NTNU

Norwegian University of Science and Technology

SH2IFT

Liquid hydrogen BLEVE modelling

SH2IFT project final workshop

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The Research Council of Norway

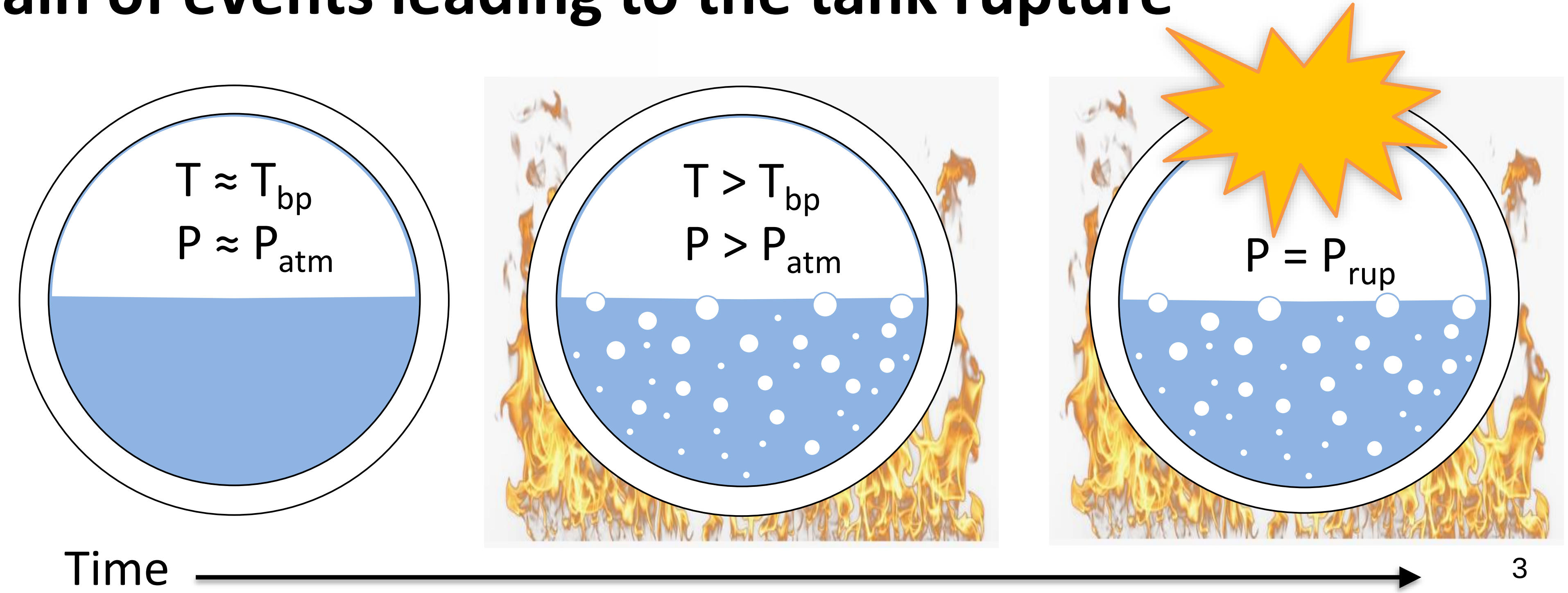
Content

Boiling Liquid Expanding Vapour Explosion

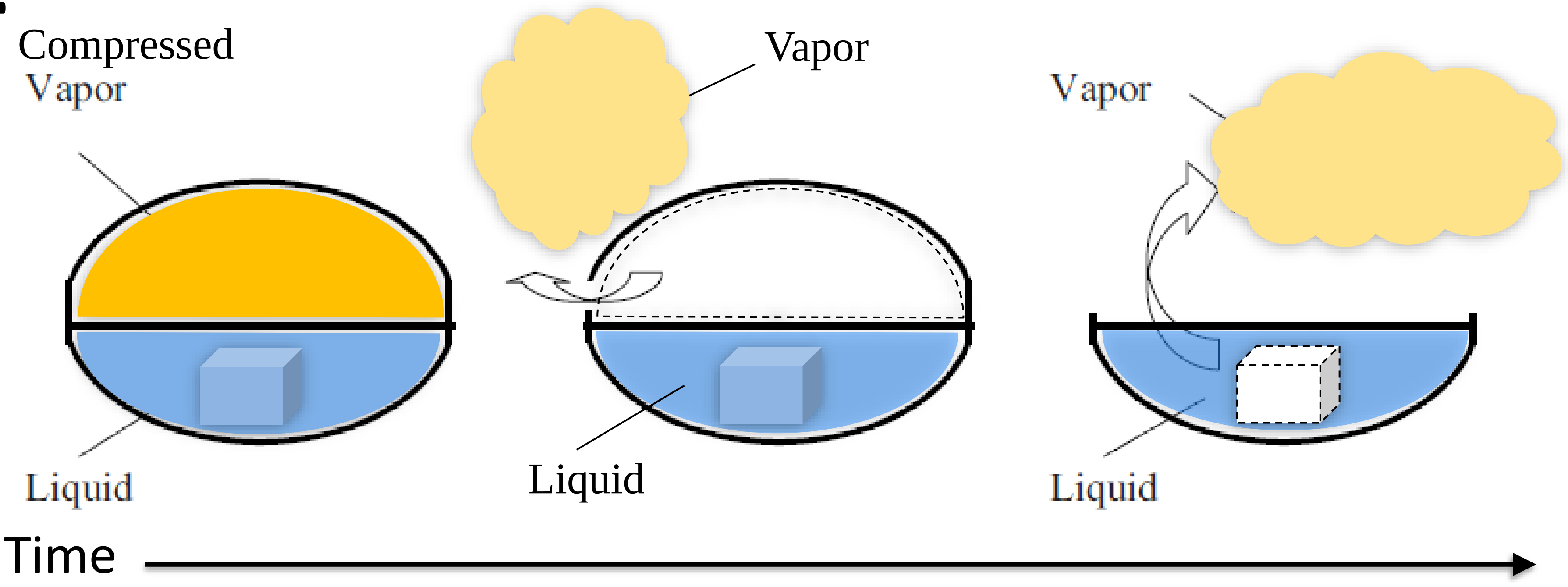
BLEVE is a physical explosion might result from the catastrophic rupture of a tank containing a superheated liquid due to the rapid depressurization

Chain of events leading to the tank rupture

Valid for cryogenic substances



BLEVE



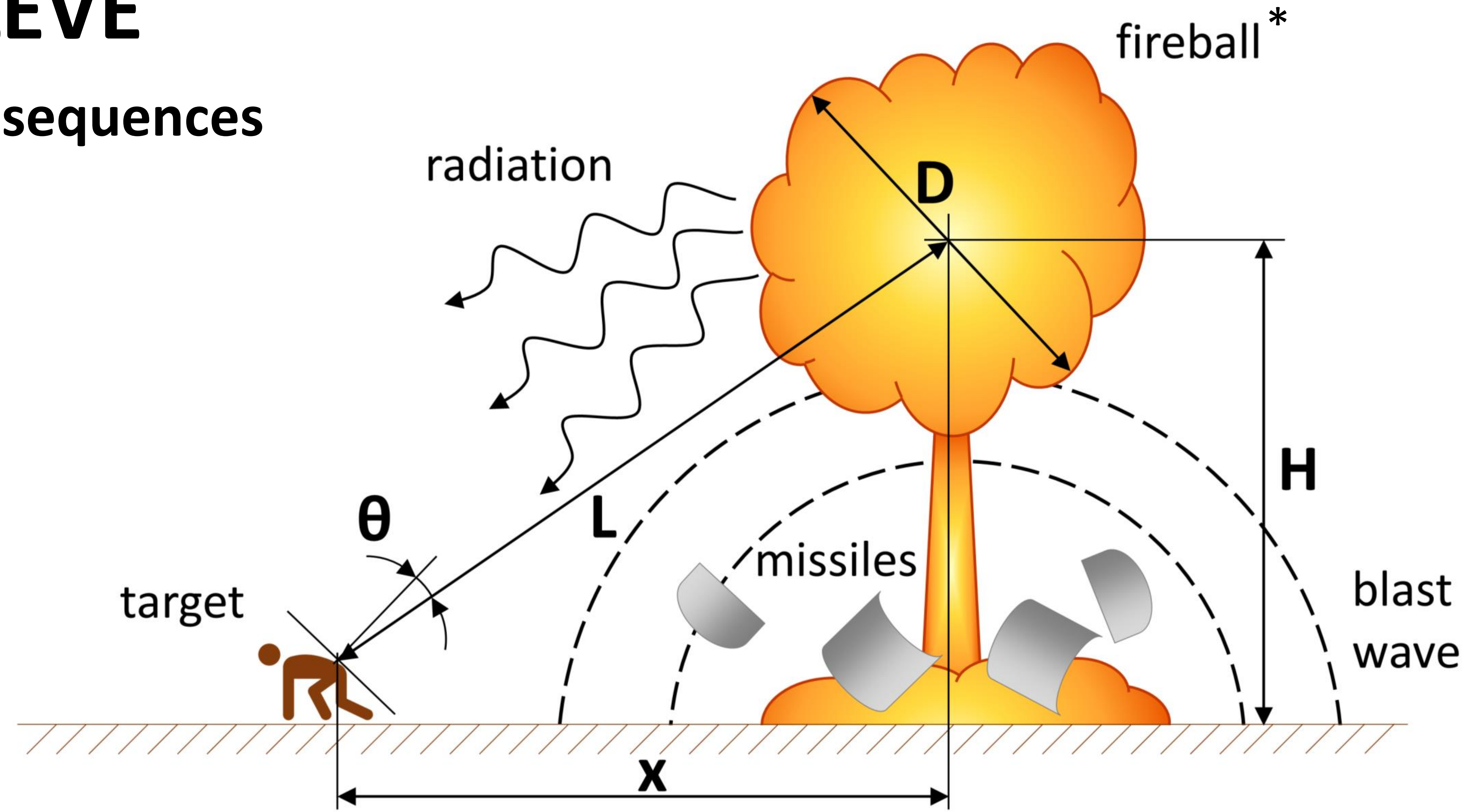
P	$P_o = 101.3\ kN\ m^{-2}$	$P_o = 101.3\ kN\ m^{-2}$
$T = T_s(P)$	T	$T_o = T_s(P_o)$
$h_l = h_l(T)$	$h_l(T, P_o) \approx h_l(T)$	$h_{lo} = h_{lo}(T_o)$
$h_g = h_g(T)$	**metastable/unstable**	$h_{go} = h_{go}(T_o)$

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

Intro

BLEVE

Consequences



*Fireball if substance is flammable and ignition source is present

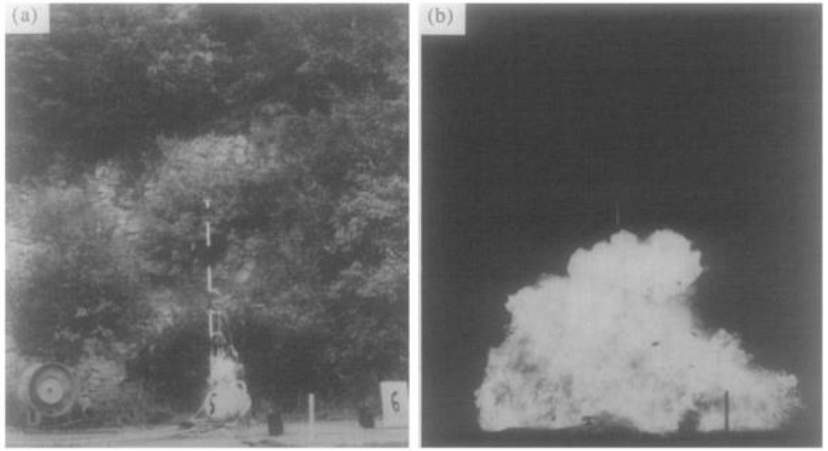
BMW safety programme

SH_2IFT LH_2 experiment has been delayed, therefore the results from the BMW tests were exploited.

