MoZEES Workshop

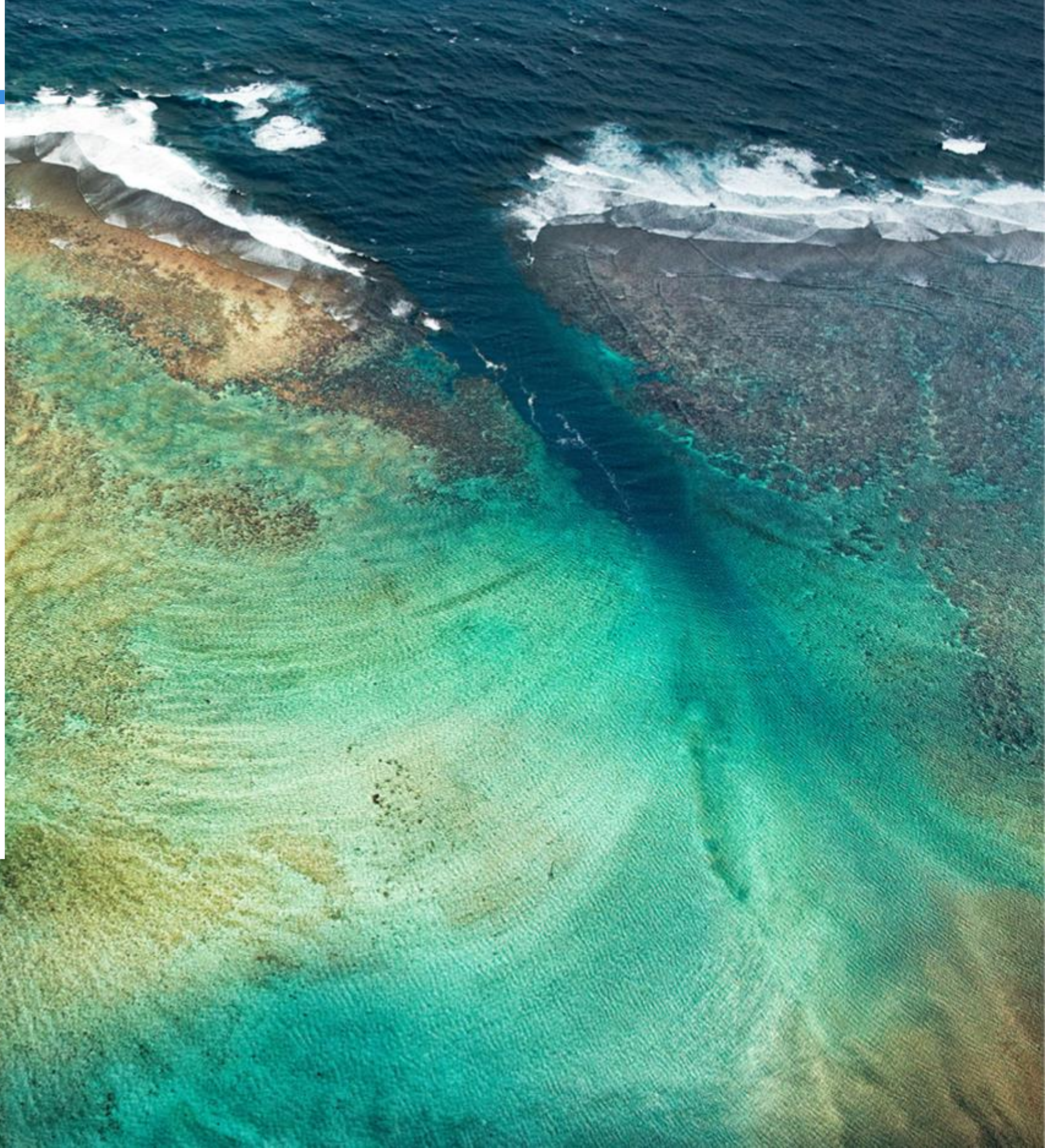
Hydrogen Safety: Kjørbo-incident, overview and perspectives

