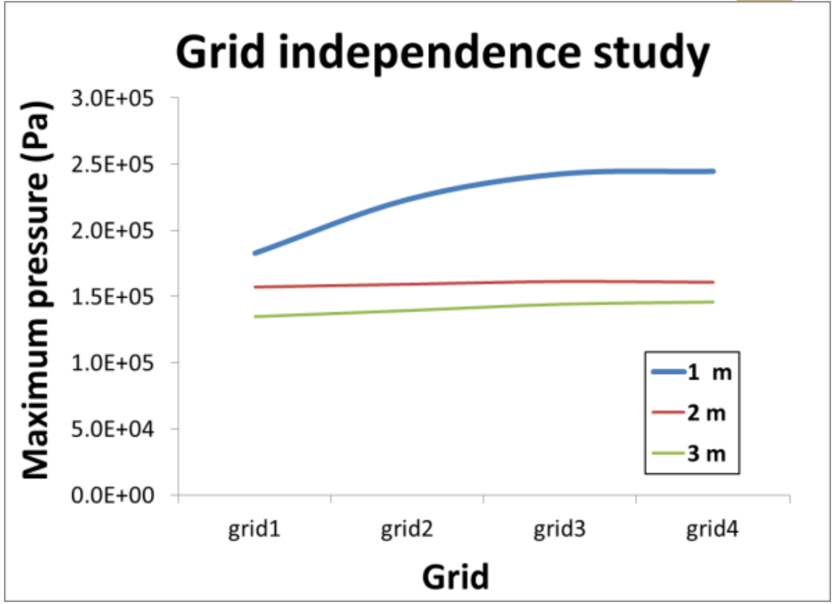
LCO_2 simulation configuration

Initial conditions of the LCO_2 BLEVE simulation (**assumption**: 100% LCO_2)

Pressure (Pa)	Temperature (K)	Density (kg/m^3)	Mass (kg)
5,200,000	289.03	772.54	30.90

Computational meshes (double symmetry along y- and x-axis):

- × Grid 1: 33,792 cells
- × Grid 2: 113,960 cells
- × Grid 3: 265,832 cells
- × Grid 4: 469,560 cells

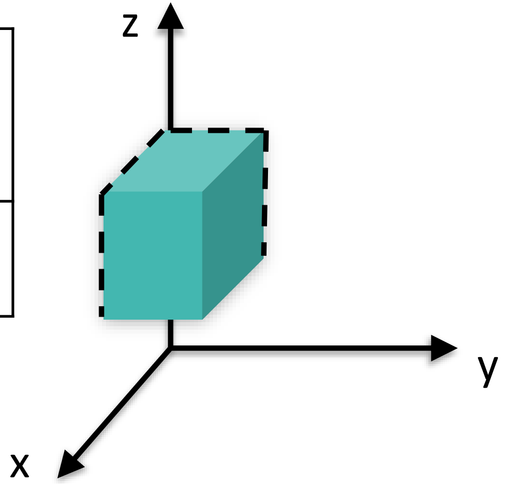


Relative error between grid 3 and 4 ≤ 1% for all three sensors

LH_2 simulation configuration

Characteristics of the simulated LH_2 tank and dimensions of the domain (double symmetry along y- and x-axis → ¼ tank)

Tank	Volume (litres)	Area (m^2)	Height (m)	Orientation	Tank height (m)	Domain dim. (m)
LH_2	120	0.177	0.706	Horizontal	1	10 × 10 × 11



