Explosion risk in hydrogen facilities – balancing simplified and comprehensive approaches

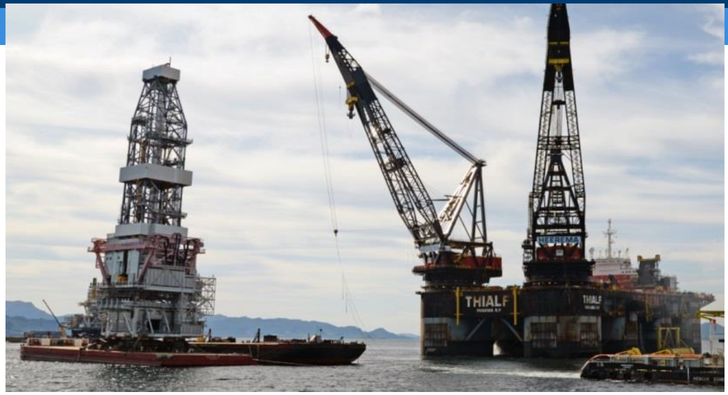
Olav Roald Hansen

35th anniversary UKELG meeting Oct 10-12, 2017 Spadeadam

Lloyd's Register

Working together for a safer world

Hydrogen explosion risk – growing field, but still "behind comma"…



Oil and gas projects still #1 source of income

Example:

Johan Sverdrup field – LQ, P1, DP, RP and P2 platforms

(peak production 660 000 bpd)

LR providing safety studies

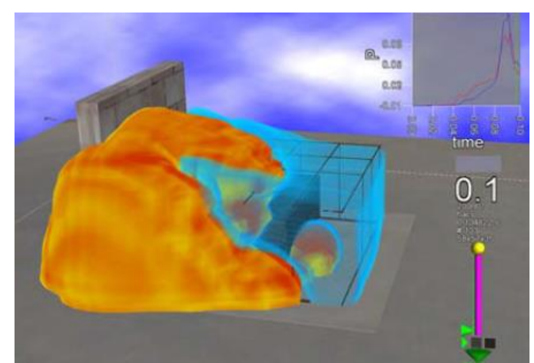
FEED, Detail Design, As-Built 2014-today

Experience within hydrogen safety

25 years CFD-dispersion/explosion modelling FLACS

- 19y CMR/GexCon, 2y GL Noble Denton and 4y LR
- 1998=> make FLACS a hydrogen safety software
- 1998-2004 R&D test projects – dispersion and explosion
- 2001-2008 – Responsible R&D and sale of FLACS CFD
- 2004-2010 EU-project HySAFE (25 partners in Europe)
- 2004-2012 IEA Expert Groups Hydrogen Safety
- Various consulting work hydrogen safety
- 15+ scientific articles within hydrogen safety

UKELG
1998 Harwell (FLACS & deluge)
2004 Cheshire (FLACS Hydrogen)
2007 Kingston (Large scale tests-overview)
2013 Cardiff (DDT and detonation modelling)
2017 Spadeadam (Hydrogen risk assessments)



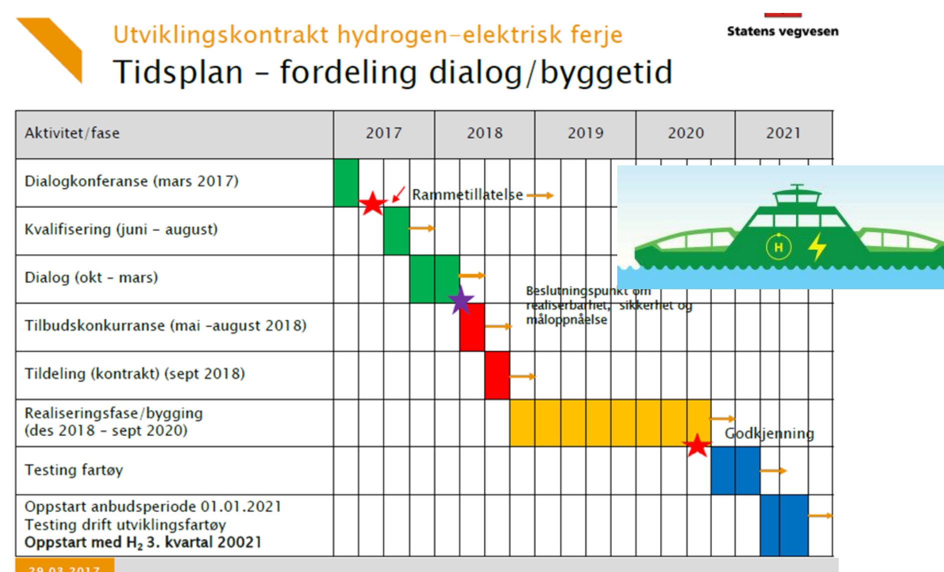
Hydrogen safety projects picking up in Norway?

- 20 hydrogen refuelling stations planned (~5 built)
- Solar H_2 production for truck refuelling
- Hydrogen car ferry by 2021
- Numerous other marine initiatives

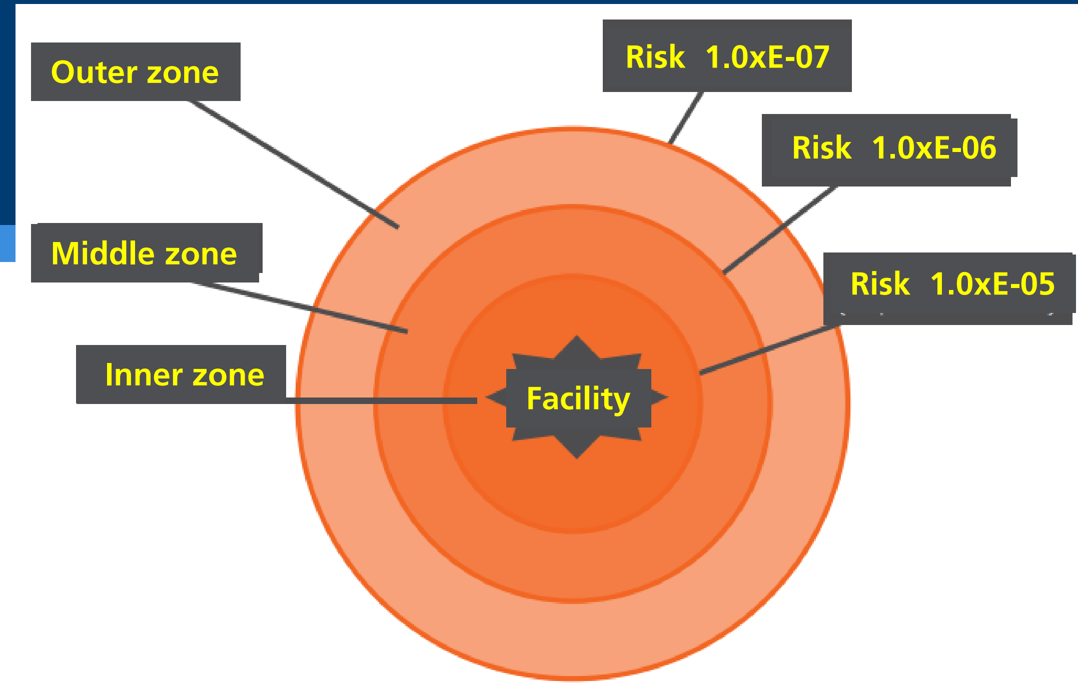
Electric & hydrogen: Positive for local pollution and noise

Bergen: ~50% of sold cars EL&plug-in

Region: Majority of 16 car ferry connections to become electric



Siting studies facilities



Inner zone (fatality risk >1E-5):

Normally within property limits#

1st party (workers on the site)

Intermittent exposure of 3rd party may be allowed

Middle zone (1E-5> fatality risk > 1E-6):

Public roads, rail, harbour areas etc.