Olav Roald Hansen

CIENS, Oslo, October 23, 2019

Lloyd's Register

MoZEES
Mobility Zero Emission Energy Systems



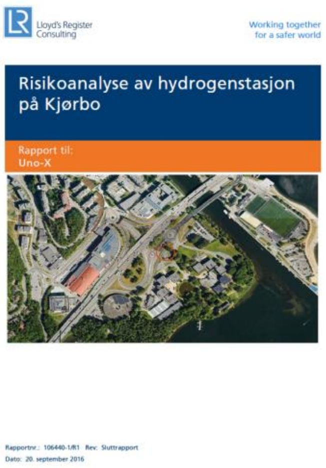
Disclaimer

Lloyd's Register performed and delivered the Kjørbo HRS risk assessment **September 2016**

The Uno-X Hydrogen refueling station was opened 3 months later in **December 2016**

Several details were unclear at the time the risk assessment was performed

e.g. selection of type of storage tanks and layout details


Lloyd's Register Consulting

Working together for a safer world

Risikoanalyse av hydrogenstasjon på Kjørbo

Rapport til:
Uno-X

Rapportnr.: 106440-1/R1 Rev: Sluttrapport
Dato: 20. september 2016

Uno-X Hydrogen/NEL did not involve LR in incident investigation, thus

LR has no insight in the accident investigation beyond what is available in the public domain

LR has performed several risk studies for Uno-X Hydrogen and NEL, and is currently performing work for NEL

When accepting to hold this presentation it was agreed with (technology owner) NEL (Bjørn Simonsen) that

LR will base the presentation only on information available in the public domain

PS! Uno-X Hydrogen is a joint venture among Uno-X (41%), NEL (39%) and Nippon Gases (20%)

June 10, 2019

Major explosion at HRS – **heard and felt miles away**

Traffic chaos as nearby roads closed

Newspapers reported/claimed various things:

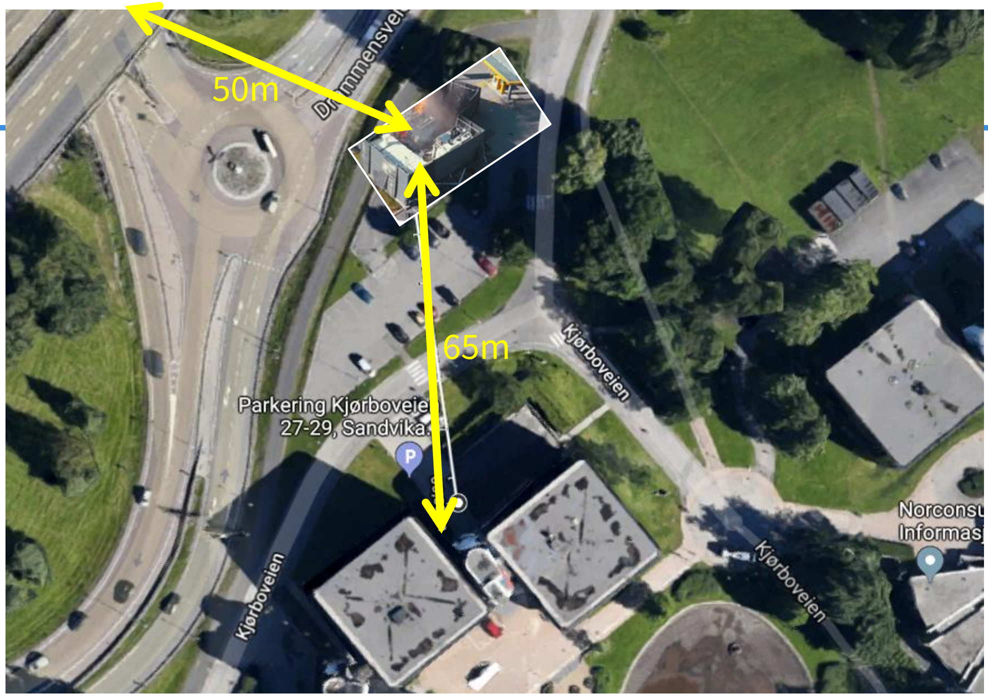
- Two people checked at emergency room **after air-bags activated**
- Some newspapers reported “tank rupture”
- Dog jumped from 4th floor, window damage at office buildings
- One witness told about **1 strong and 3 weaker explosions**

budstikka.no/nyheter/kjorbo-anlegget-ble-aldri-behandlet-politisk/204285!/

All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

Overview

- Road and roundabout ~ 10m away
- Main highway (E18) 50m away (elevated)
- Office buildings ~65m away