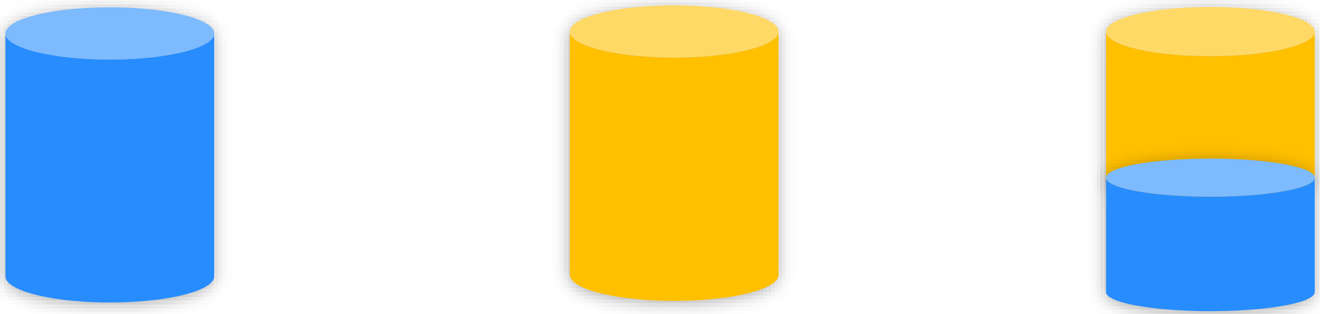
Combustion was not simulated

LH_2 simulation configuration

Initial conditions of the LH_2 BLEVE parametric analysis

Simulation	Phase and status	Pressure (Pa)	Temperature (K)	Density (kg/m^3)	Mass (kg)
LH2	Saturated L	1,101,325	32.10	42.42	1.27
GH2	Superheated V	1,101,325	32.93	15.00	0.45
LH2-GH2	L and V	1,101,325	32.10, 32.50	42.42 (L), 16.30 (V)	0.77

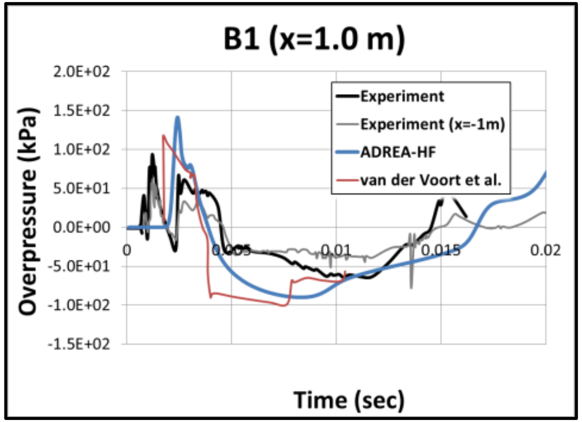
fd = 37%

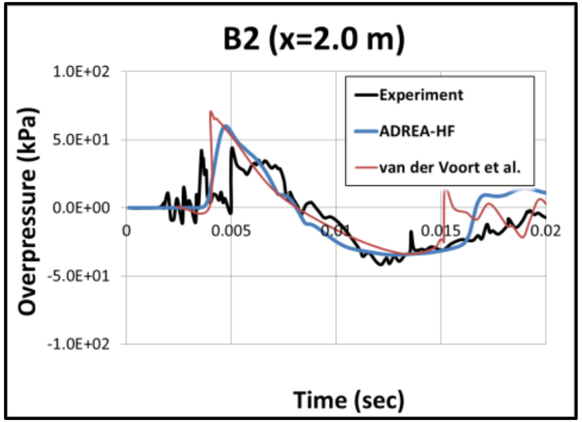


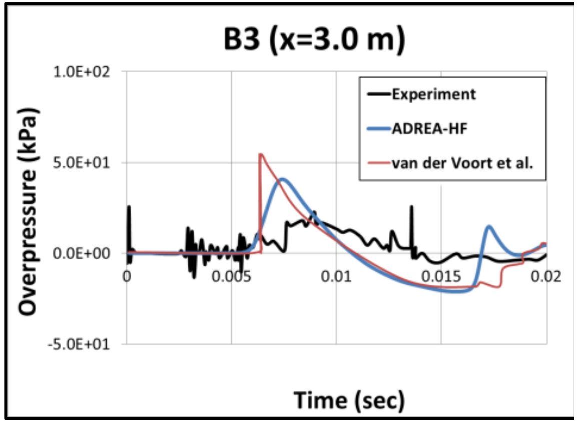
LH2 GH2 LH2-GH2

ADREA-HF code validation

Results of the LCO_2 BLEVE simulations: peak overpressure of the blast wave in three different positions