Industrial sites and offices

No hotels or homes (scattered homes may be allowed)

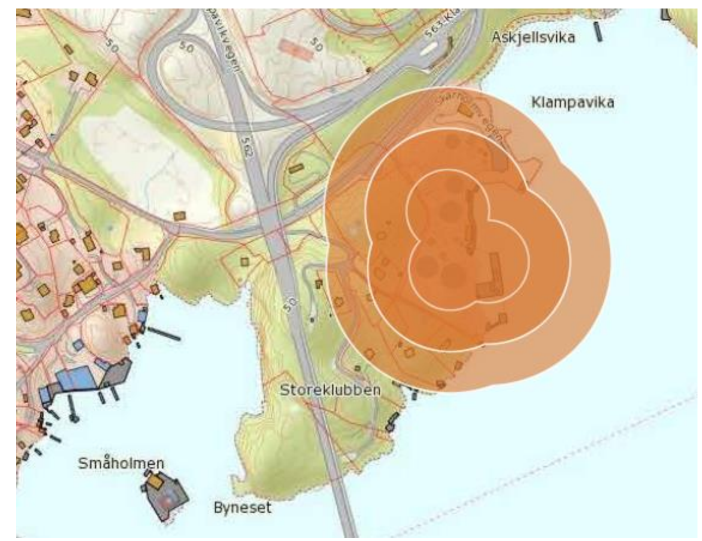
Outer zone (1E-6> fatality risk > 1E-7):

Homes, shops, guesthouses

Beyond outer zone (fatality risk < 1E-7):

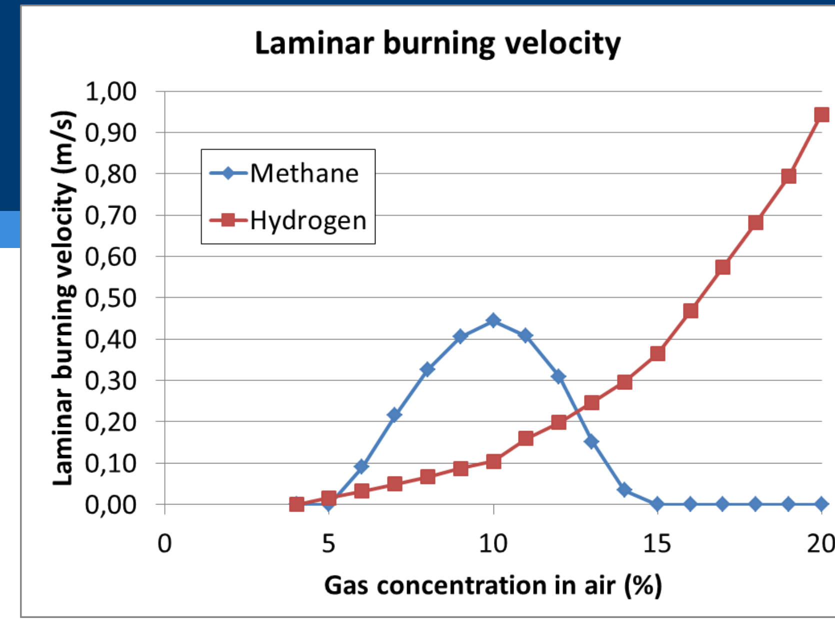
Schools, kindergarten, hospitals, care homes

Shopping malls, hotels and arenas



Vulnerability assumptions also required:
Pressure (people and buildings), radiation, projectiles

Hydrogen risk assessment approaches



Some important aspects with hydrogen:

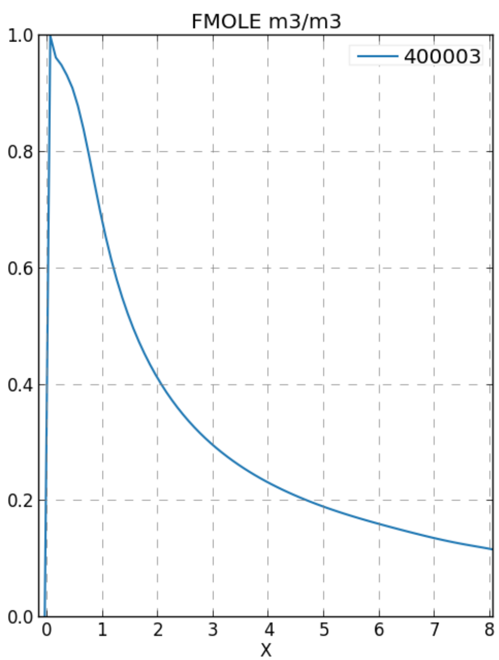
1) Explosion risk very low with < 10-15% H_2 in air $P \sim Bv^2$

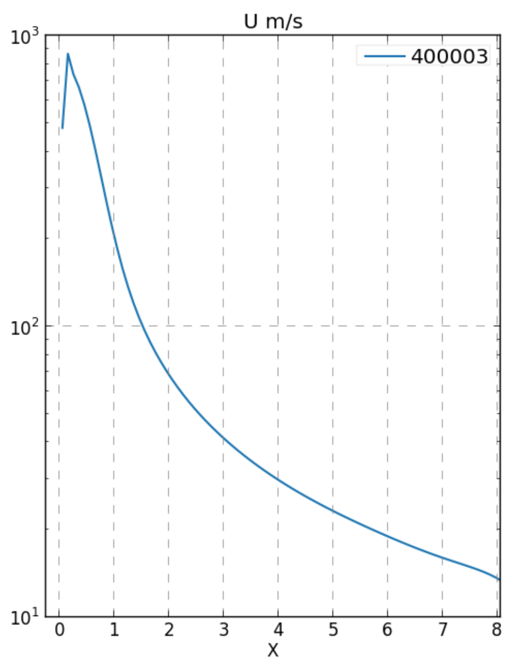
2) Buoyancy very high (reactive gas concentrations)

