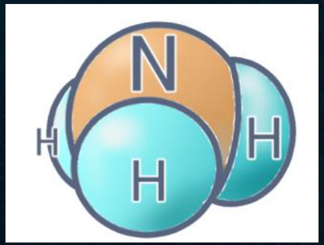
Hydrogen Safety from Liquid to Gaseous

SH2IFT Final Project Workshop

Olav Roald Hansen

May 3rd, 2022

HYEX SAFETY



LH2 interesting challenge

What are the hazards, concerns and uncertainties?

- LH2 colder than freezing point of air
- High reactivity / wide flammability / low ignition energy
- Can LH2-vapour detonate?
- Is LH2-vapour dense or buoyant?
- Oxygen enriched condensed air + LH2 detonation …
- Exothermic ortho to para-conversion …
- Sloshing – will we manage to keep pressure in tank?
- Vent mast explosion?
- Is RPT a concern? What about BLEVE?

Main safety challenges LH2 vessel design

- Storage tank and TCS
- Bunkering
- Fuel cells
- Gas mast
- Ensure stable power generation


Illustration 2018 LH2-ferry – Tender lost

Norled.no


Illustrasjon LH2-yacht


Havila.no


HYEX Safety model

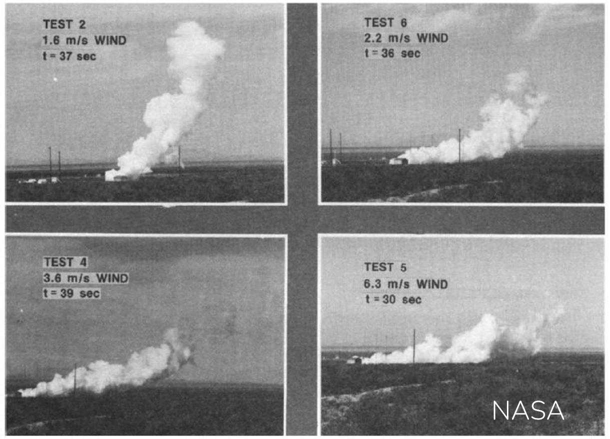
Experiments have helped understand LH2

AD Little (1960)

- Dispersion, explosion, condensed air detonation ++

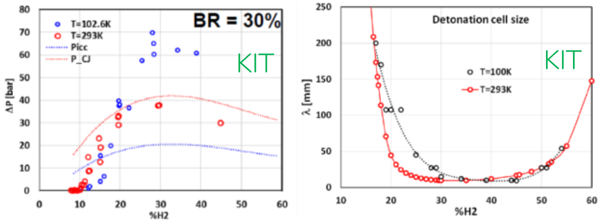
NASA (1984)

- Limited pool formation – vapour cloud dense and buoyant



PresLHy (2019-2021)

- HSL - dispersion/explosion/water spray (condensed air detonation, 2010)
- KIT – reactivity and detonation propensity for cold mixtures, pool and condensed air detonation

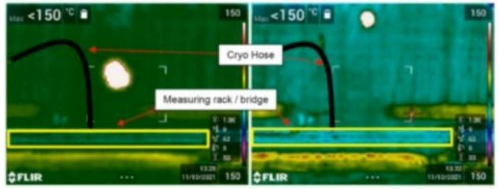


NPRA & DNV (2019-2020)

- TCS major leak and explosion challenges
- Major LH2 releases with ignition relevant for bunkering

SH_2IFT(2018-2022)

- RPT and BLEVE tests



NPRA tests – valuable to give confidence to quantitative models

How to model LH2-release and ignition tests with precision?

- Near field representation, buoyancy aspect, plume behaviour, concentrations and temperatures
- Self-developed pseudo-approach developed 2018 used, see Hansen (2020)

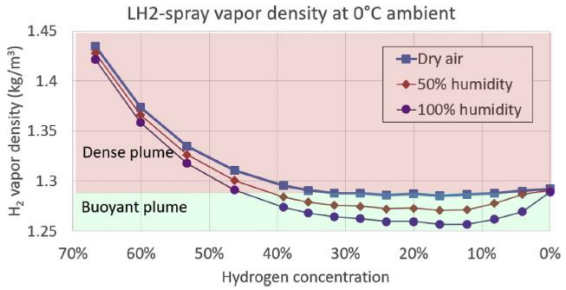
Table 2: Experiments and simulations compared.