Fire tests: double walled vessel filled at 50% fully engulfed in propane fire.

Bursting tank scenario test: ten vessels (0.120 m^3) filled with different amount of LH2 (1.8 ÷ 5.4 kg) were wrecked by means of cutting charges.

Figure 11: Bonfire test of a liquid hydrogen fuel tank (Source: BAM)



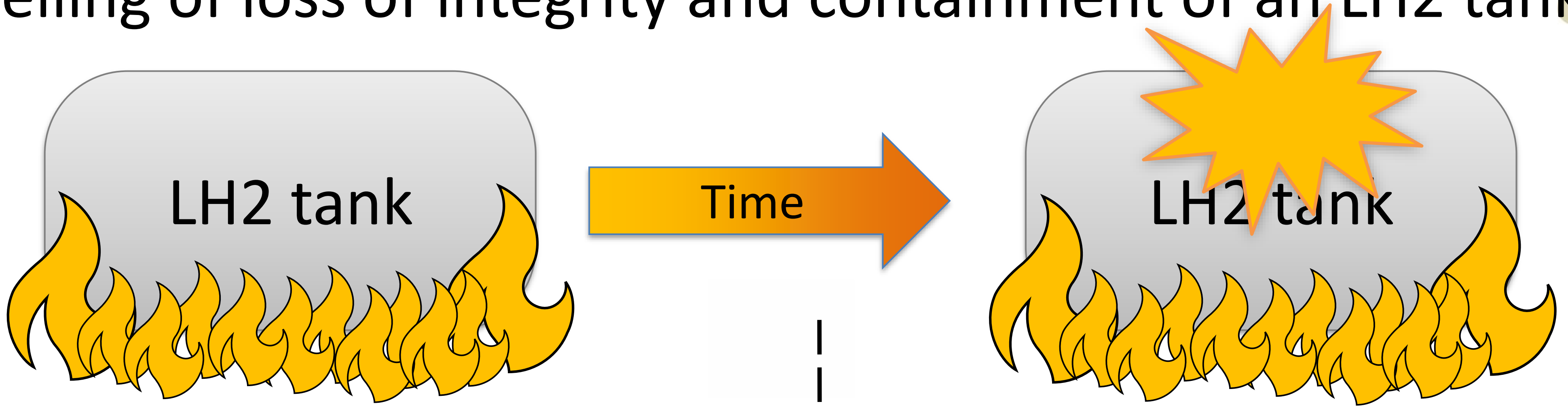
Development of a fireball. (a) Ignition; (b) 250 ms after ignition

A 7 Series BMW with hydrogen IC engine and LH_2 storage

[Pehr K. Aspects of safety and acceptance of LH2 tank systems in passenger cars. Int J Hydrogen Energy 1996;21:387–95]

Consequence analysis (CA)

Modelling of loss of integrity and containment of an LH2 tank



Fire test:

- Pressure build up and temperature gradient in LH2 tank

How:
1. Lumped models
2. Numerical models (CFD)

Catastrophic rupture (BLEVE):

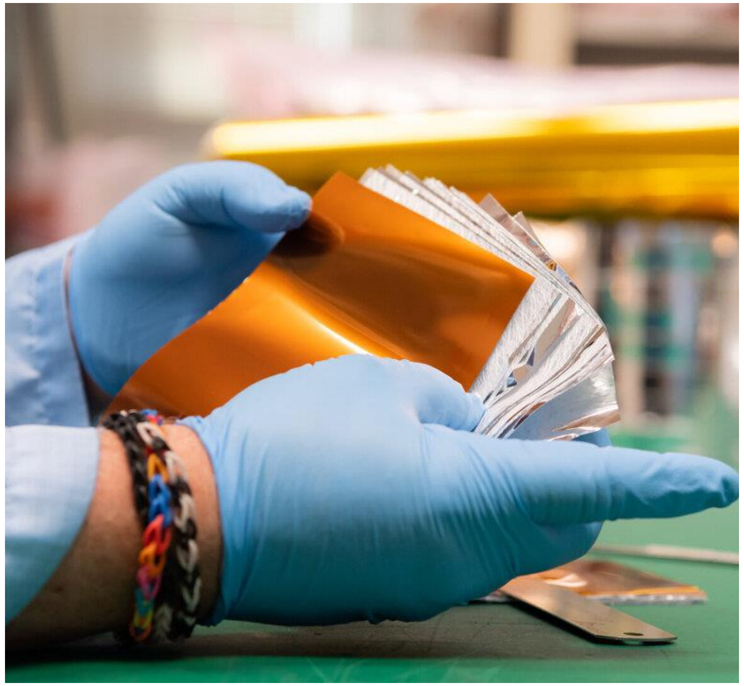
- Pressure wave
- Fragments
- Fireball

How:
1. Engineering tools
2. Numerical models (CFD)

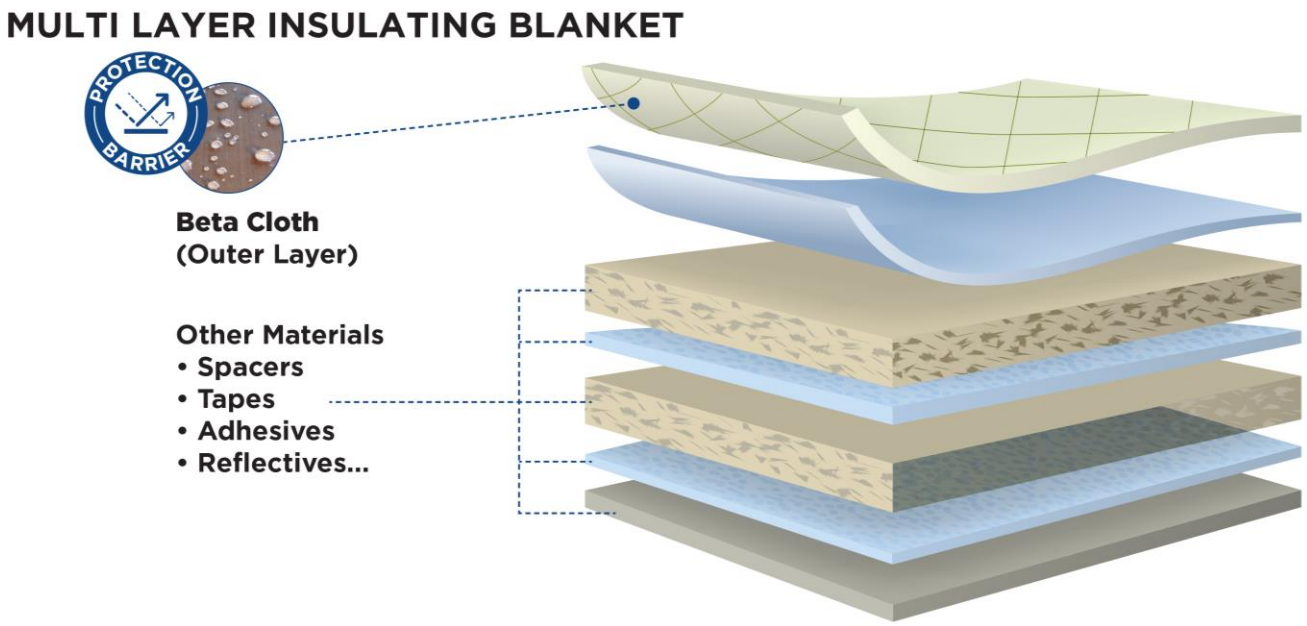
CA

Fire test modelling

Focus: LH2 tank with multi-layer vacuum insulation (MLVI)



Credit: ESA-SJM Photography



Source: chemfab.com

Fire test

Lumped model - Methodology

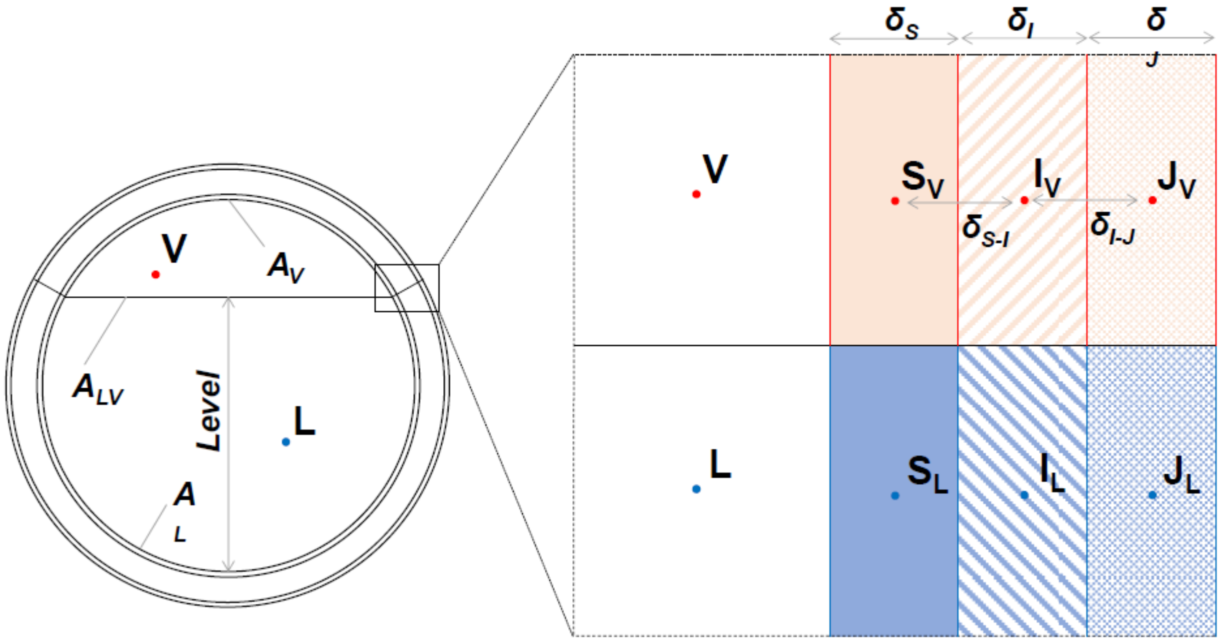


Figure 1: Schematization of thermal nodes discretization. L = liquid phase, V = vapour phase, S = shell, I = insulant, J = jacket, A_L = liquid wetted area, A_V = vapour wetted area, A_{LV} = liquid-vapour interface area.