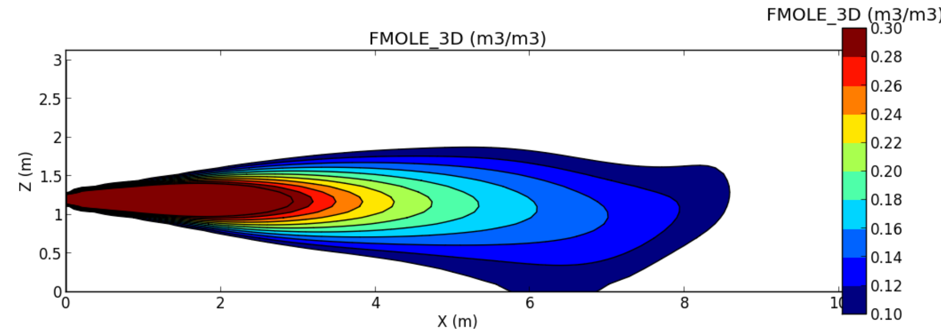
3) Jet velocity & mixing high

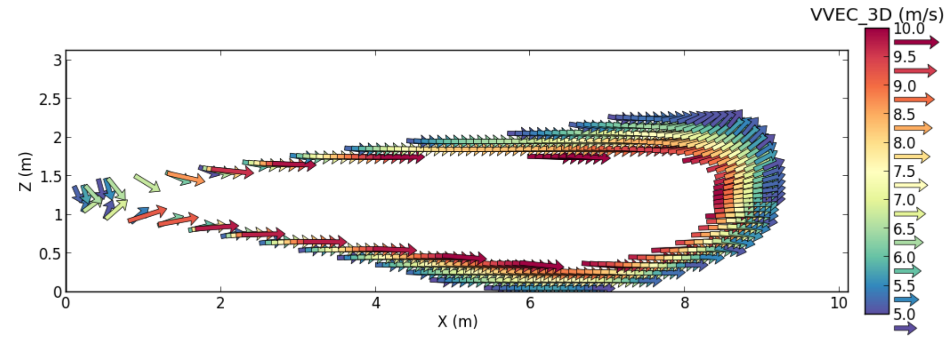
4) Wind mostly irrelevant; no need to assess 12 directions 2F & 5D

=> Simplified assessment useful in many cases









Hydrogen risk assessment approaches

Simplified assessment useful in many cases (LR risk screening sheet developed by Olav RH shown)

Input in orange cells only	Estimated	Input	Unit	Input in orange cells
Segment volume		0,1	m3	
Segment pressure		200	bara	
Segment temperature		293	K	
Pipe or vessel diameter		16	mm	Diameter at location of release
Upstream flow restriction/orifice		0	mm	Orifice diameter, not used if zero
Hole size	4,61	5	mm	Hole size, estimate consider pipe & restriction
Discharge coefficient		0,85	(-)	Cd=1.0 to fit NFPA-2, Cd=0.85 recommended
Release rate	176,65	0,00	g/s	Manual input used if greater than zero
Release rate (g/s) at given time (s)	33	20	g/s and s	Input (s) gives estimated release rate
Kompressibility factor Z	1,12		(-)	Estimated using Boyle-Charles equation
Detection and isolation time		5	s	if no isolation, use big number
Total mass segment	1,50		kg	
Deflagration pressure ignited jet	0,077	0,00	bar	Manual input used if greater than zero
Deflagration volume (Q9)	0,77	0,00	m3	Manual input used if greater than zero
Detonation volume (Q8)	15,54	0,00	m3	Manual input used if greater than zero
Vessel burst- volume of vessel		2335	liter	Using segment pressure and temperature above

Dispersion	Safety distances jet releases						Cloud sizes							
	LFL (4%)		8 %		15 %		Flammable cloud		8% cloud		Q9		Q8	
Free jet	17,72	m	8,86	m	4,43	m	60,11	m3	7,51	m3	0,77	m3	15,54	m3
Near ground or vertically	22,15	m	11,07	m	5,54	m	84,15	m3	10,52	m3	1,08	m3	21,76	m3

Jet fires	Distance		Radius to contours		Rmax				Chosen radiation level		Visible flame length	
Radiation distances jet fire	max radiation		1,58kW/m2		4,73kW/m2		25,2 kW/m2		12,5	kW/m2	Lvis	
Free jet	4,72	m	7,75	m	4,47	m	1,94	m	2,75	m	7,43	m
Near ground or vertically	5,90	m	10,27	m	5,93	m	2,57	m	3,65	m	9,29	m
	X(Rmax)		Drad (total safety distance)									
Free jet			12,47	m	9,19	m	6,66	m	7,47	m		
Near ground or vertically			16,17	m	11,83	m	8,47	m	9,55	m		

Vessel burst	Distance to pressure level						Pressure level			Distance		"Loose brick"			
Safety distances and loads	1 barg		0.2 barg		0.05 barg		0,065	bar		2	m	length	0,2	m	
Distance	9,86	m	24,59	m	56,89	m	46,89	m	Pressure	18,709	barg	density	2000	kg/m3	
Pressure impulse	249,2	Pa s	110,9	Pa s	51,89	Pa s	59,2	Pa s		860,9	Pa s	area	0,015	m2	
Pressure duration	5,35	ms	11,91	ms	21,41	ms	18,40	ms		1,01	ms	side-on impulse	0	Pa s	If zero Q17 im
Reflected loads									Reflected			projectile	Side-on blast		Reflected
Reflected pressure	2,00	barg	0,40	barg	0,10	barg	0,13	barg		37,42	barg	weight	6	kg	
Reflected impulse	498,5	Pa s	221,8	Pa s	103,8	Pa s	118,4	Pa s		1721,9	Pa s	velocity	2,15	m/s	4,30
Reflected pressure duration	5,35	ms	11,91	ms	21,41	ms	18,40	ms		1,01	ms	energy	0,01	kJ	0,06
												max distance	0,47	m	1,89

Gas explosion pressures	Initial pressure	Distance	5	m	10	m	15	m	20	m	60	m
Deflagration	0,077	bar	0,038	bar	0,019	bar	0,013	bar	0,010	bar	0,003	bar
DDT	20	bar	1,422	bar	0,339	bar	0,179	bar	0,113	bar	0,033	bar

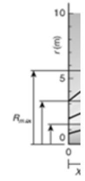
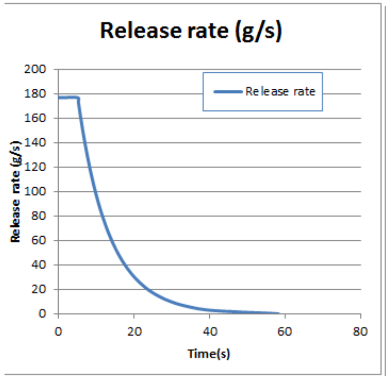