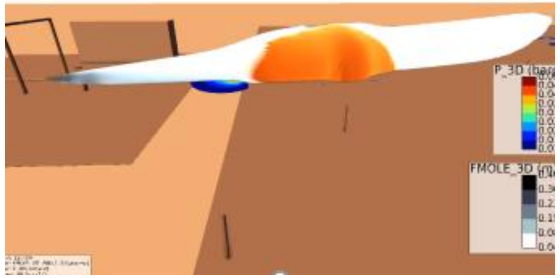
Test	Leak direction	Wind	Distance	Concentration Experiment	Simulation	Temperature Experiment	Simulation
5	739 g/s down	4 m/s	30 m	7.6%	~7%	-8.5°C	-9°C
			50 m	2% (T3: 3.5%)	3.5%	-2°C	-3°C
			100 m	1.5%	2.0%	Not readable	0°C
6	833 g/s along wind	2.5 m/s	30 m	21%	22-23%	-35°C	-50 °C
			50 m	2% (missed arc)	8%	-2°C (T4: -13°C)	-20 °C
			100 m	No recordings	Plume lift-off	No recordings	Plume lift-off

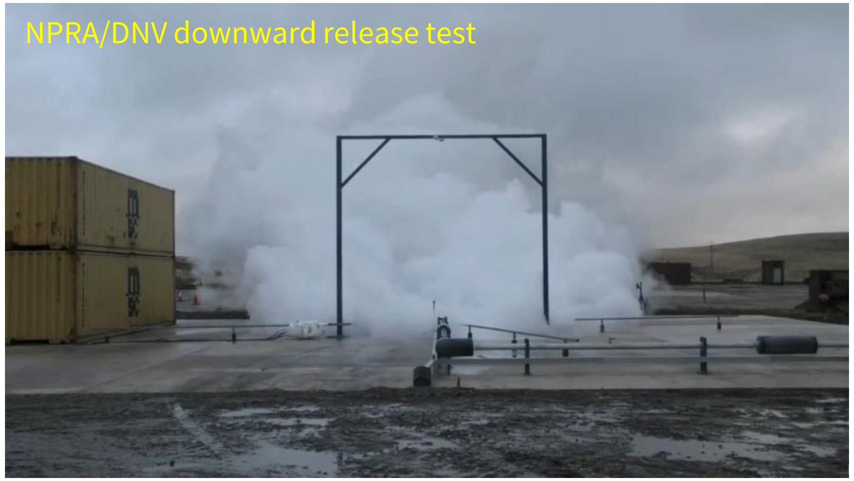
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 45 (2020) 1343–1358
Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/he
ELSEVIER

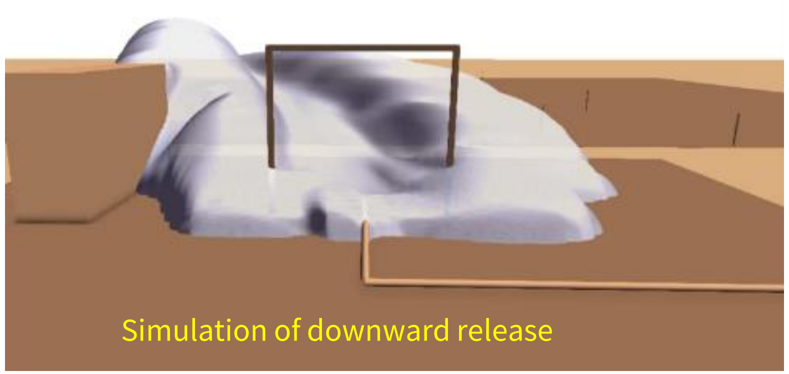
Liquid hydrogen releases show dense gas behavior