Table 1: Thermal and mass balances for the nodes depicted in Figure 1.

Node	Variable	Equation	Eq.
L	T_L	$m_L cp_L \frac{dT_L}{dt} = A_L h_L (T_{SL} - T_L) + A_{LV} h_{LV} (T_V - T_L) + q_R + m_C(\hat{H}_V(T_V) - \hat{H}_L(T_L)) - m_E(\hat{H}_V(T_L) - \hat{H}_L(T_L))$	(1)
	m_L	$\frac{dm_L}{dt} = m_C - m_E$	(2)
V	T_V	$m_V cv_V \frac{dT_V}{dt} = A_V h_V (T_{SV} - T_V) - A_{LV} h_{LV} (T_V - T_L) - m_E\left(\hat{H}_V(T_L) - \hat{H}_V(T_L)\right) + \frac{RT_V}{M}\frac{dm_V}{dt}$	(3)
	m_V	$\frac{dm_V}{dt} = -m_C + m_E - m_{PSV}$	(4)
S_L	T_{SL}	$\delta_S \rho_{SL} cp_{SL} \frac{dT_{SL}}{dt} = -h_L(T_{SL} - T_L) + \frac{k_{S-I}}{\delta_{S-I}}(T_{IL} - T_{SL})$	(5)
S_V	T_{SV}	$\delta_S \rho_{SV} cp_{SV} \frac{dT_{SV}}{dt} = -h_V(T_{SV} - T_V) - q_R + \frac{k_{S-I}}{\delta_{S-I}}(T_{IV} - T_{SV})$	(6)
I_L	T_{IL}	$\delta_I \rho_{IL} cp_{IL} \frac{dT_{IL}}{dt} = -\frac{k_{S-I}}{\delta_{S-I}}(T_{IL} - T_{SL}) + \frac{k_{I-J}}{\delta_{I-J}}(T_{JL} - T_{IL})$	(7)
I_V	T_{IV}	$\delta_I \rho_{IV} cp_{IV} \frac{dT_{IV}}{dt} = -\frac{k_{S-I}}{\delta_{S-I}}(T_{IV} - T_{SV}) + \frac{k_{I-J}}{\delta_{I-J}}(T_{JV} - T_{IV})$	(8)
J_L	T_{JL}	$\delta_J \rho_{JL} cp_{JL} \frac{dT_{JL}}{dt} = -\frac{k_{I-J}}{\delta_{I-J}}(T_{JL} - T_{IL}) + A_L q_{FIRE}$	(9)
J_V	T_{JV}	$\delta_J \rho_{JV} cp_{JV} \frac{dT_{JV}}{dt} = -\frac{k_{I-J}}{\delta_{I-J}}(T_{JV} - T_{IV}) + A_V q_{FIRE}$	(10)
-	P	$\frac{dp}{dt} = \frac{\rho_V}{m_V}\left(\frac{P}{\rho_L}\frac{dm_L}{dt} + \frac{RT_V}{M}\frac{dm_V}{dt} + \frac{Rm_V}{M}\frac{dT_V}{dt}\right)$	(11)
-	Level	$\frac{dLevel}{dt} = \frac{1}{\rho_L}\left(\frac{dV_L}{dLevel}\right)^{-1}\frac{dm_L}{dt}$	(12)

T = temperature, m = mass, P = pressure, V_L = liquid volume, cp = specific heat capacity at constant pressure, cv = specific heat capacity at constant volume, h = convective heat transfer coefficient, $\hat{H}$ = specific enthalpy, R = gas constant, M = molecular weight, m_E = evaporation rate, m_C = condensation rate, m_{PSV} = PSV discharging rate, ρ = density, δ = thickness, k = thermal conductivity, q = heat flux

Fire test

[Scarponi GE, Landucci G, Ovidi F, Cozzani V. Lumped Model for the Assessment of the Thermal and Mechanical Response of LNG Tanks Exposed to Fire. Chem Eng Trans 2016;53:307–12]

Lumped model - Assumptions

Known: tank volume (0.120 m^3), insulation thickness (35 mm)

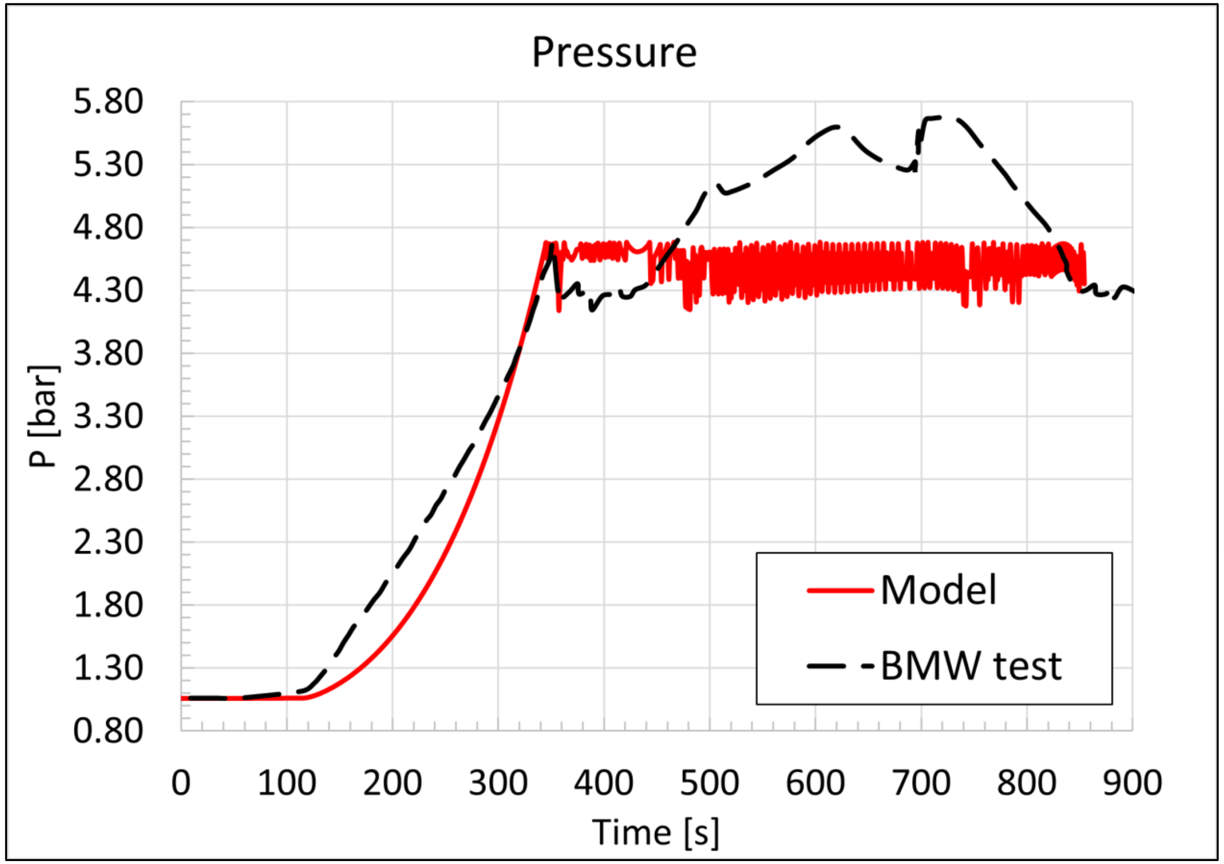
Test duration: 14 min (1st PRV opening after 6 min)

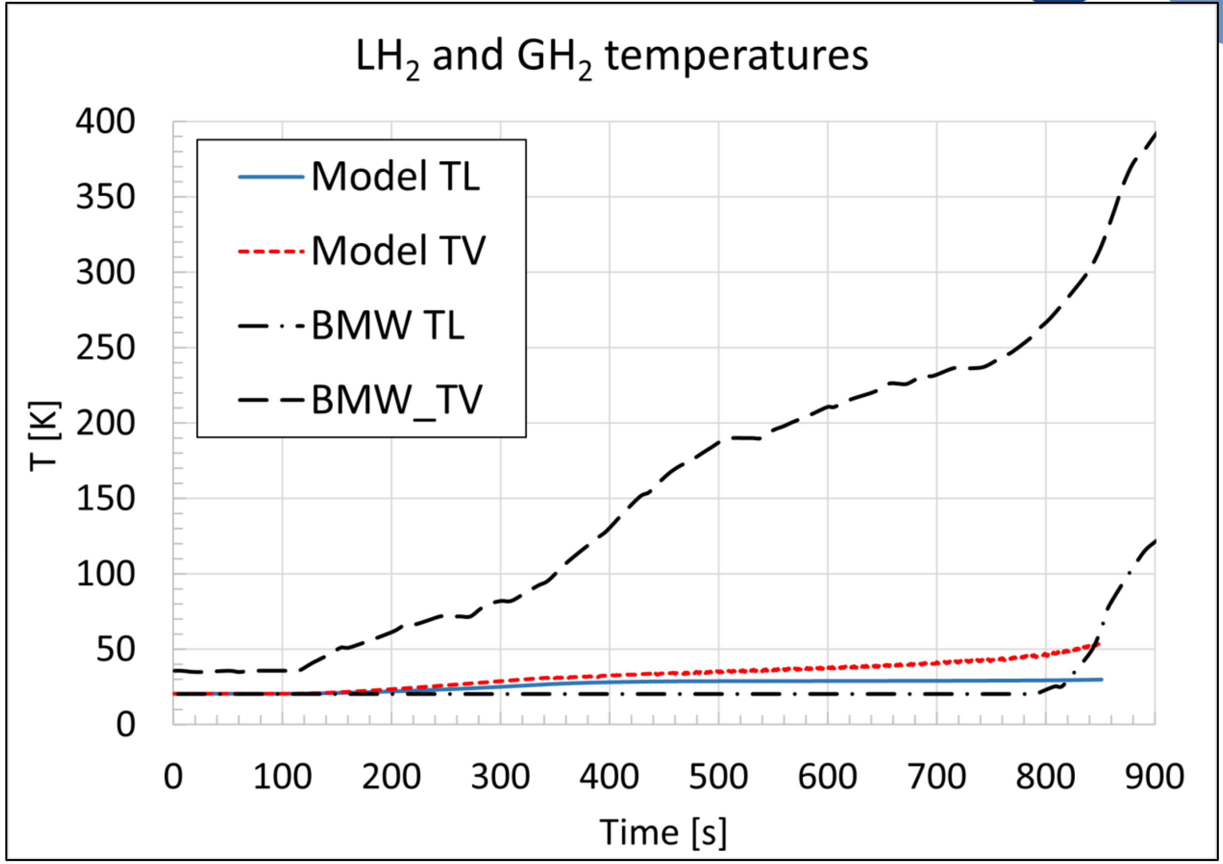
- PRV diameter (ISO 21013-3:2016): 9.6 mm
- MLVI thermal conductivity changed to 0.110 W m^{-1} K^{-1} at t=115 s
- Tank dimensions:
  - diameter: 460 mm
  - length: 722 mm