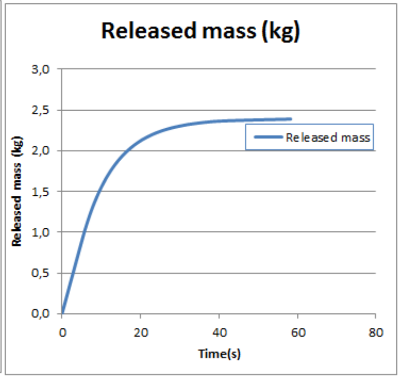
FIGURE E.4. Hydrogen Jet Tank Pressur

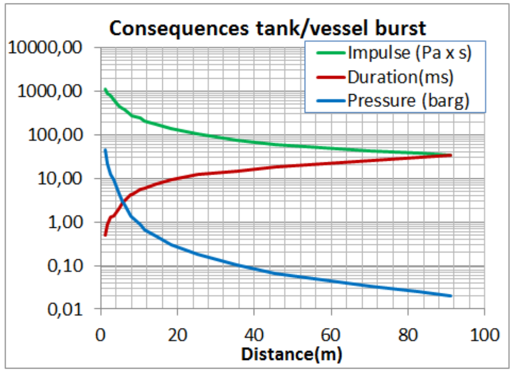
The xls-sheet is developed for efficient consequence modeling for hydrogen safety studies. The document is preliminary and being developed by Olav Roald Hansen.

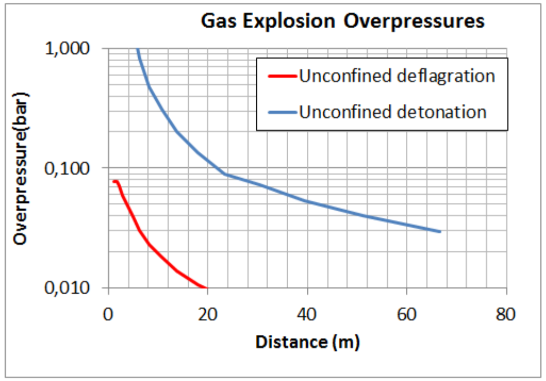
CFD-assessment should be performed if:
* Congestion/confinement within 10-15% dispersion distance
* Indoor with potential for gas build-up or explosion reflections
* Vessel burst among objects near vulnerable targets
* For exact estimates of explosion loads onto targets

Models:
- Boyle-Charles Compressibility factor
- Release rate - hole size and pipe impact
- Dispersion distances and cloud sizes
- Jet fire lengths and radiation levels
- TNO-Multienergy blast (deflagration&DDT)
- Vessel burst pressure, duration and impulse
- Projectile (loose brick) evaluation









Hydrogen risk assessments – when CFD is required

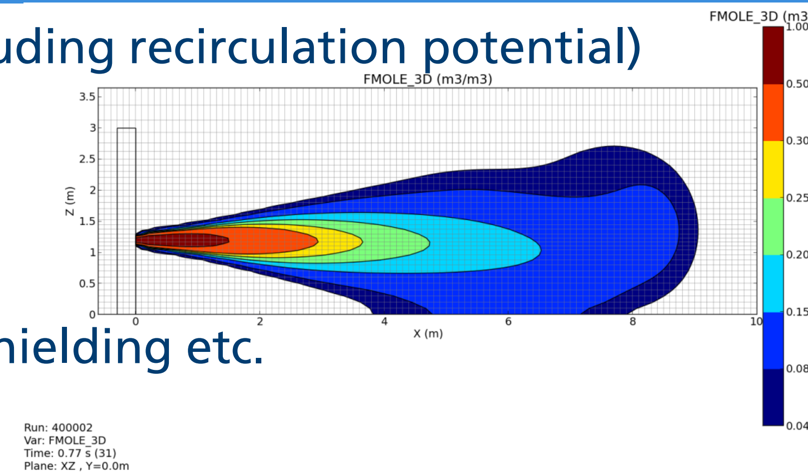
Concentration > 10-15% AND congestion or confinement (including recirculation potential)

⇒ Release and explosion effects

⇒ Pre-ignition (jet-) turbulence

⇒ Geometry effects at explosion source

⇒ Blast waves detailed loading (3D) – durations, reflections & shielding etc.



Most indoor scenarios….

- What detection time can be expected?
- Is emergency ventilation effective?
- What is actual release rate from pipe?
- Is there a potential for DDT, if so…

Vessel burst scenarios near targets

Liquid hydrogen

H_2 smallest molecule– 0.07 x density of air

- Important safety principle – hydrogen to disappear upwards

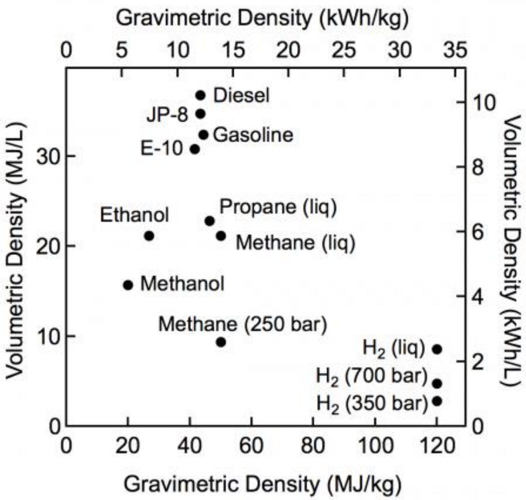
Exception: Liquid hydrogen (~20 K)

- Costly to cool (1/3 of combustion energy)
- Vapours denser than air, in particular pressurized releases
- Challenge: O_2 and N_2 “snow” due to condensation/freezing of air
- O_2-doped air may give strong increase of gas reactivity

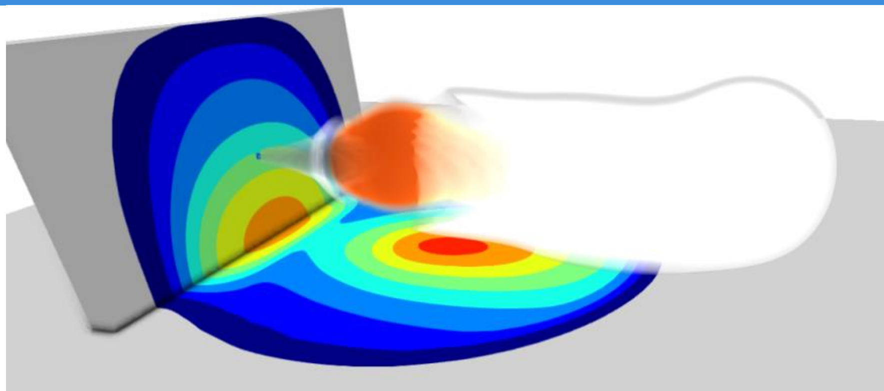
Photos from HSL experiments:

Ichard, M., Hansen, O.R., Middha, P. & Willoughby, D. (2012). CFD computations of liquid hydrogen releases. International Journal of Hydrogen Energy, 37: 17380-17389