Olav Roald Hansen









Deflagration to detonation transition (DDT)

DDT to be expected for strong hydrogen explosions

- With DDT entire reactive cloud (> 15-18%) may burn within milliseconds
- Method to model detonation with FLACS with decent precision found (see Hansen & Johnson, 2015)


Journal of Loss Prevention in the Process Industries 35 (2015) 293–306

Contents lists available at ScienceDirect

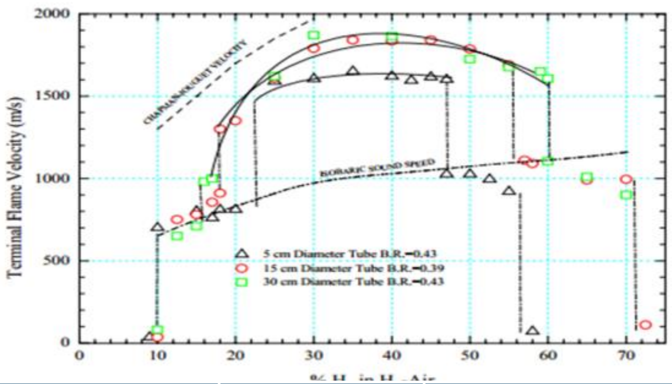
Journal of Loss Prevention in the Process Industries

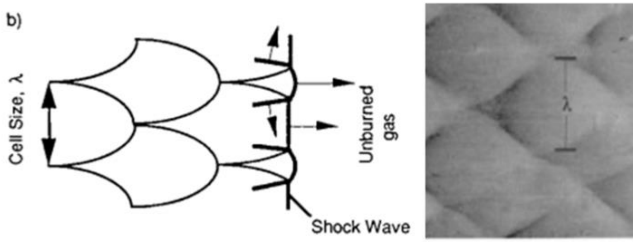
journal homepage: www.elsevier.com/locate/jlp

Improved far-field blast predictions from fast deflagrations, DDTs and detonations of vapour clouds using FLACS CFD

Olav R. Hansen [a, *], D. Michael Johnson [b]

[a] Lloyd's Register Consulting, Bergen, Norway
[b] DNV GL Group, Loughborough, UK





Property	Hydrogen	Methane
Detonation initiation	1 g TNT	1000 g TNT
Detonation cell size	1 cm	30 cm
Detonation pressure	15.8 bar	17.4 bar
Detonation velocity	1968 m/s	1802 m/s
Detonation limits	~15-60%	5-15%

Kjørbo incident – likely DDT and detonation

Significant leak (0.5-1.0 kg/s for 3 s) from ~950 bar storage

- High-momentum release near ground inside enclosure
- Concentrations above 15% H_2 rise upwards
- After ~3 s turbulent gas cloud near release ignites and accelerates to DDT
- Reactive cloud above enclosure detonates
- Hard (impossible?) to explain far-field blast without DDT

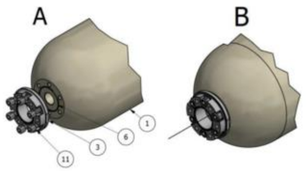

– Alle airbagene ble utløst

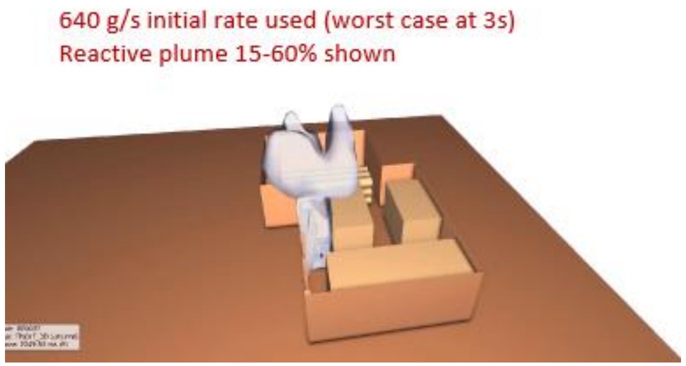
Hunden Lulu (l) ble skremt av hydrogeneksplosjonen: – Hoppet ned ni meter