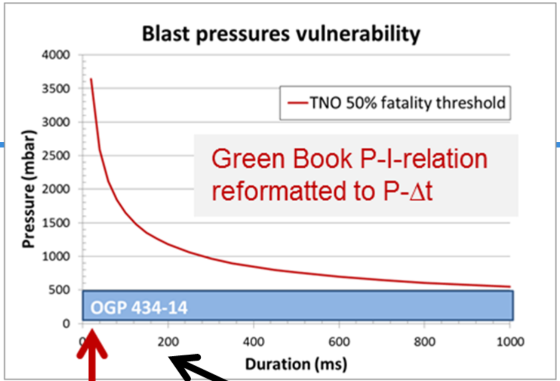
The fence around the hydrogen units generally fulfilled its mission and protected the near surroundings from flames and direct explosion effects.

A limited part of the fence towards the roundabout however failed, generating potentially dangerous projectiles.

Vulnerability of humans and buildings

Humans –fatality criteria for risk assessment

- Significant exposure to fire/flashfire and high radiation
- Projectiles
- Explosion pressures – 0.3-0.5 bar side-on load assumed (humans should survive > 2-3 bar for relevant load durations)
- Building collapse



H_2 scenarios $\Delta t \sim$ 2-20ms

HC on oil platform $\Delta t \sim$ 50-250 ms

Building damage (OGP-434, 1972-article, side-on pressures)

- 20-70 mbar windows shattered (1% fatality assumed at 50 mbar-100 mbar)
- 140-170 mbar partial collapse of homes
- 350-500 mbar nearly complete destruction of houses (50-100% fatality assumed)

Side-on pressures (not reflected)

Pressure		Damage
Psig	kPa	
0.02	0.14	Annoying noise (137 dB if of low frequency 10-15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage[1] below this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5-1.0	3.4-6.9	Large and small windows usually shattered; occasional damage to window frames.
0.7	4.8	Minor damage to house structures
1.0	6.9	Partial demolition of houses, made uninhabitable
1.0-2.0	6.9-13.8	Corrugated asbestos shattered; corrugated steel or aluminium panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	9.0	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2.0-3.0	13.8-20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.8	Lower limit of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3000 lb) in industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3.0-4.0	20.7-27.6	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	27.6	Cladding of light industrial buildings ruptured
5	34.5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building, slightly damaged
5.0-7.0	34.5-48.2	Nearly complete destruction of houses
7	48.2	Loaded, lighter weight (British) train wagons overturned
7.0-8.0	48.2-55.1	Brick panels, 8-12 inch thick, not reinforced, fail by shearing or flexure
9	62	Loaded train boxcars completely demolished
10	68.9	Probable total destruction of buildings; heavy machine tools (7,000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survive
300	2068	Limit of crater lip

[1] Understood to be to typical brick built buildings

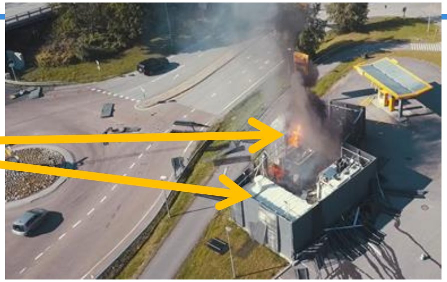
Clancey V J, 1972. Diagnostic features of explosion damage *6th Intl. Meeting on Forensic Sciences*, **Edinburgh, Scotland**

PS! Damage data often based on nuclear bomb tests/observations, which has a significantly longer blast duration and higher impulse than small hydrogen explosions

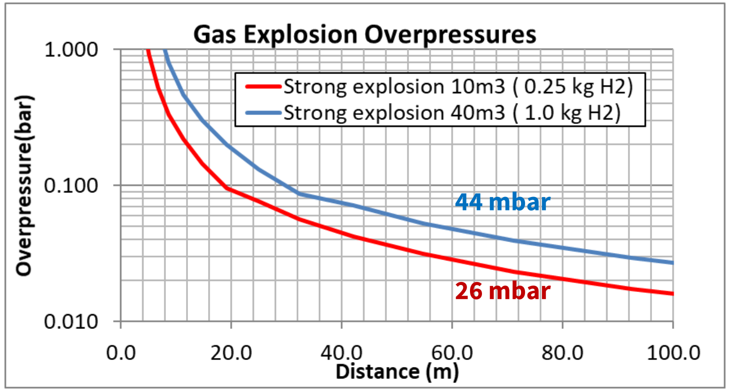
What happened? One or several explosions?