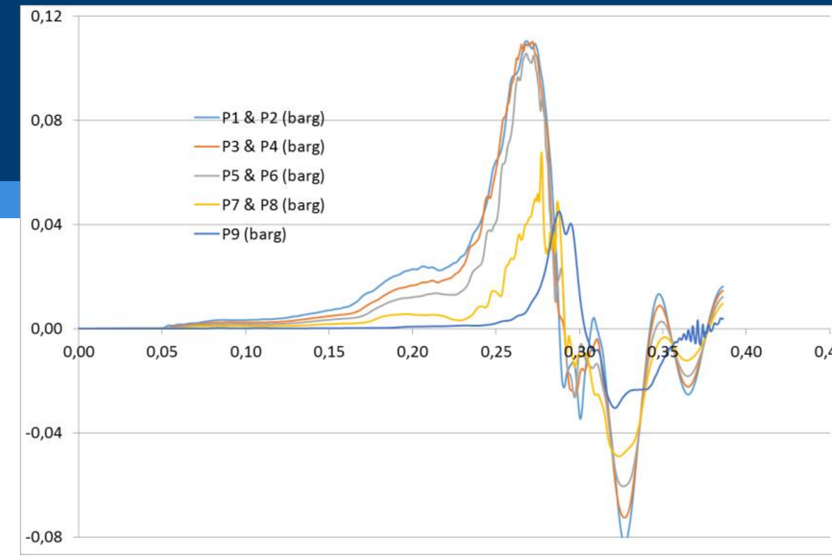
Storage/handling efficiency may require LH_2



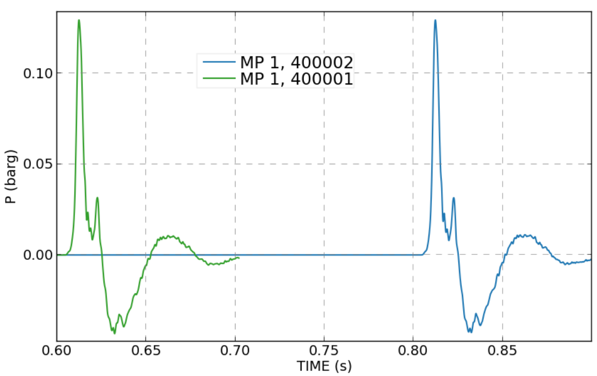
Pre-ignition turbulence & DDT

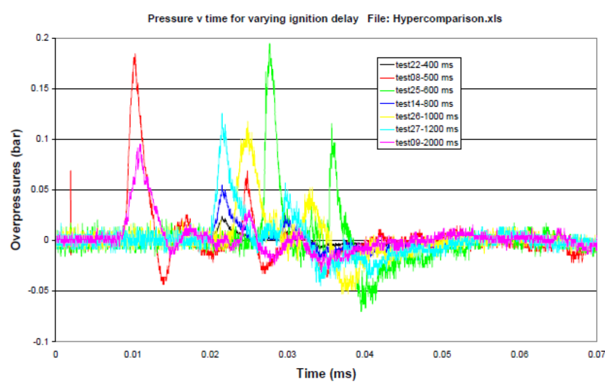


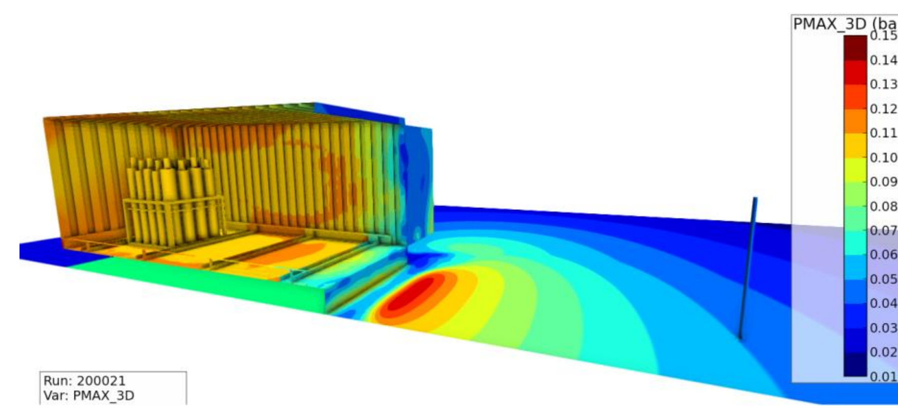
HSL ignited jet 350 g/s, ignited at ~0.8s ~ 150 mbar
~260 g hydrogen released



HySEA container benchmark ~100 mbar
15%, some congestion, fully open door
~450 g hydrogen