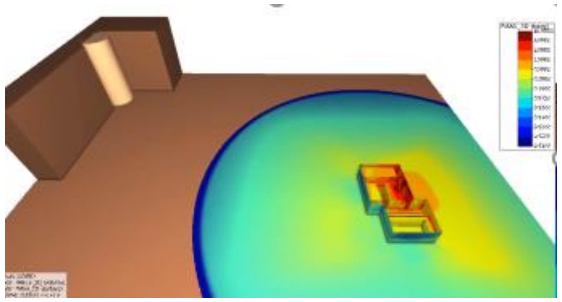
Kjørbo Incident 2019

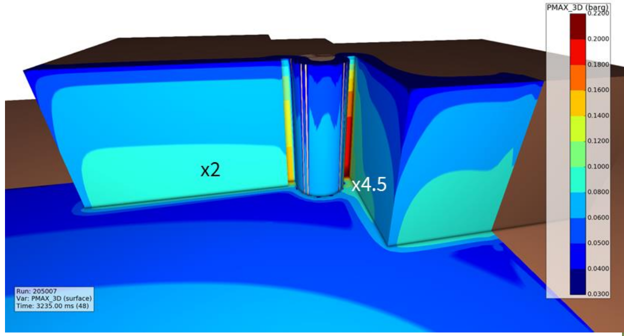
DDT and detonation simulations regularly performed in hydrogen studies

- Detonation not always worse than deflagration – but different
- Detonation gives strong blast in all directions









HYEX SAFETY

Gaseous hydrogen – more popular due to cost and availability

The use of MEGC – 20 and 40 ft multi-element compressed gas containers, on the increase

Safety challenges compared to LH2

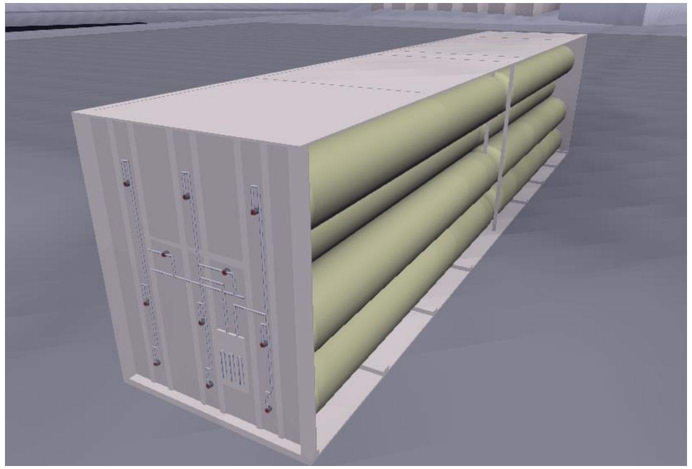
- Much more leak points
- High pressures
- Vulnerable to fire and impact
- Logistics – only 500-1000 kg per container

UMOE Advanced Composited tanks

Hexagon Purus X-store MEGC

Safety advantages compared to LH2

- GH2 very buoyant when released (outdoors)
- Energy per cylinder much lower
- No boil-off (but some limited permeation)