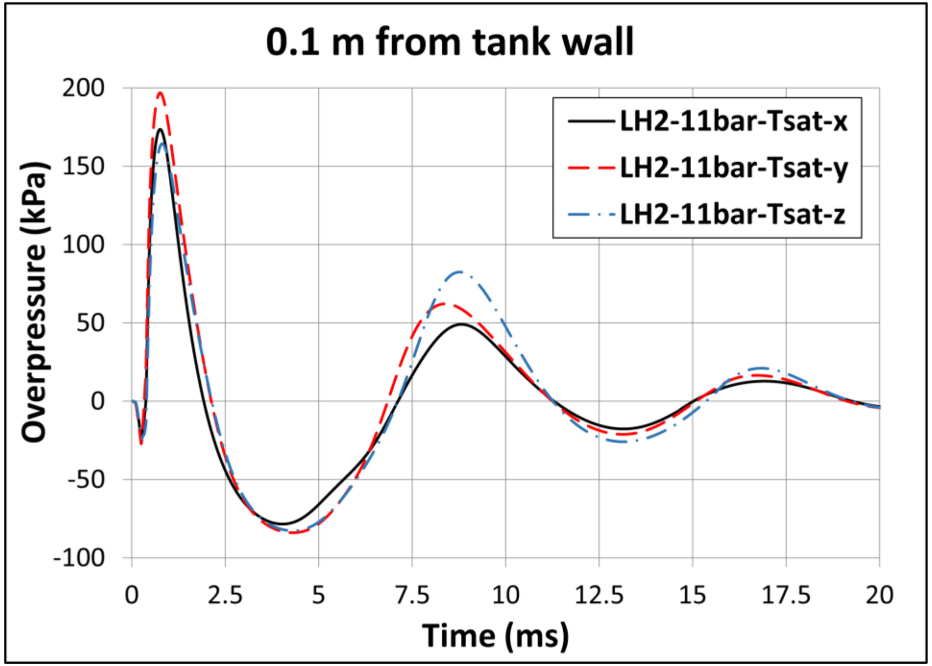


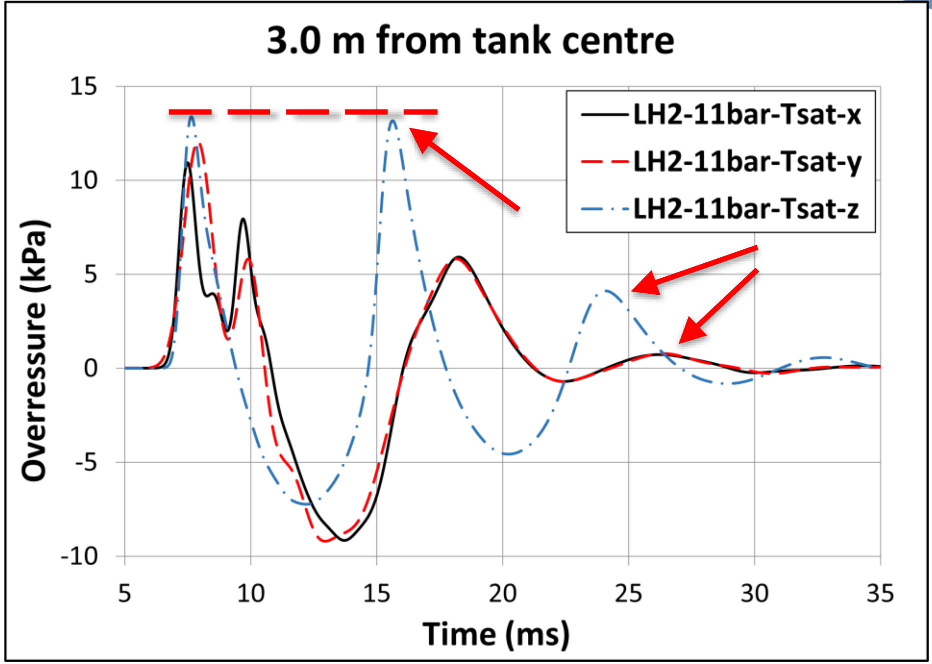




Experimental results are disturbed by the blast wave reflection on the bunker walls