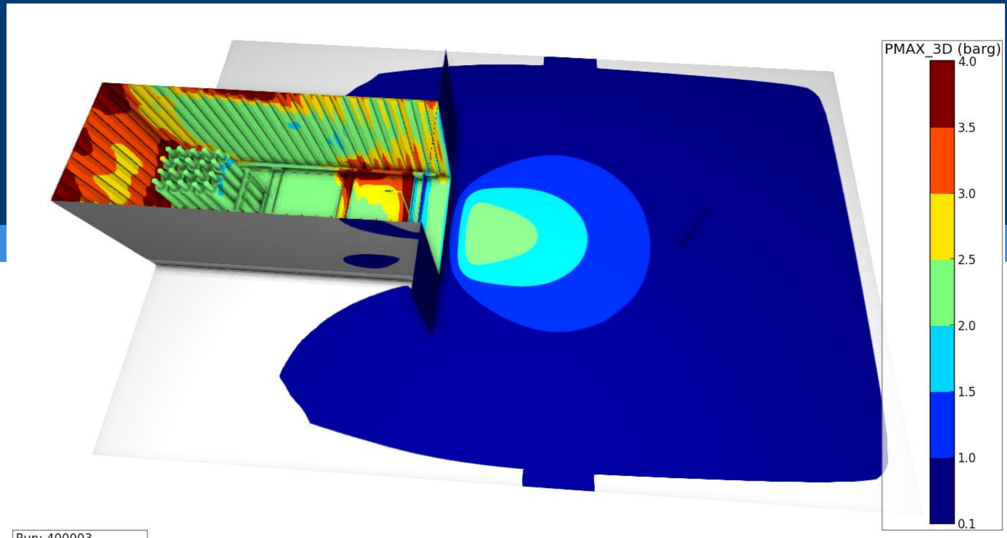


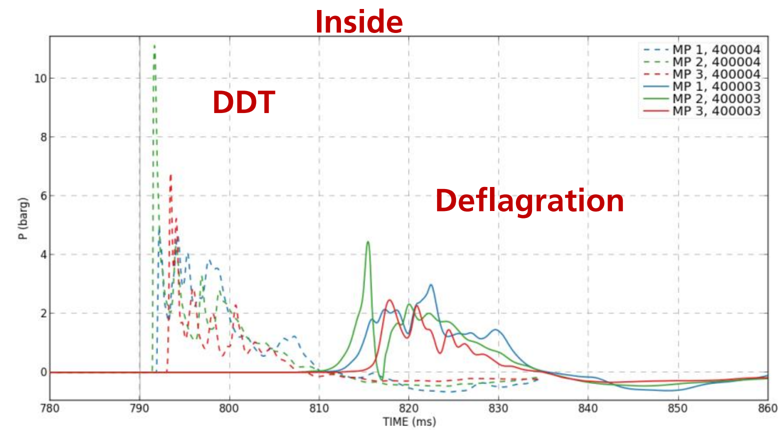


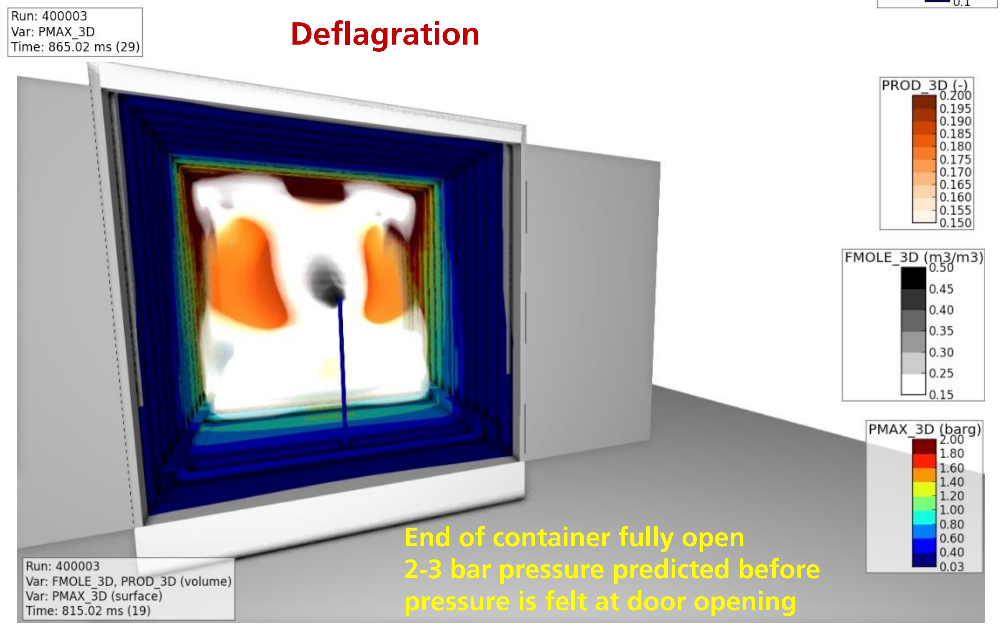
What if we combine these scenarios?
=> 260 g catastrophically released inside container

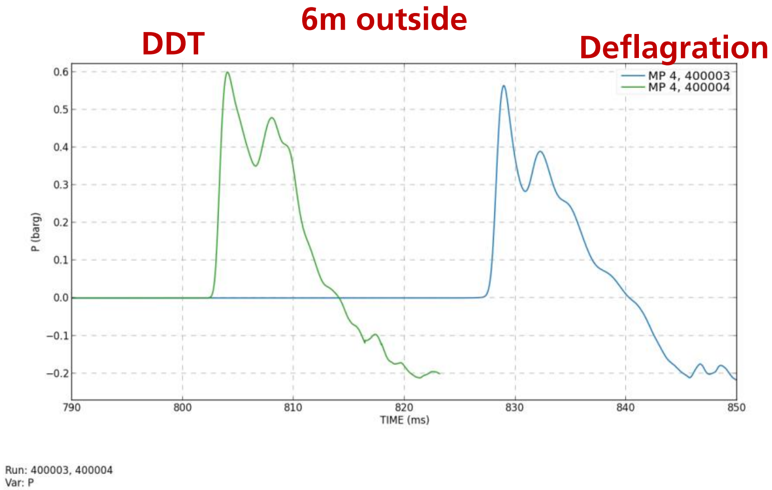
Jet release into open container-ignited

HSL jet 350 g/s into container, ignited at ~0.8s ~ 150 mbar
~260 g hydrogen released
Simulated both as deflagration and DDT/detonation









Questions:

Is scenario credible? *Release rate ~100 g/s filling container surely is …*

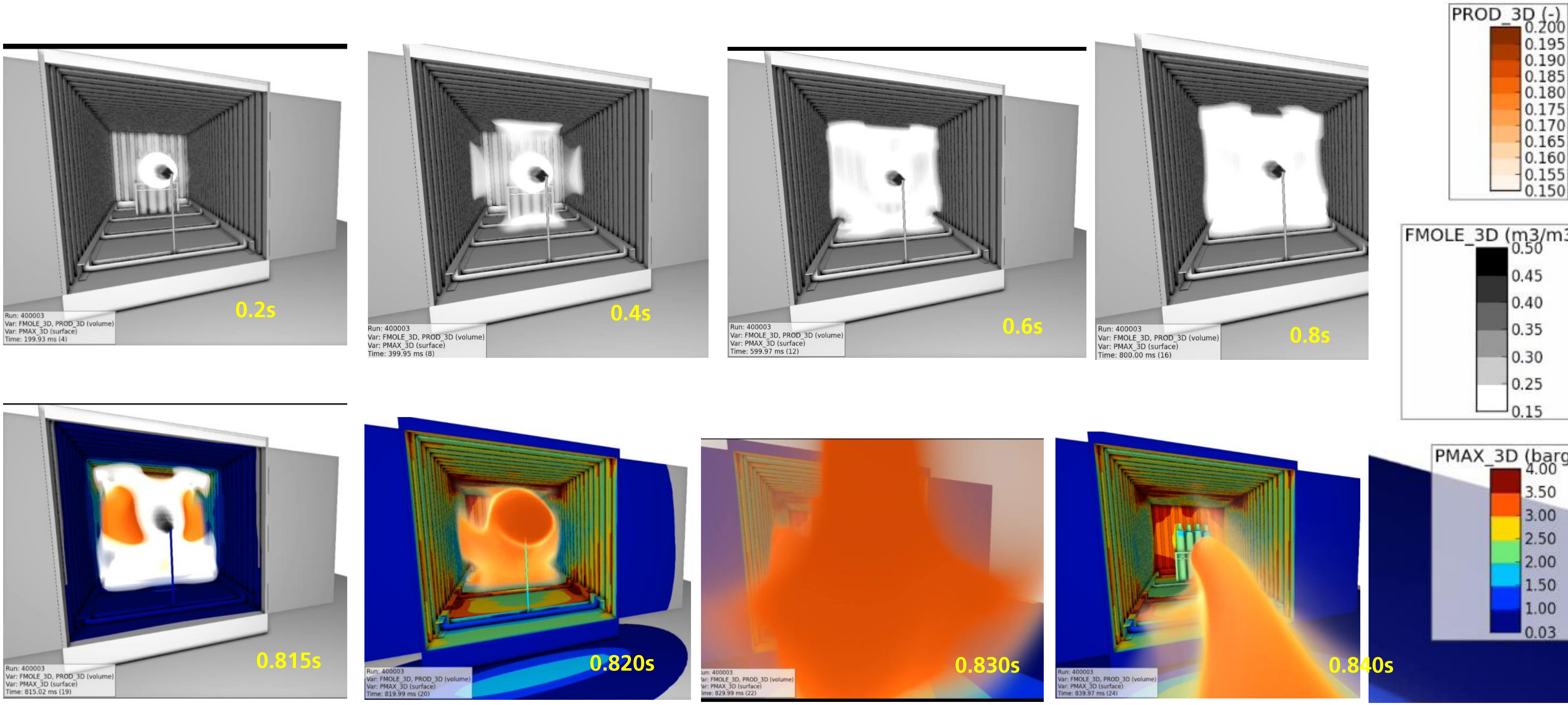
How to take into account in risk & safety study? *CFD modelling*

What is the beneficial effect of explosion venting? *Limited for severe cases*

What about emergency ventilation? *Ventilation good for moderate release rates*

Jet release into open container-ignited – video frames

HSL jet 350 g/s into container with fully open endwall, ignition at 0.8s, deflagration simulation



Tank burst

Challenge 1:

What is the frequency of catastrophic tank burst?