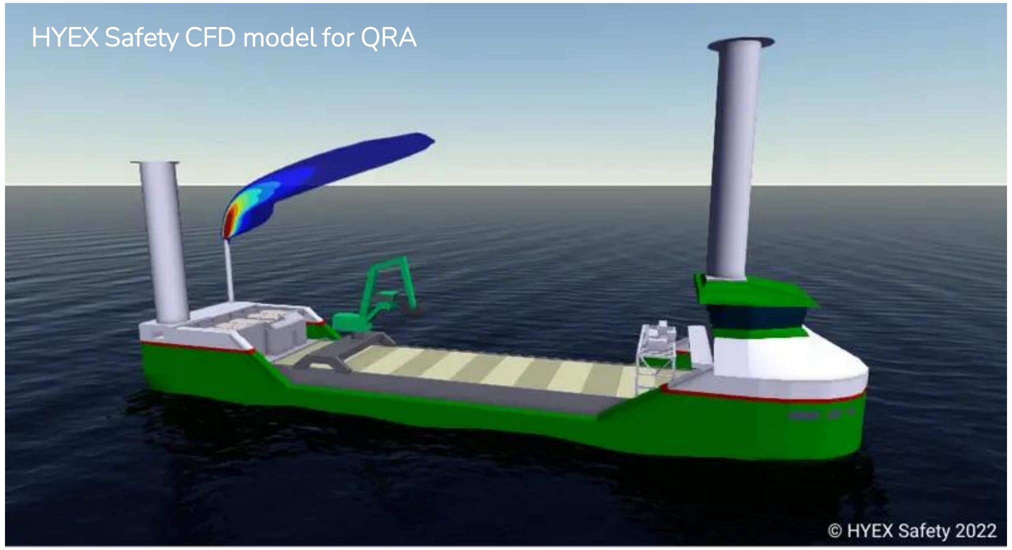


HYEX CFD simulation models

Gaseous hydrogen – more popular due to cost and availability

Hydrogen vessel projects on GH2

- Bodø-Moskenes car ferry 3h open sea crossing
- Felleskjøpet Agri-Heidelberg Cement
- MSC Maas retrofit (Futureproof Shipping)
- ZeroCoaster concept (Vard Engineering)
- Gen2Energy / Sirius hydrogen MEGC transport vessels



High-pressure tank ruptures

High-pressure hydrogen tanks

- Impact or jet-fire may lead to tank rupture (~1 per million years)
- Blast from physical explosion
- If ignition is delayed, gas explosion may give 2x-4x stronger blast

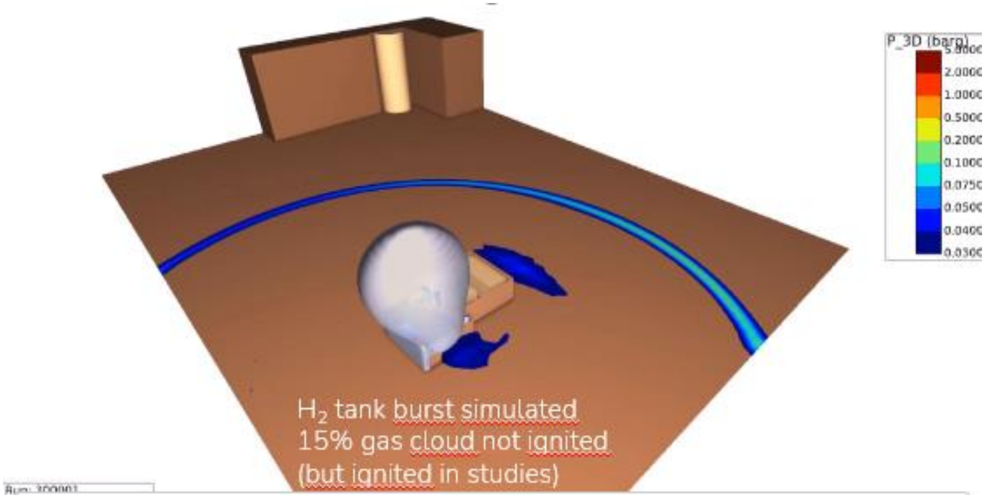
FLACS-simulations of tank rupture regularly performed in studies

- High speed of sound in hydrogen gives strong physical explosions
- Challenging to model tank burst, very high flow speeds (> 2000 m/s)


Netherlands NG-bus


Perugia NG-bus – April 2022


Stockholm NG-bus 2019 – rupture + delayed ignition/explosion



H_2 tank burst simulated
15% gas cloud not ignited
(but ignited in studies)

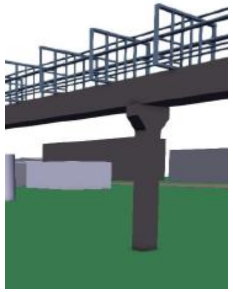

H_2 350 bar transport containers at Kjørbo
No burst – but TPRDs activated and damage