Fire test

[Pehr, K., 1996. Experimental examinations on the worst-case behaviour of LH2/LNG tanks for passenger cars, in: Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart 23–28 June 1996. Stuttgart, pp. 2169–87]

Lumped model - Results





- Tank pressure approximate well the measurements
- LH2 GH2 temp. do not agree with experimental (thermal nodes approach)

Fire test

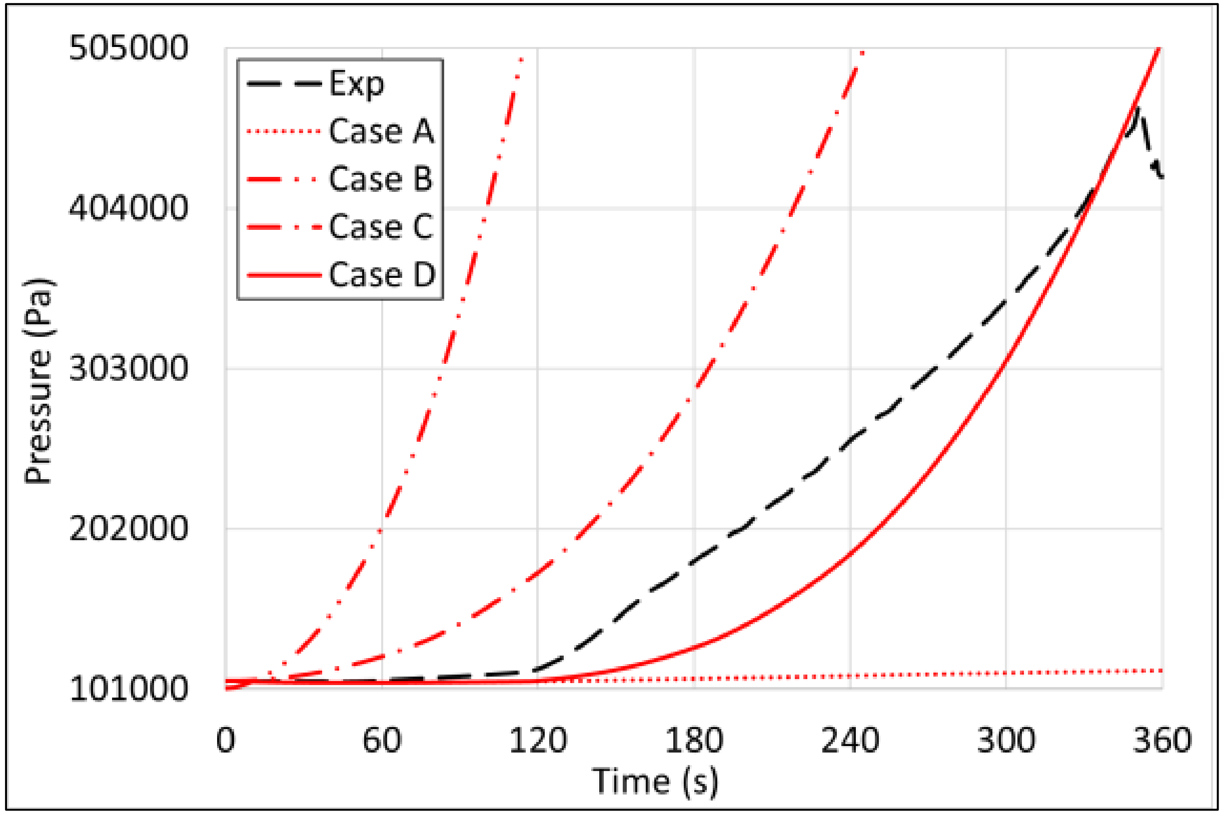
[Ustolin, F., Iannaccone, T., Cozzani, V., Jafarzadeh, S., Paltrinieri, N., 2021. Time to Failure Estimation of Cryogenic Liquefied Tanks Exposed to a Fire, in: 31st European Safety and Reliability Conference. pp. 935–942]

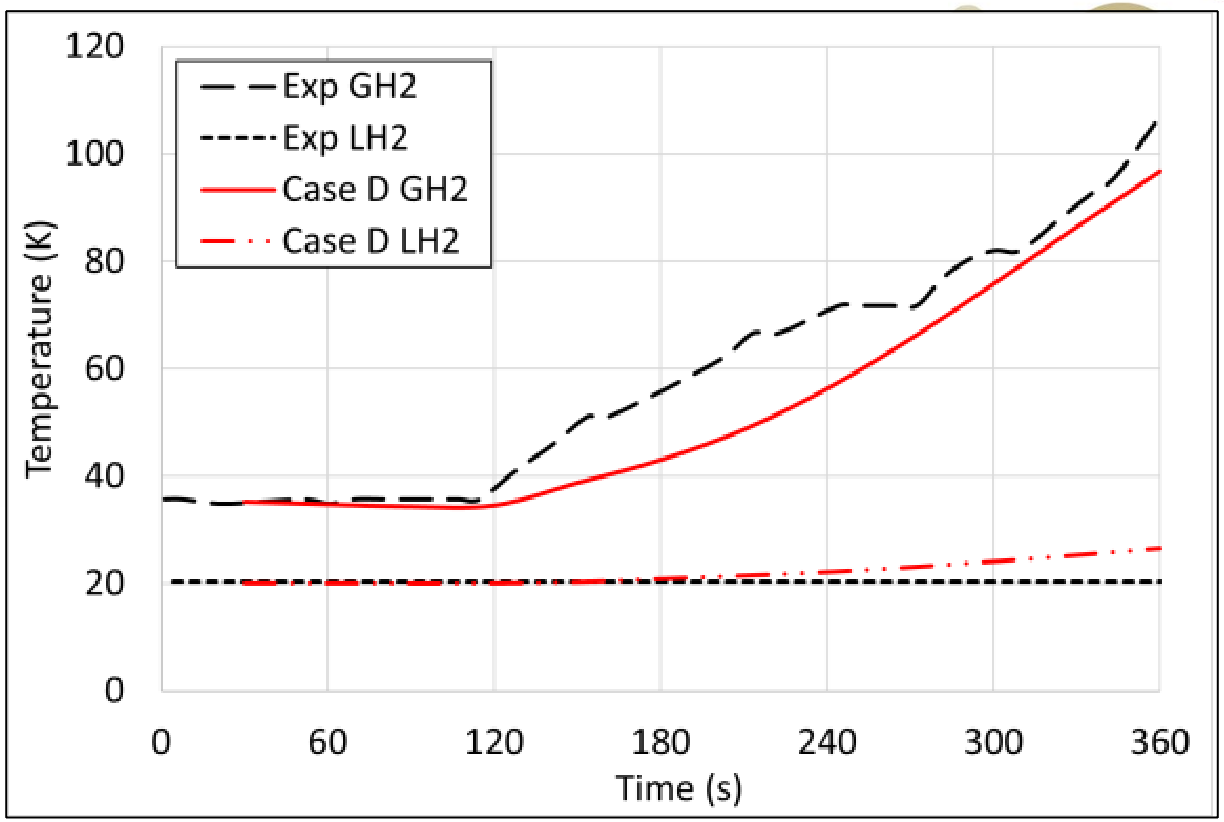
CFD analysis - Methodology

- **Type**: 2D
- **Software**: Ansys Fluent
- **Multiphase model**: Volume of Fluid
- **Turbulence model**: k-omega SST
- **Evaporation-condensation model**: Lee (Hertz-Knudsen)
- **Pressure-velocity coupling algorithm**: SIMPLEC
- **Thermodynamic properties**: implemented from NIST database
- **Symmetry**: axial