Type 4 steel tanks

– very well tested and rated, wide safety margins

Frequency = zero… or something else?

Challenge 2:

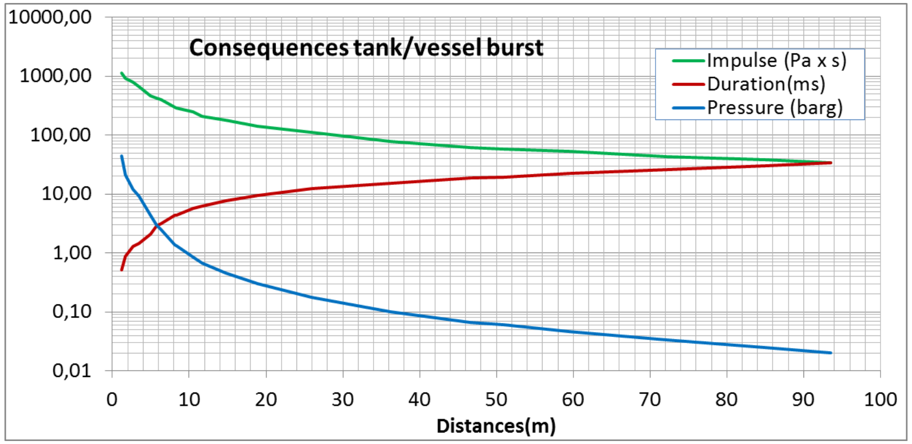
Very high pressures with very short duration…

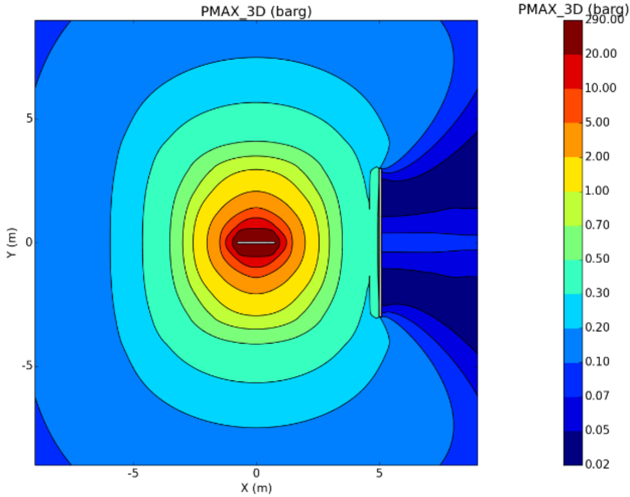
Typical building resistance values 0.10-0.30+ bar

Simple tool and CFD in agreement

What is the hazard to people behind the wall?

- Loose brick assessment…





Example tank burst in the open using CFD

What pressures were we exposed to from 15.6m^3 hydrogen detonation demonstration?

Approach 1: "Vessel burst"

Input:

Adiabatic flame temp: 2254 K

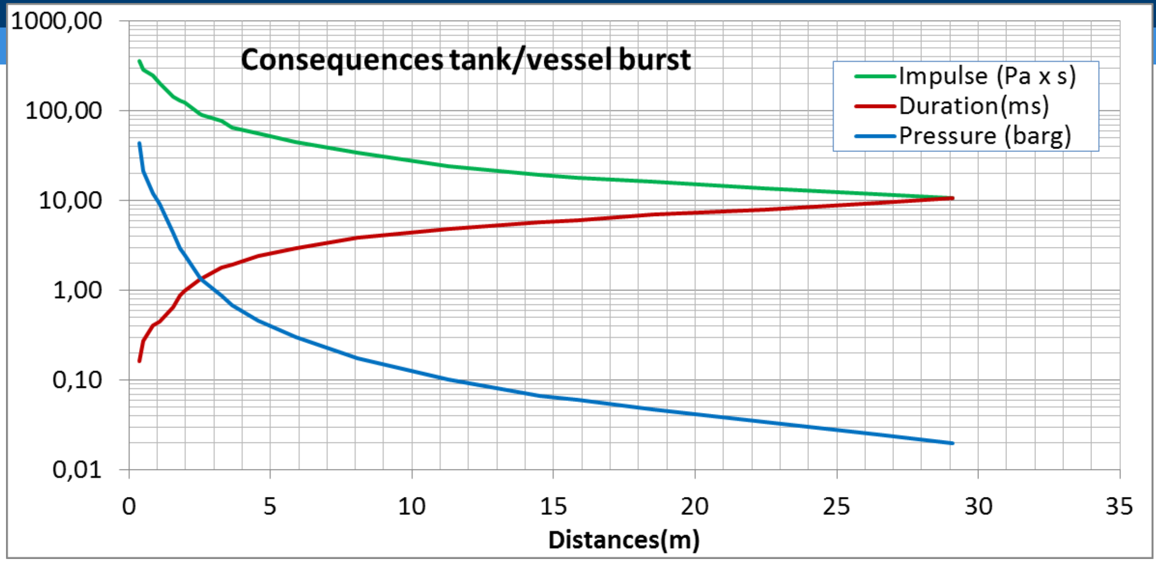
Pressure: 8.2 bara

Volume: 15.6m^3

Preparation time: 1 minute

Prediction: 20 mbar at 30m

Not really optimal source, explosion dynamics lost



Gas explosion pressures	Initial pressure		Distance	5 m		10 m		15 m		20 m		60 m	
Deflagration	0,200	bar		0,200	bar	0,096	bar	0,064	bar	0,048	bar	0,016	bar
DDT	20	bar		1,429	bar	0,340	bar	0,179	bar	0,114	bar	0,033	bar