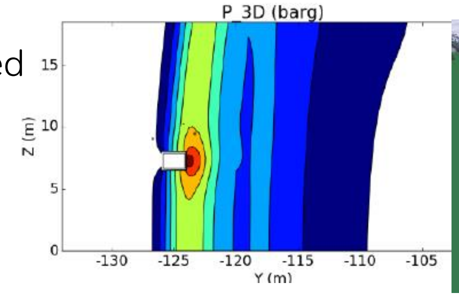

Stockholm NG-bus 2019

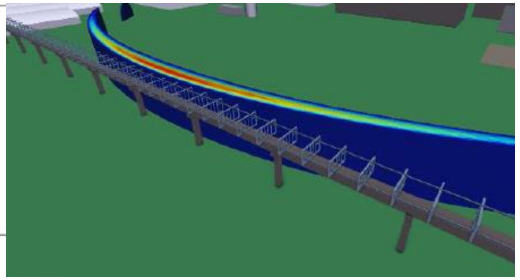
Extracting explosion loads – pressure versus impulse

What will be received blast load onto people and structures?

- Proper modelling of blast source and receiving object
- Load integration using panel method illustrated in Hansen et al. (2016)
- Detailed transient and directional loads on piperack sections can be extracted







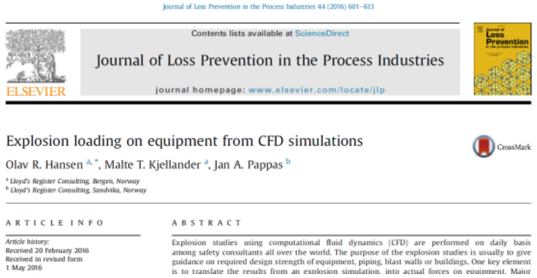
Journal of Loss Prevention in the Process Industries 41 (2016) 382–398
Contents lists available at ScienceDirect
Journal of Loss Prevention in the Process Industries
journal homepage: www.elsevier.com/locate/jlp

Estimation of explosion loading on small and medium sized equipment from CFD simulations

Olav R. Hansen [a,*], Malte T. Kjellander [a], Remi Martini [a], Jan A. Pappas [b]
[a] Lloyd's Register Consulting, Bergen, Norway
[b] Lloyd's Register Consulting, Sandvika, Norway

ARTICLE INFO
Article history:
Received 16 May 2015
Received in revised form

ABSTRACT
Explosion studies for design purposes are performed on daily basis among safety consultants all over the world. For oil and gas facilities offshore, and often onshore, the computational fluid dynamics (CFD) tool FLACS is usually applied, while others use simple blast curve formulations, like the TNO-Multi Energy



Journal of Loss Prevention in the Process Industries 44 (2016) 601–613
Contents lists available at ScienceDirect
Journal of Loss Prevention in the Process Industries
journal homepage: www.elsevier.com/locate/jlp

Explosion loading on equipment from CFD simulations

Olav R. Hansen [a,*], Malte T. Kjellander [a], Jan A. Pappas [b]
[a] Lloyd's Register Consulting, Bergen, Norway
[b] Lloyd's Register Consulting, Sandvika, Norway

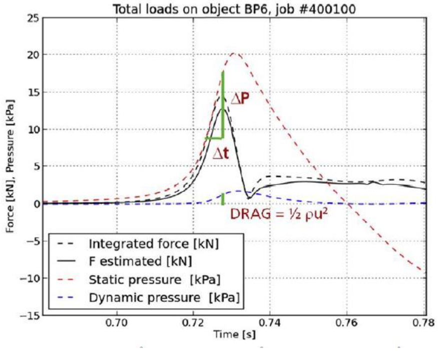
ARTICLE INFO
Article history:
Received 20 February 2016
Received in revised form
1 May 2016

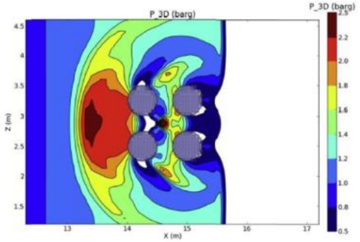
ABSTRACT
Explosion studies using computational fluid dynamics (CFD) are performed on daily basis among safety consultants all over the world. The purpose of the explosion studies is to give guidance on required design strength of equipment, piping, blast walls or buildings. One key element is to translate the results from an explosion simulation into actual forces on equipment. Major