Fire test

CFD analysis - Results



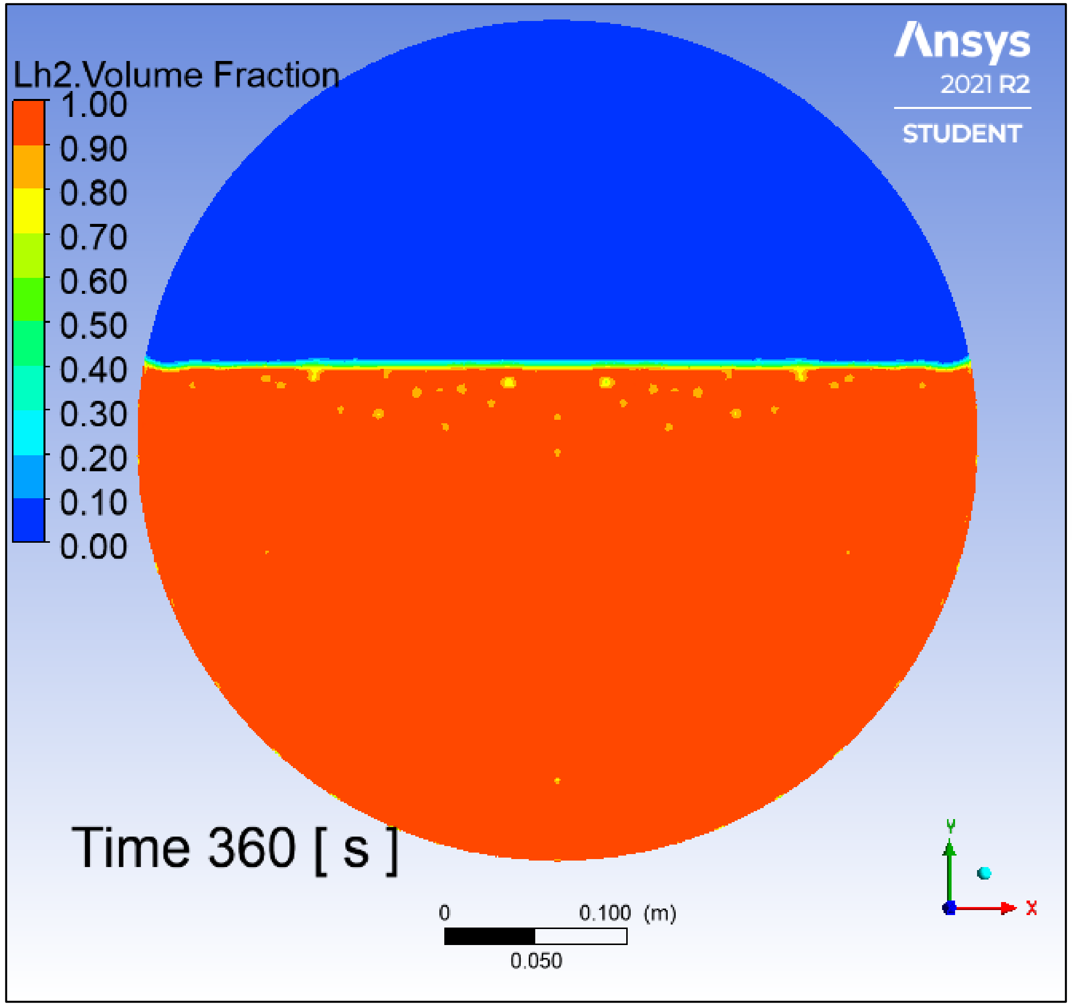


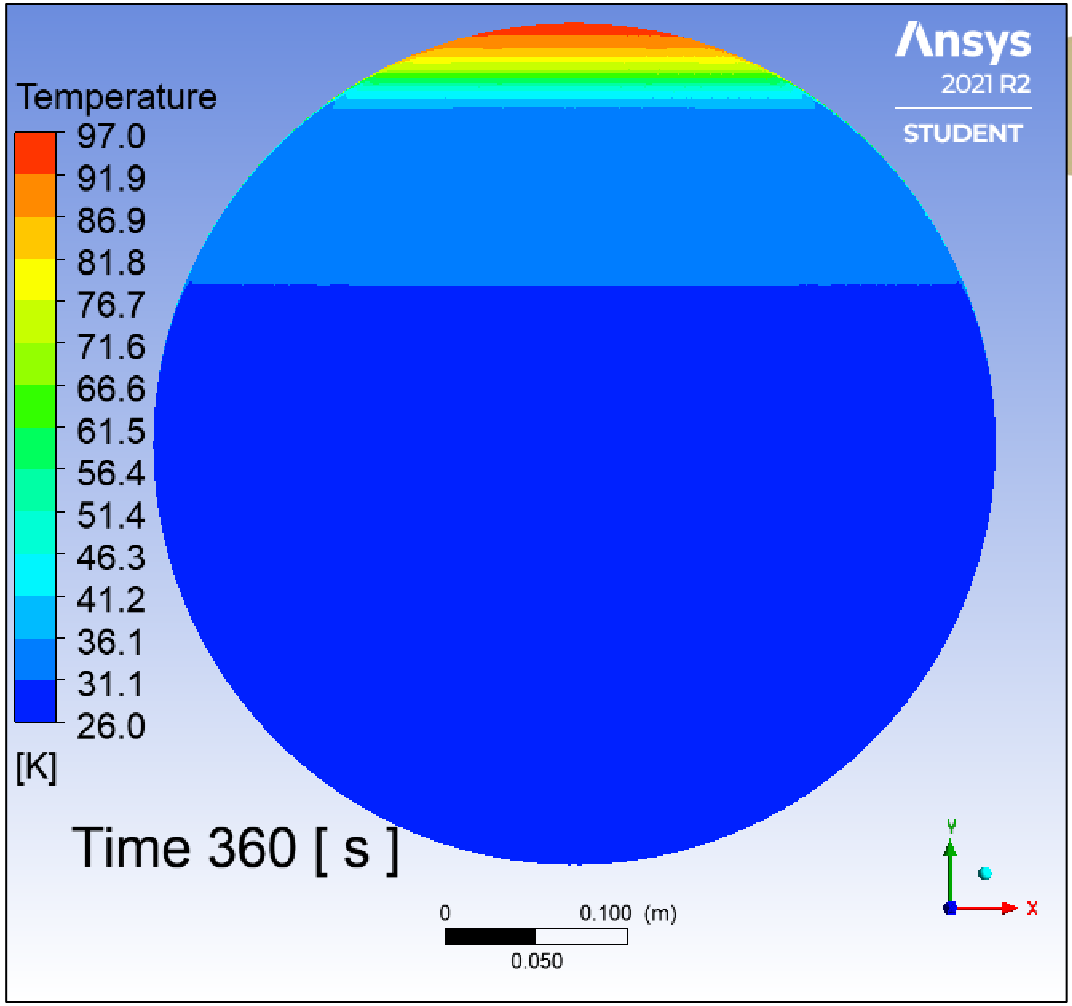
Case A: 1.5 mW/m K **Case B**: 239.0 mW/m K **Case C**: 160.0 mW/m K

Case D: 1.5 mW/m K if t<115 s; 160.0 mW/m K if t>115 s

Fire test

CFD analysis - Results





Case D: 1.5 mW/m K if t<115 s; 160.0 mW/m K if t>115 s

Fire test

Consequences of an LH_2 BLEVE

Two approaches were selected to carry out the BLEVE consequences analysis (blast wave):

1. Integral models

- Mechanical energy
- Overpressure and impulse

2. Numerical model (CFD)

- Blast wave (no combustion)

Integral models - Methodology

Methods: theoretical models for mechanical energy

Proposed by	Equation
Brode (1959)	$E_{Brode} = \frac{P - P_0}{\gamma - 1} V^*$
Smith and Van Ness (1996)	$E_{IE} = P \cdot V^* \cdot \ln \frac{P}{P_0}$
Crowl (1992, 1991)	$E_{TA} = P \cdot V^* \left[\ln\left(\frac{P}{P_0}\right) - \left(1 - \frac{P_0}{P}\right)\right]$
Prugh (1991)	$E_{Prugh} = \frac{P \cdot V^*}{\gamma - 1}\left(1 - \frac{P_0}{P}\right)^{\frac{\gamma - 1}{\gamma}}$
van den Bosch and Weterings (2005)	$E_{TNO} = m_V (u_V - u_{V_{is}}) + m_L (u_L - u_{L_{is}})$
Planas-Cuchi et al. (2004)	$E_{Planas} = -[(u_{L0} - u_{V0}) m_T \cdot x - m_T \cdot u_{L0} + U_i]$
Casal and Salla (2006)	$E_{SE} = k \cdot m_L (h_L - h_{L0})$
Genova et al. (2008)	$E_{Genova} = \psi \cdot m_L \cdot c_{p,L} (T_L - T_{L0})$
Birk et al. (2007)	$E_{Birk} = m_V (u_V - u_{V_{is}})$

Ideal gas behaviour models (Brode, Smith and Van Ness, Crowl, Prugh)

Real gas behaviour models (van den Bosch and Weterings, Planas-Cuchi et al., Casal and Salla, Genova et al., Birk et al.)

Blast wave overpressure and impulse (far field):
- ➢ TNT equivalent mass
- ➢ Sachs scaling law (Baker curves)

Safety distance → $P < 1.35$ kPa

BLEVE

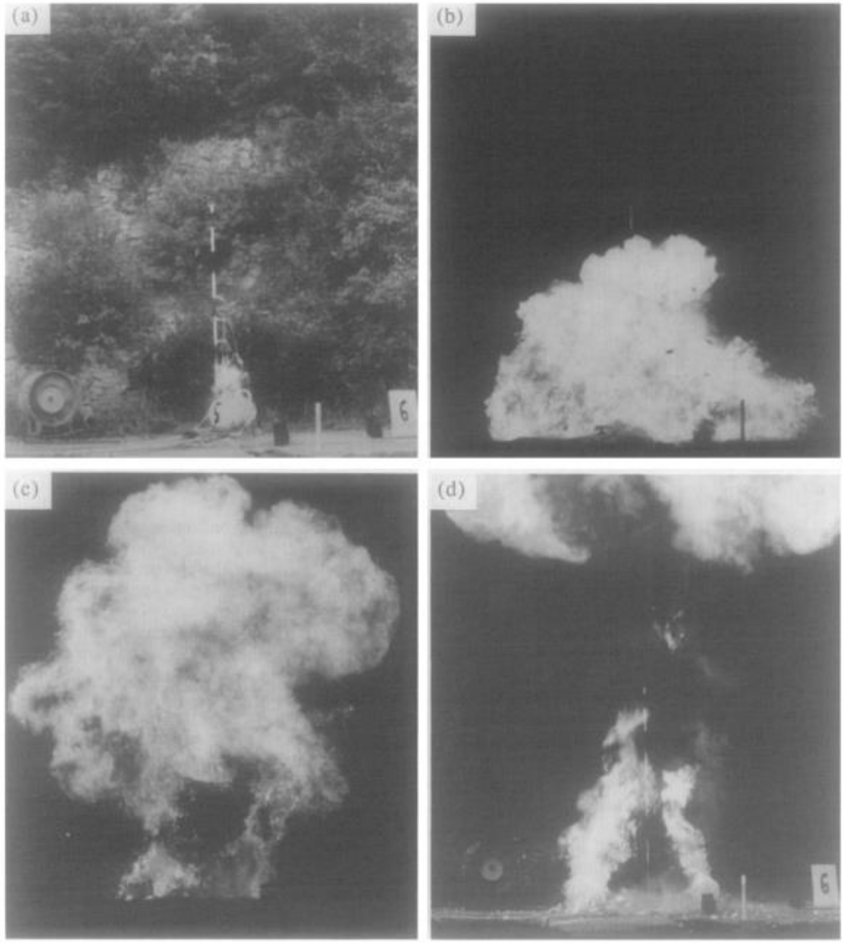
Integral models - Assumptions

Ten LH2 vessels with different H2 content and initial pressure and temperatures were tested by BMW