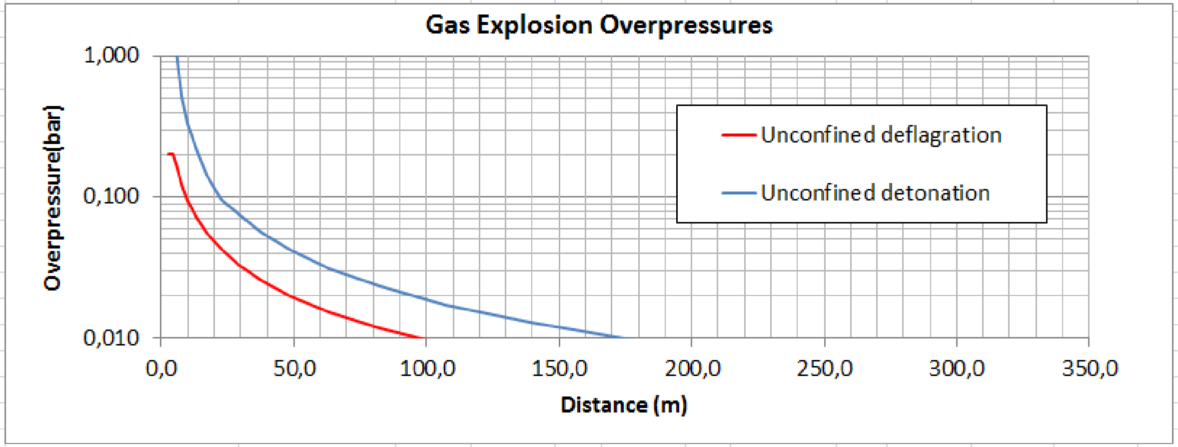
Approach 2: TNO-MEM curve 10

Input: cloud volume 15.6m^3

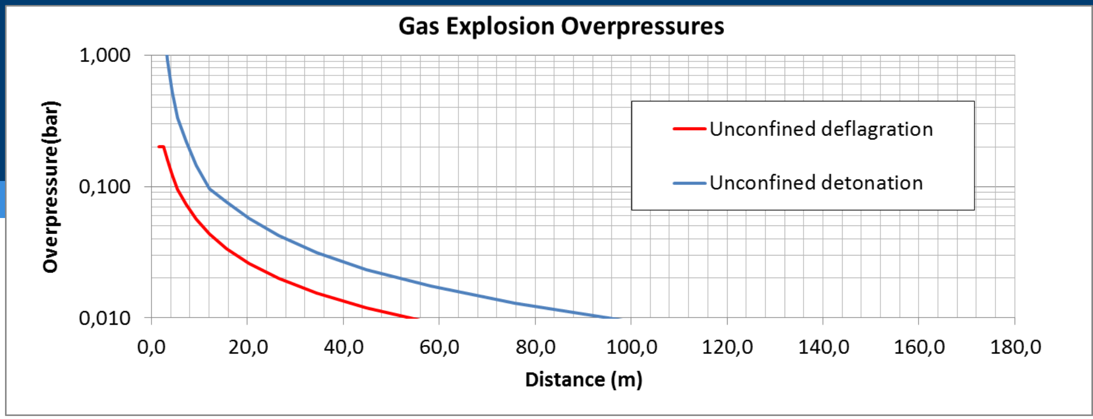
Pressure: 20 bar (becomes 10 bar i.e. TNO curve 10)

Preparation time: 1 minute

Prediction: 33 mbar at 60m



Comparison TNO-MEM & "quick CFD" for 2.5m³ hydrogen detonation?



Approach 2: TNO-MEM curve 10

Input: cloud volume 2.5m³

Pressure: 20 bar (becomes 10 bar i.e. TNO curve 10)

Preparation time: 1 minute

Prediction: 17 mbar at 60m

Gas explosion pressures	Initial pressure	Distance	5 m	10 m	15 m	20 m	60 m
Deflagration	0,200 bar		0,104 bar	0,052 bar	0,035 bar	0,026 bar	0,009 bar
DDT	20 bar		0,372 bar	0,129 bar	0,080 bar	0,058 bar	0,017 bar
FLACS			0.40 bar	0.125 bar	0.064 bar	0.038 bar	?

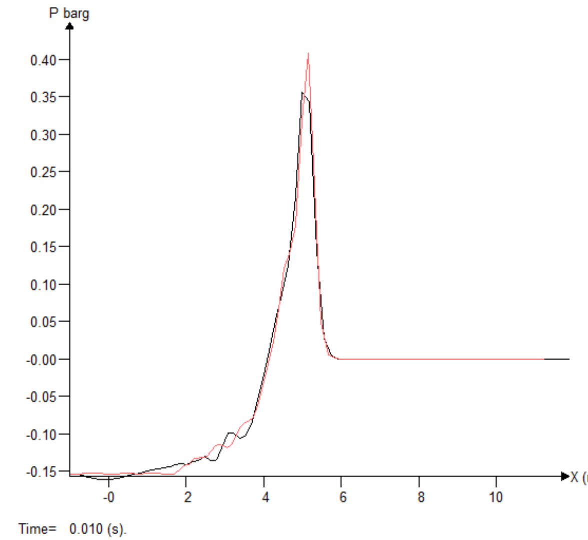
CFD accurate in near-field, too much decay in far field due to coarse grid used (simulation shown was performed quickly night before to predict demonstration)

Approach 3: FLACS (with LR DDT-tweak)

Input: Detailed cloud location size/shape, ignition point, grid, output variables and times

Preparation time: 20 minutes, run time: hours (5 to 20 hours)

Prediction: 20 mbar at 30m (simulation not completed)



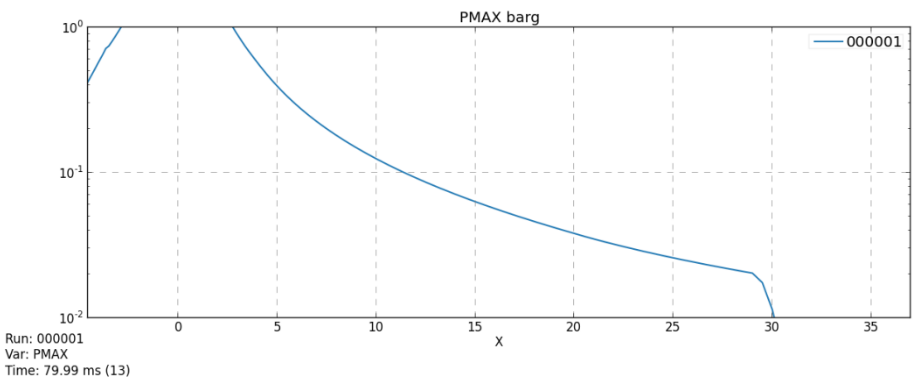
Far-field

TNO-MEM screening likely accurate

CFD: powerful when details required

Requires fine grid (time consuming)

=> Detailed load pattern the benefit



Conclusions

Numerous hydrogen initiatives emerging in society

Hydrogen has in many ways extreme properties

Safety is a critical aspect, but budgets normally limit depth of risk studies
=> Balance between quick assessment approaches and CFD when required

Optimal design and safety may require other solutions than for natural gas etc.

- Emergency ventilation?
- Explosion venting?
- Optimal size of compartments
- Liquid hydrogen should be handled with particular care

Optimal safety requires competence and understanding …

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