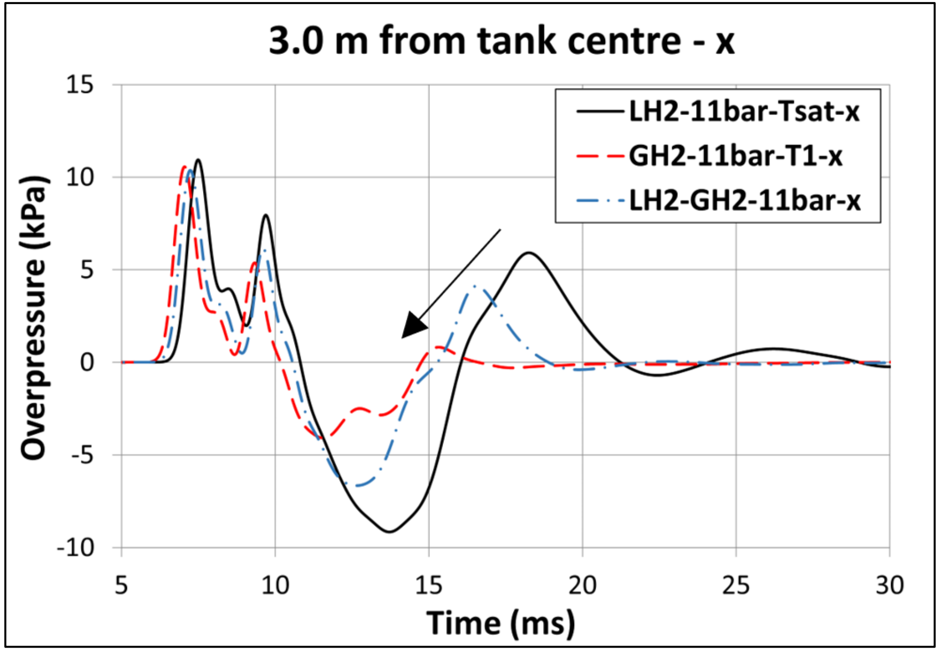
BLEVE blast wave overpressure

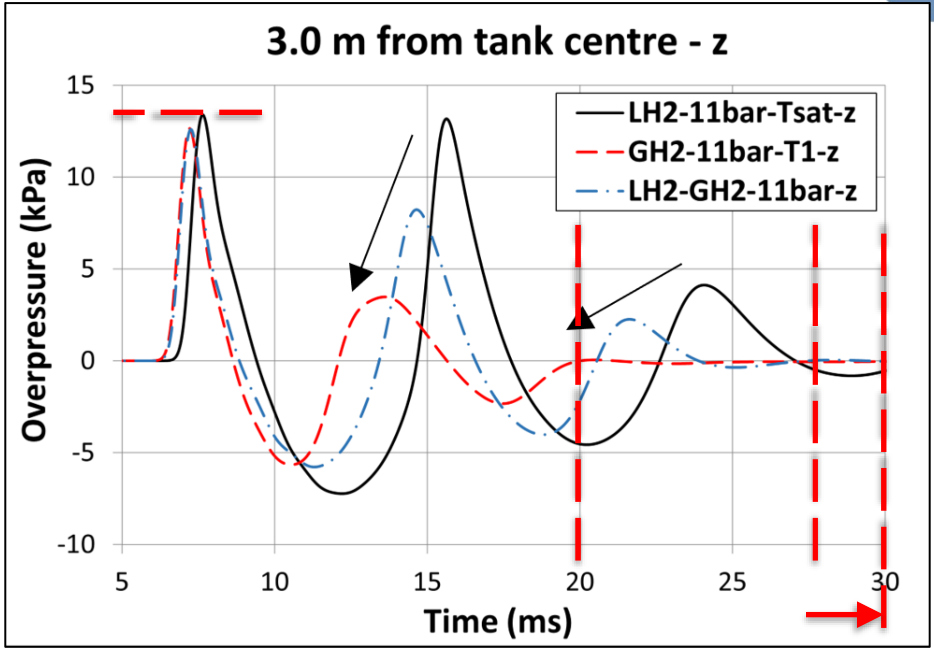




Second pressure peak at vertical axis as high as the first one at 3 m from the tank centre

BLEVE blast wave overpressure





- <u>Second pressure peak</u> at horizontal axis decreases with GH2
- <u>Third press peak</u> manifests only when LH2 is initially present
- No large differences in <u>max overpressure</u> yet in <u>explosion duration</u>

Conclusions

- Differences in the overpressure of the pressure wave along vertical and horizontal axes
- Both LH_2 or GH_2 contribute to the explosion yield (similar maximum overpressure values)
- GH_2 simulation produces the shortest explosion, thus the smallest impulse
- Two pressure peaks for 100% GH_2, while three peaks for the 100% LH_2
- Maximum overpressure was not mainly affected by the hydrogen mass, while this parameter affects the blast wave impulse.

Thank you for your attention

The Research Council of Norway

SH2IFT

Project coordinator (Sintef):
Anders Ødegård: Anders.Odegard@sintef.no

WP 4 (LH_2 modelling) leader:
Lars Odsæter: lars.odsater@sintef.no

WP 4 researchers:
Federico Ustolin: federico.ustolin@ntnu.no
Nicola Paltrinieri: nicola.paltrinieri@ntnu.no