- **Tank volume:** 0.120 m^3
- **Rupture pressure**: 2, 4, 11 and 15 bar

Uncertainties

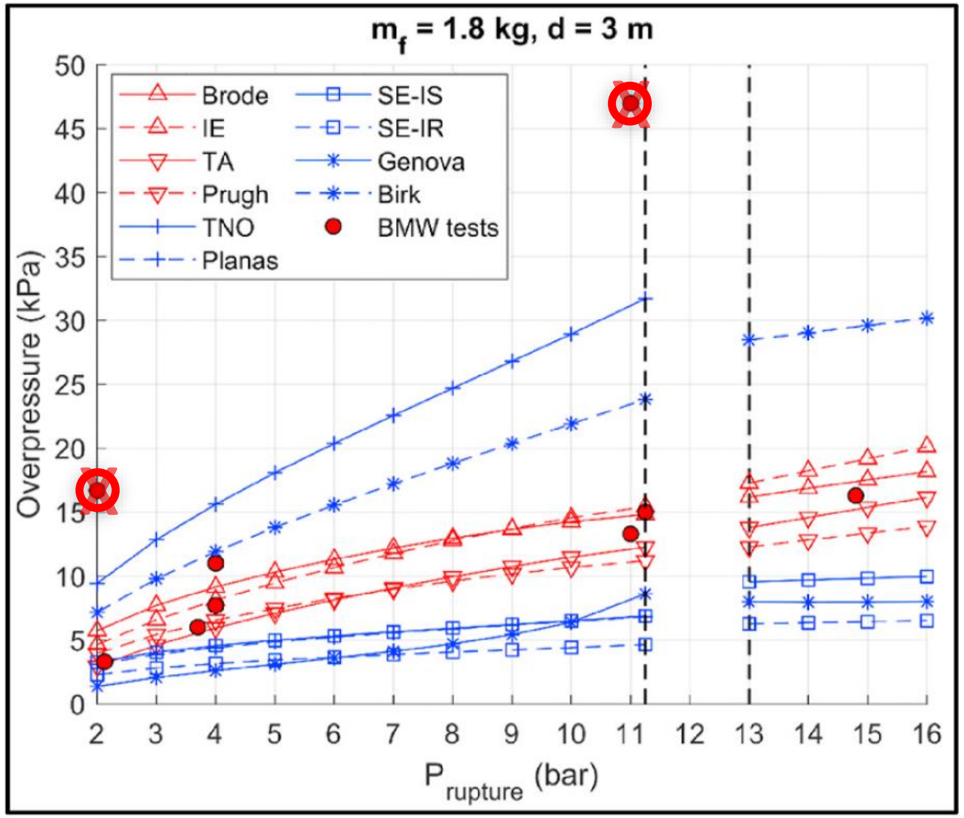
- **Temperature (LH2, GH2)**: saturation
- **Hydrogen mass**: 1.8, 5.4 kg

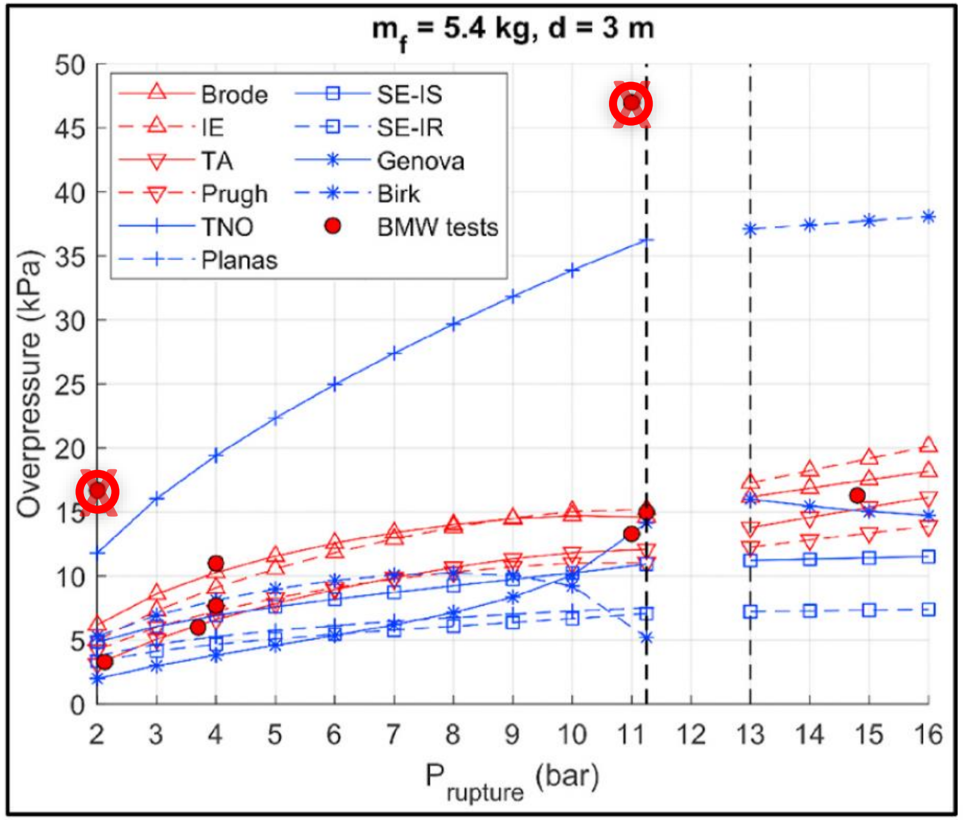


BLEVE

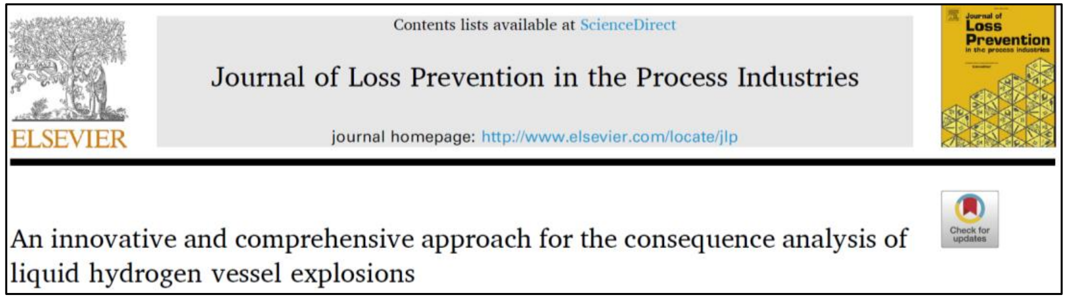
[Pehr, K., 1996. Aspects of safety and acceptance of LH2 tank systems in passenger cars. Int. J. Hydrogen Energy 21, 387–395]

Integral models - Results





TNT equivalent mass method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ELSEVIER

An innovative and comprehensive approach for the consequence analysis of liquid hydrogen vessel explosions

BLEVE

Integral models (combustion)

1. **Mechanical energy**: real gas behaviour model (van den Bosch and Weterings, 2005)

$$E_{mech} = m_V\,(u_V - u_{V_{is}}) + m_L\,(u_L - u_{L_{is}})$$

2. **Chemical energy** (combustion process): methodology proposed by Molkov and Kashkarov (2015) for pressurized H2 tanks:

$$E_{ch} = \beta \cdot \left(\frac{r_{sh}}{r_b}\right)^3 \cdot LHV$$

$$\beta = 0.052$$

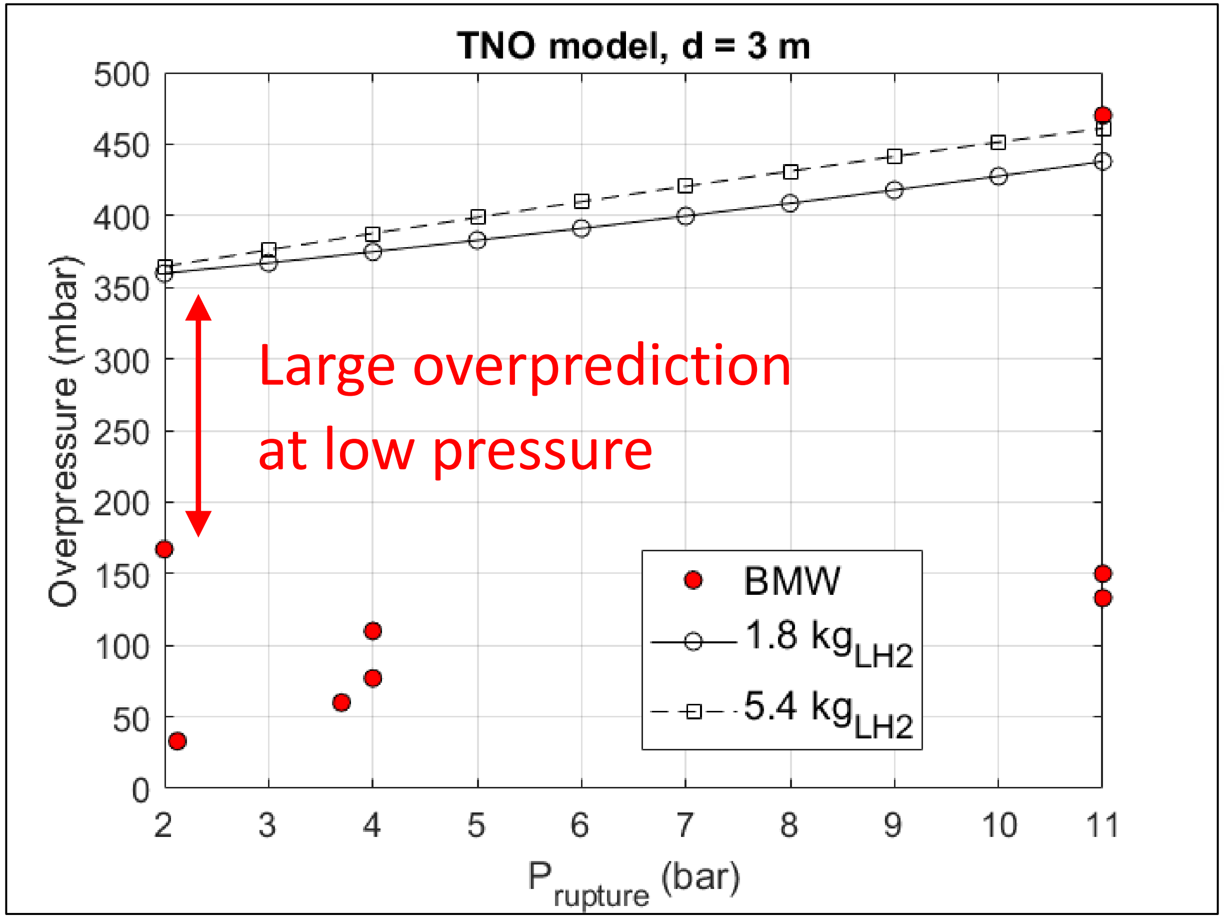
$$\alpha = 2.00$$

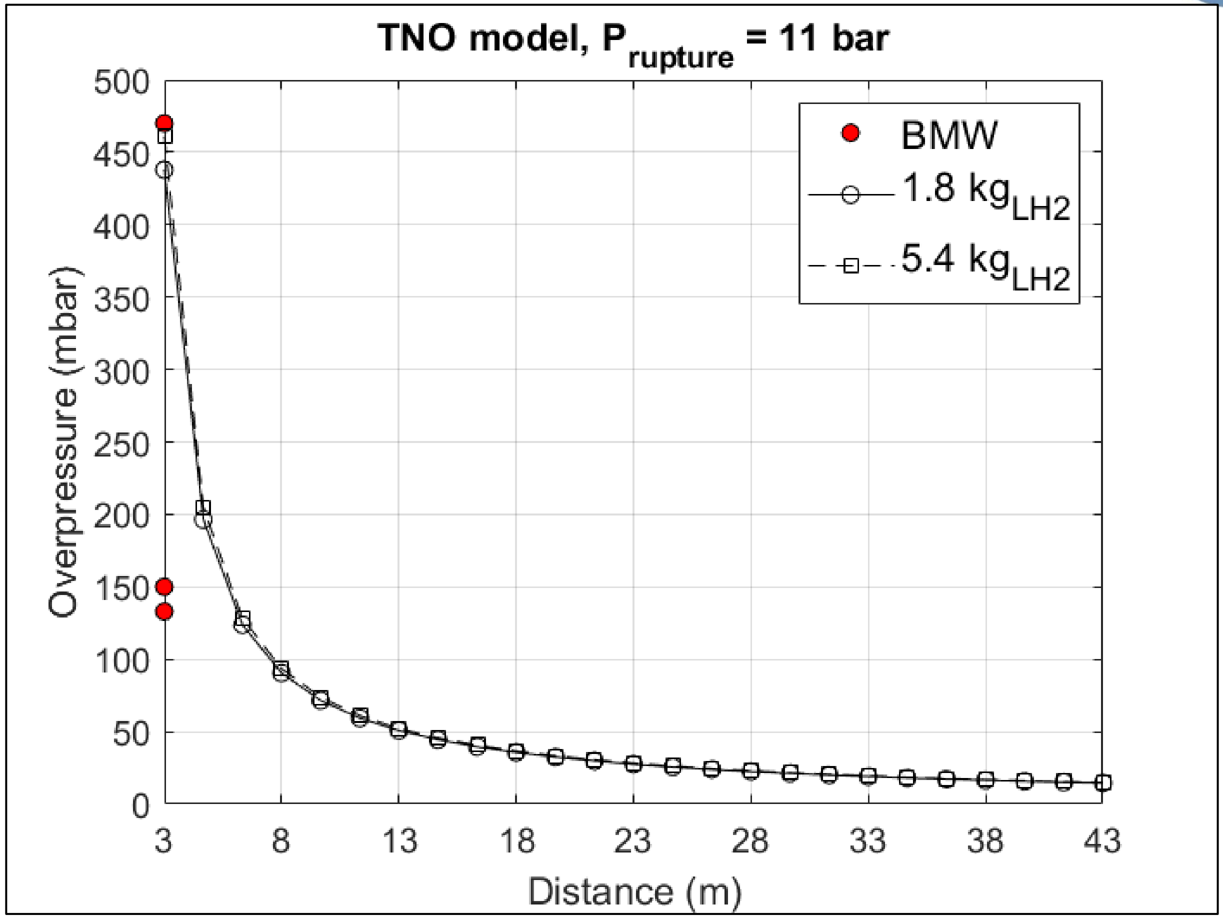
$$E_{TOT} = \alpha \cdot E_{mech} + E_{ch}$$

3. **Scaling law**: curves proposed by Baker (1983) to convert total energy (mechanical + chemical) in overpressure

BLEVE

Integral models (combustion) - Results





TNO: most conservative model

Overestimation at low pressure (2, 4 bar)

BLEVE

CFD analysis

Main finding dynamic of pressure wave
Influence on the overpressure and impulse of:

- hydrogen liquid and gaseous phase
- hydrogen mass
- initial temperature and pressure

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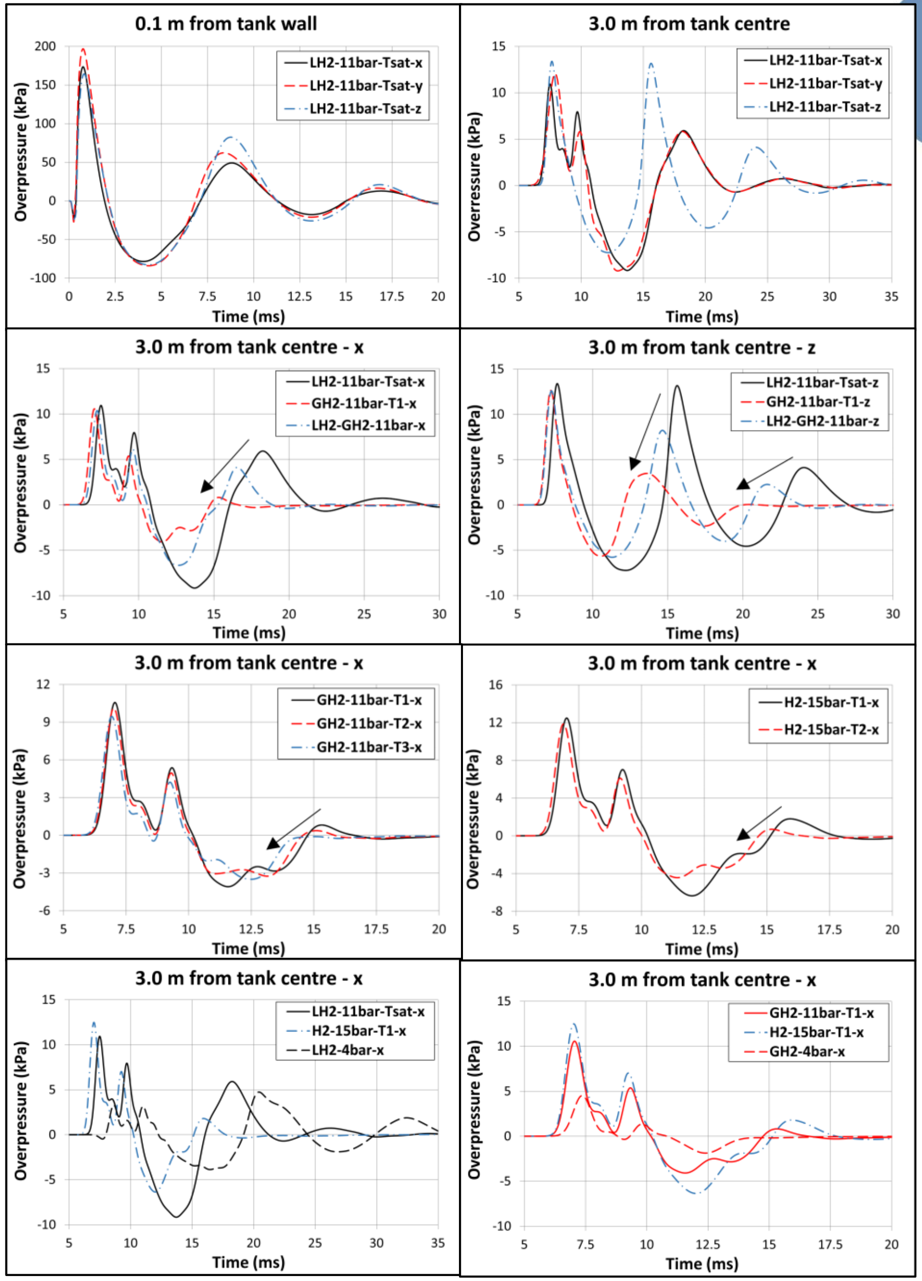
ELSEVIER

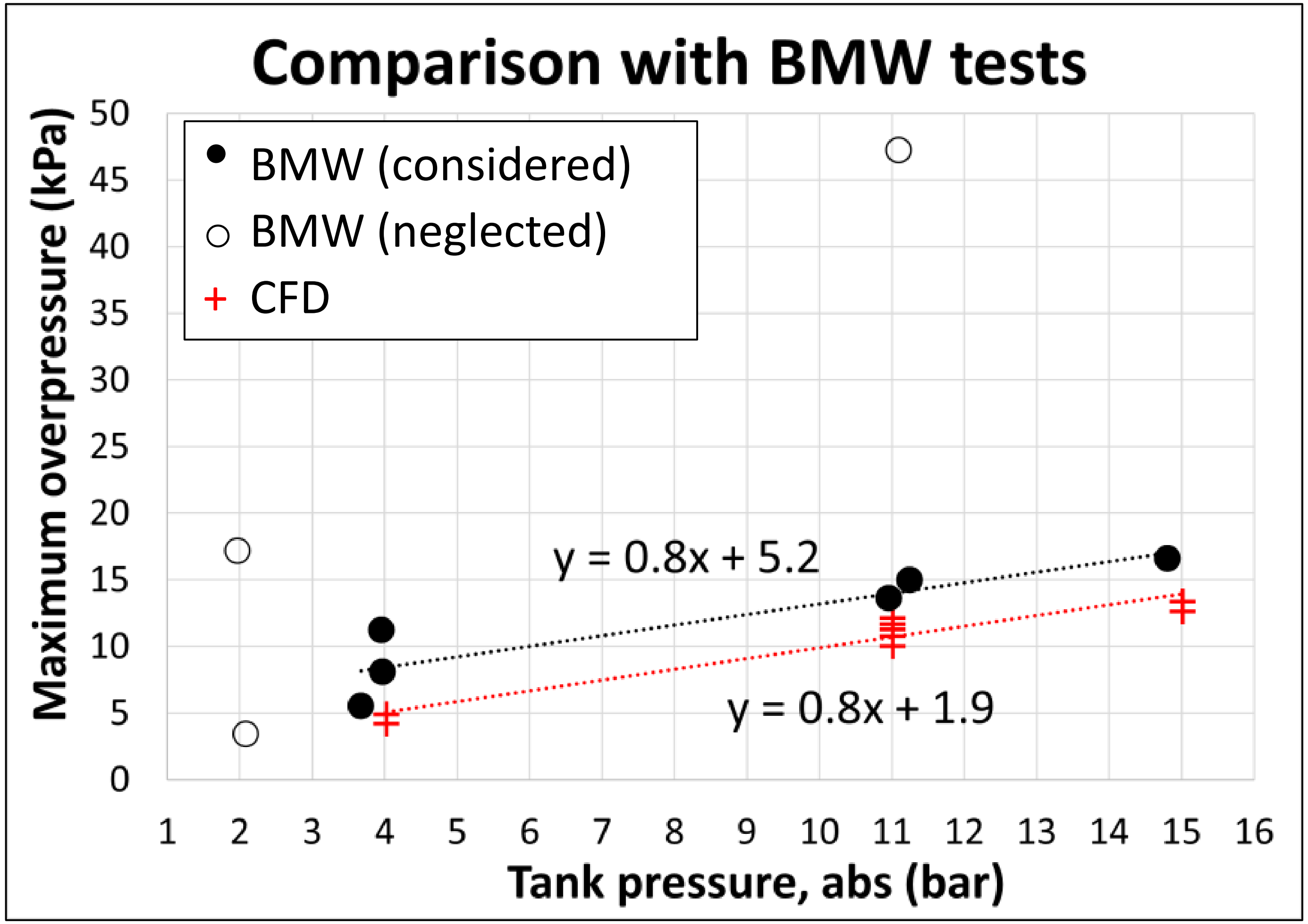
A CFD analysis of liquefied gas vessel explosions

Federico Ustolin[a,b,*], Ilias C. Tolias[a], Stella G. Giannissi[b], Alexandros G. Venetsanos[b], Nicola Paltrinieri[a,c]