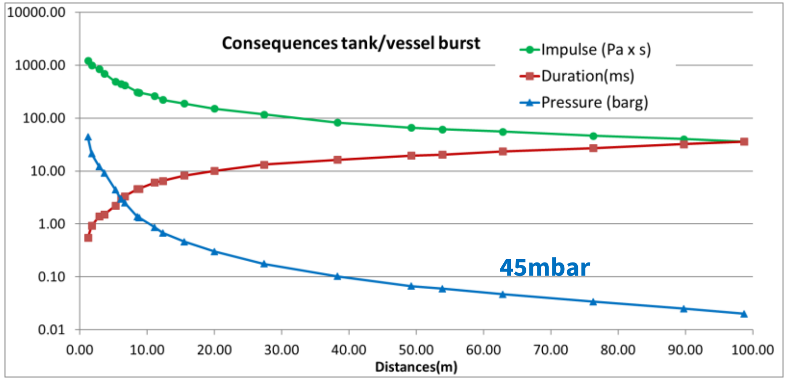
Main candidates to the blast breaking windows at 65m distance:

- Compressor module (on fire) or electrolyser module (seemed unaffected)
- Outdoors explosion between compressor module and fence?
- Rupture of large composite tanks?



Prediction by LR consequence screening tool – used for risk assessments





Hard to explain fence failure by module explosion, storage tank rupture soon reported not to be source of blast

Better wait for more information …

All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

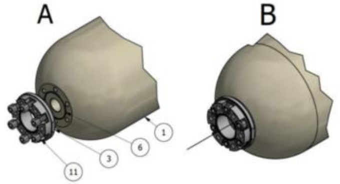
Gexcon incident investigation for NEL

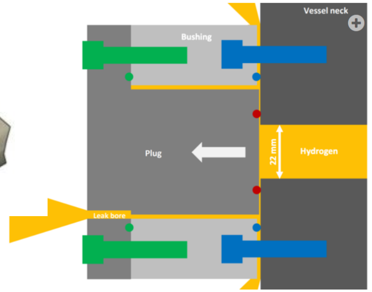
Results were regularly communicated through NEL website

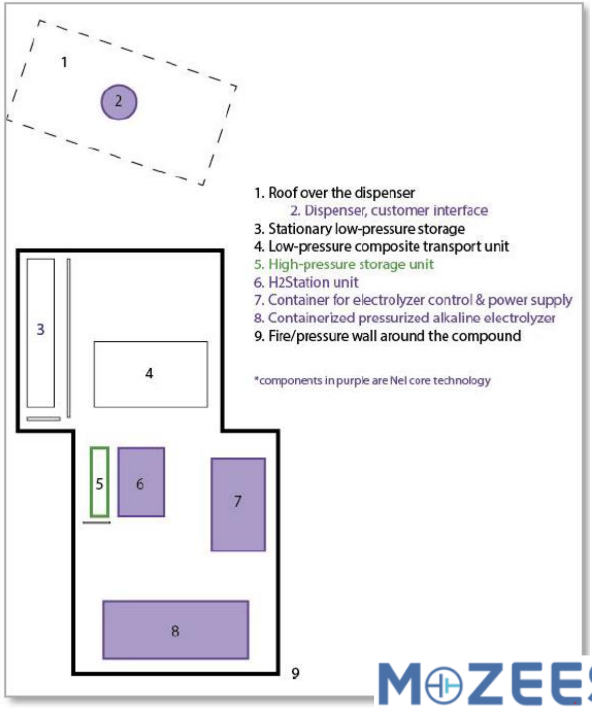
Press conference was held June 28, 2019 (18 days after incident)