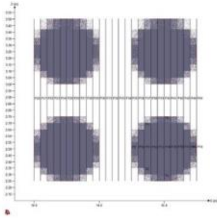
$$Force(t) = \frac{1}{2}C_d\rho A|U(t)|U(t) + (\rho V + m)\frac{\partial U}{\partial t} + \frac{\partial p}{\partial t}VU(t) + F_{DP} + F_{HE}$$

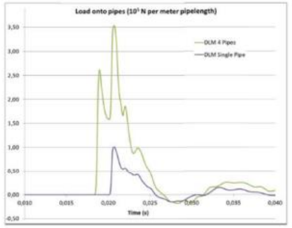
Form drag — Accelerated mass — Flame effects — Differential pressure — Oscillations

Force/area(t) = Drag(t) + Ps(t) - Ps(t-Δt)









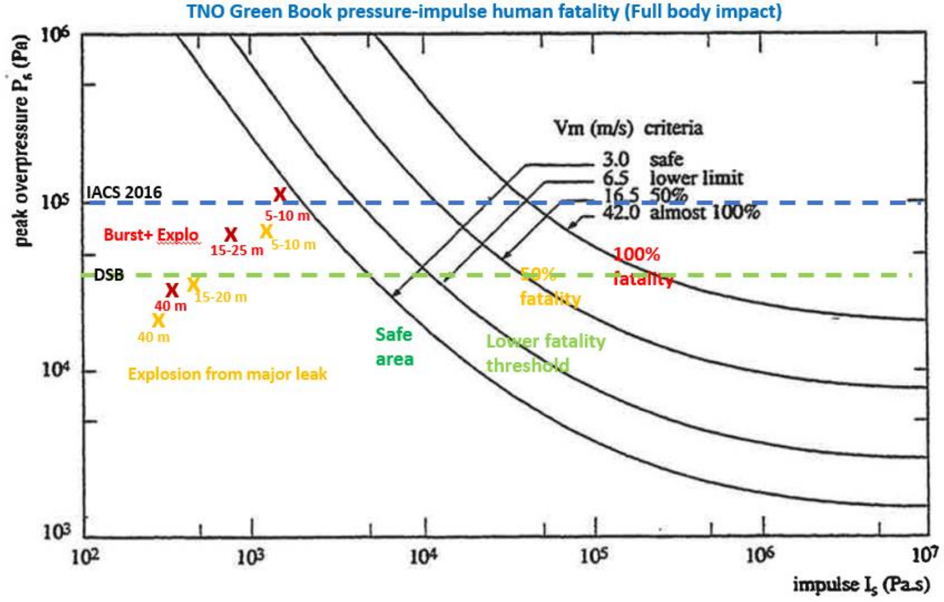


Fig. 11: P-I graph for impact of the whole body.

Summary

Important to understand hydrogen properties and behaviour for safe design

- Experiments helps understand/confirm mechanisms
- For design optimization and permitting/approval processes– quantitative assessments usually required
- Important phenomena to quantify include
  - LH2-vapour dispersion, humidity effects to be considered
  - Tank burst and potential delayed ignition
  - Explosions (leak, dispersion deflagrations/detonations)
- Consequence models and methodology should be validated against relevant experiments

- Risk tolerance criteria are often very strict e.g.

DSB - 1E-5, 1E-6 and 1E-7/year

IMO - fraction of 1E-3 to 1E-4/year

⇒ For many cases worst-case events must be tolerable (e.g. MEGC tank rupture)

⇒ Worst-case events should anyway be assessed to understand dynamics – possibly there are ways to mitigate?

- Important to assess received explosion load properly – acting force and impulse (H_2 explosions of short duration)

Thank You

Mail: olav@hyexsafe.com
Phone: +47 91 17 17 87
www.hyexsafety.com

HYEX SAFETY