BLEVE

LH_2 BLEVE CFD analysis



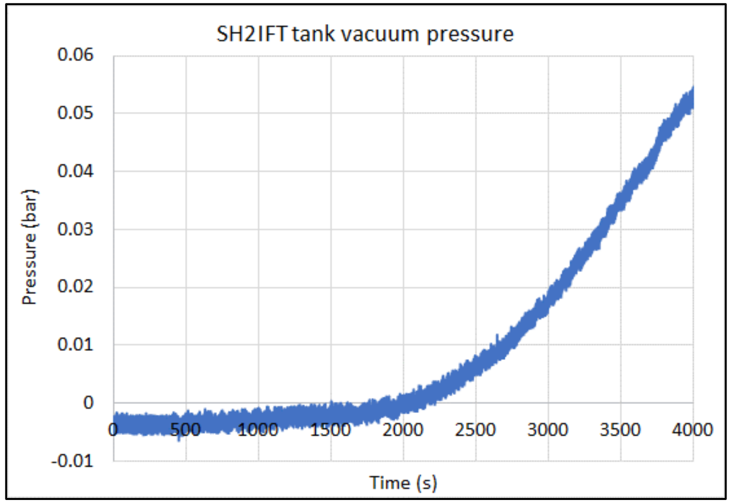
Speculation: the difference in overpressure is caused by the combustion (not simulated)

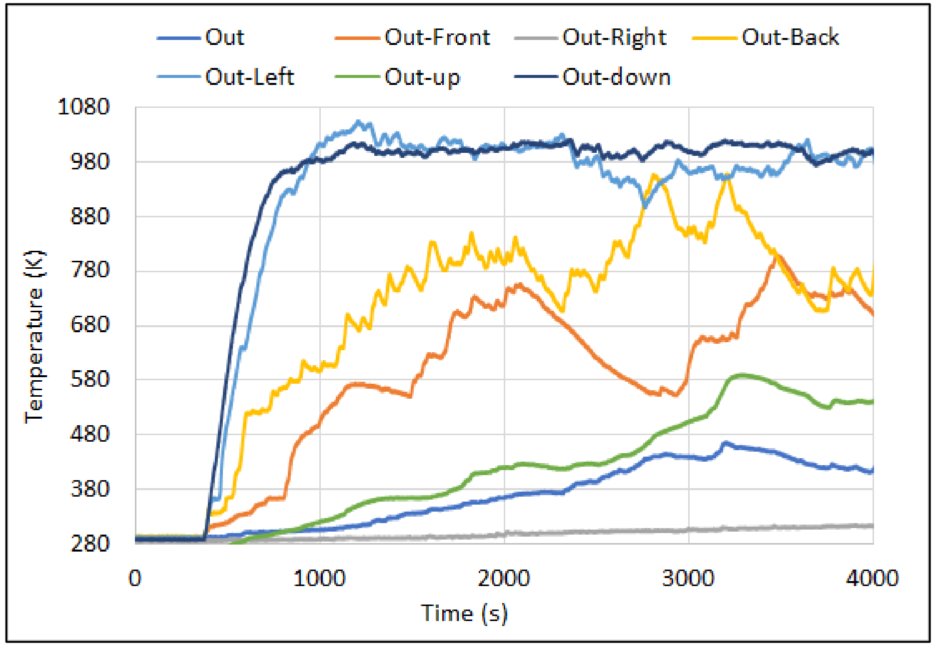
BLEVE

Discussion

Fire test

- ➢ material behaviour (e.g. tank insulation) exposed to fire must be investigated
- ➢ outdoor conditions in medium-scale tests are difficult to control and affect the simulations
- ➢ initial conditions (e.g. mass and temp.) affect the simulation outcomes





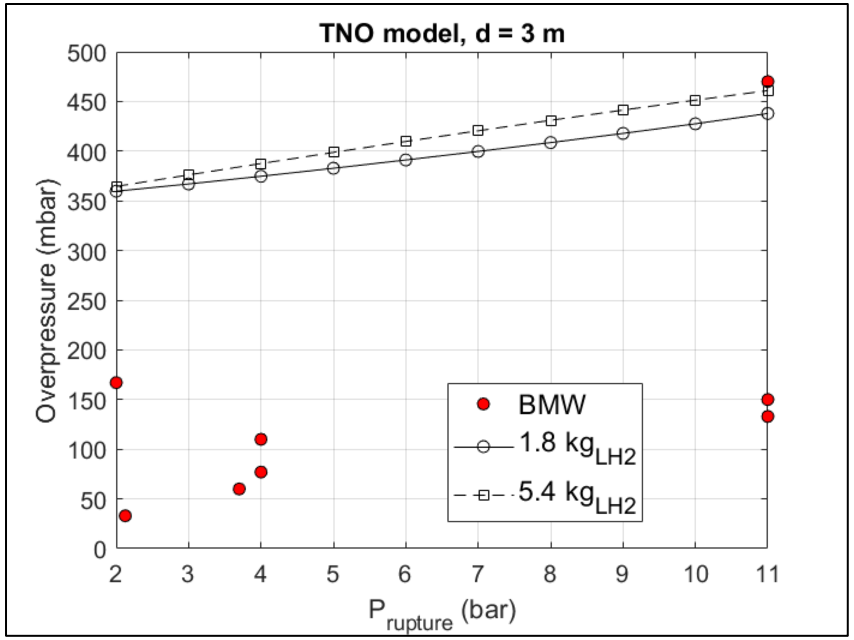
Temperatures measured in different positions on the outer LH2 tank shell during the SH2IFT fire test

Discussion

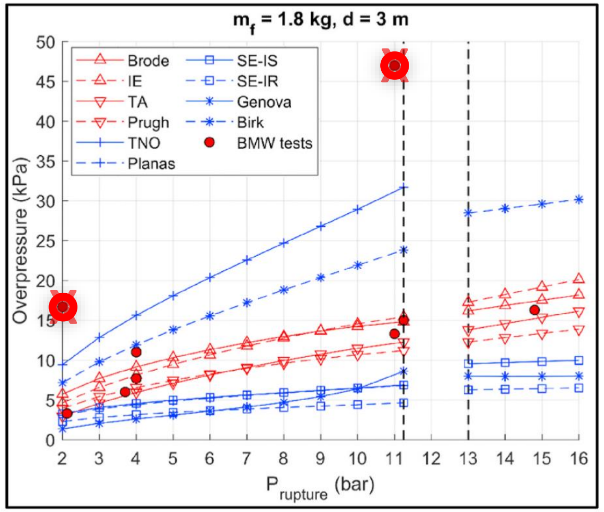
Catastrophic rupture (BLEVE)

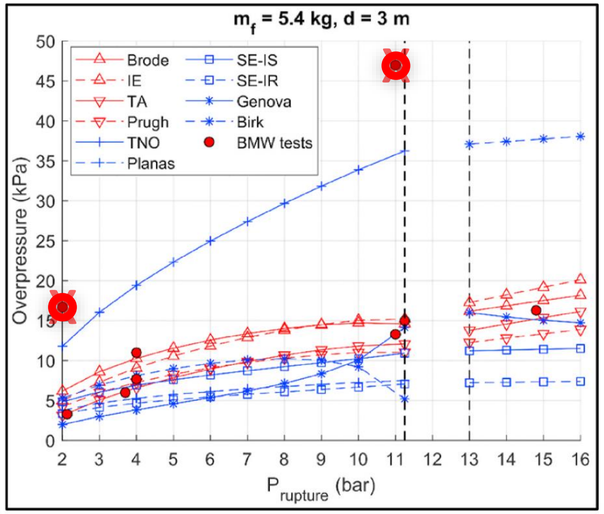
- ➢ correlation between initial conditions (e.g. LH2 and GH2 mass, temperature) and blast wave yield
- ➢ combustion process should be considered to estimate the LH2 BLEVE pressure wave to avoid underpredictions

With combustion contribution



Without combustion contribution



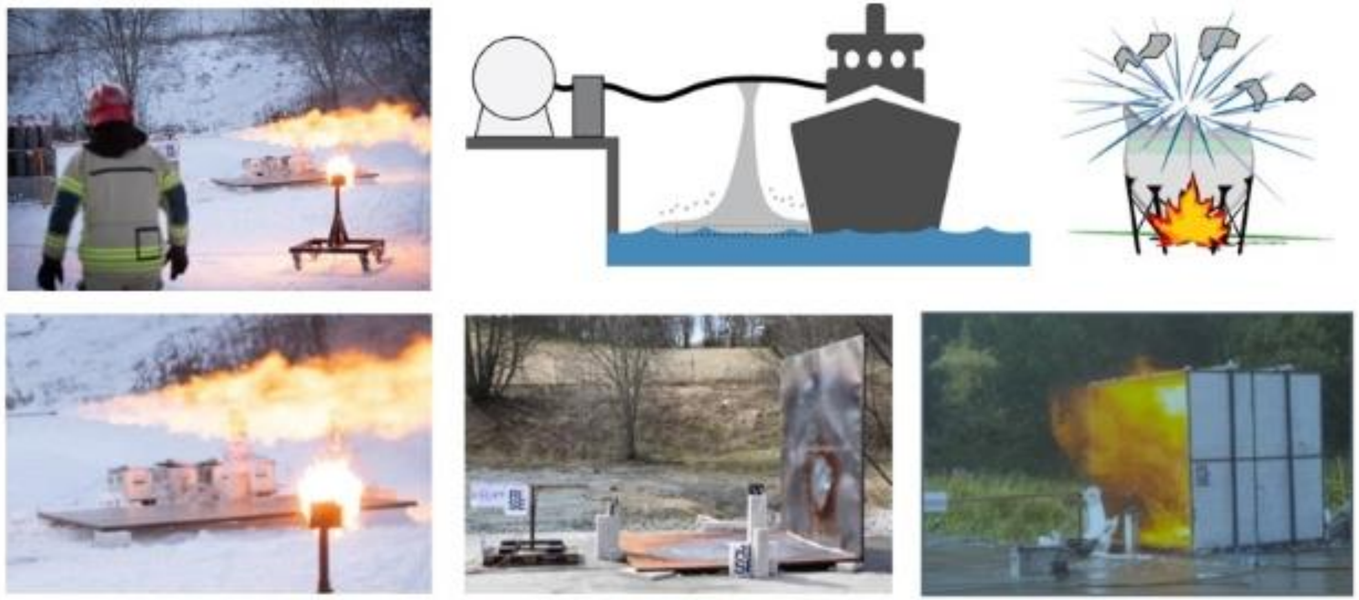


Conclusions

Despite the uncertainties and highlighted knowledge gap:

- ✓ developed models show good agreement with experiments
- ✓ physical, lumped and CFD models are good starting points for developing more accurate models
- ✓ Currently, the models are used to simulate the SH2IFT experiments

Thank you for your attention



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