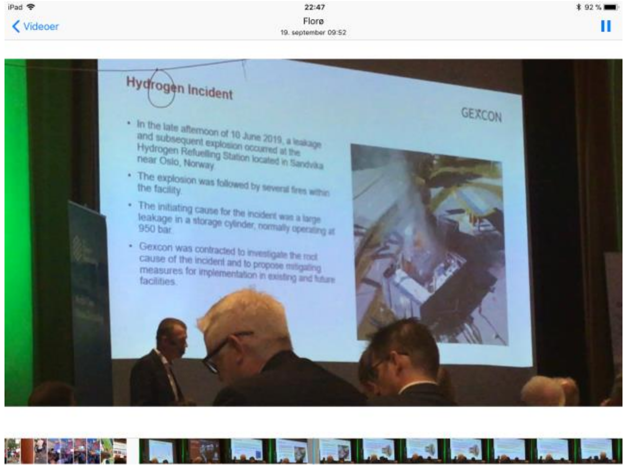
Information from current presentation was found in:

- Presentation by NEL CEO Jon André Løkke, Jun 28, 2019
- Media coverage
- Presentation of Gexcon/Geirmund Vislie, Florø, Sep 19, 2019



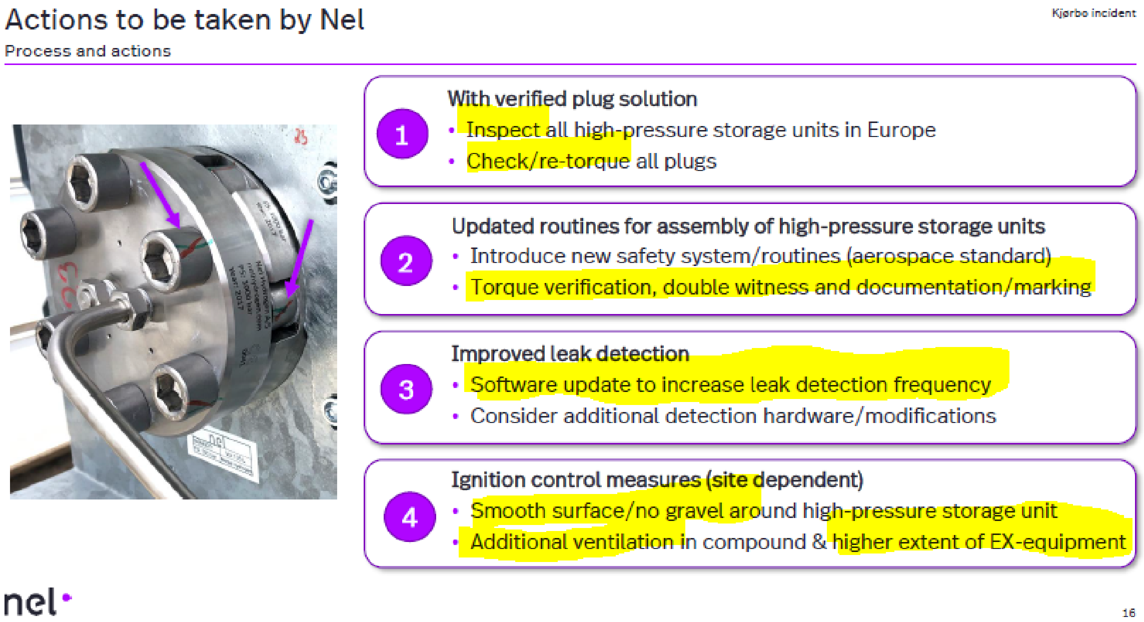






Gexcon incident investigation for NEL

- Small leak for a couple of hours (0.04 g/s ?) from 950 bar tank
- Sudden failure of seals => 1.5-3.0 kg released in 3 seconds (Gexcon Florø presentation)
- Strong explosion (followed by second explosion inside compressor module?)
- “Maybe local DDT in compressor module” (Gexcon response to my question in Florø whether DDT was considered)



Kjørbo incident

Actions to be taken by Nel

Process and actions

1. **With verified plug solution**
   - Inspect all high-pressure storage units in Europe
   - Check/re-torque all plugs
2. **Updated routines for assembly of high-pressure storage units**
   - Introduce new safety system/routines (aerospace standard)
   - Torque verification, double witness and documentation/marking
3. **Improved leak detection**
   - Software update to increase leak detection frequency
   - Consider additional detection hardware/modifications
4. **Ignition control measures (site dependent)**
   - Smooth surface/no gravel around high-pressure storage unit
   - Additional ventilation in compound & higher extent of EX-equipment

nel

16

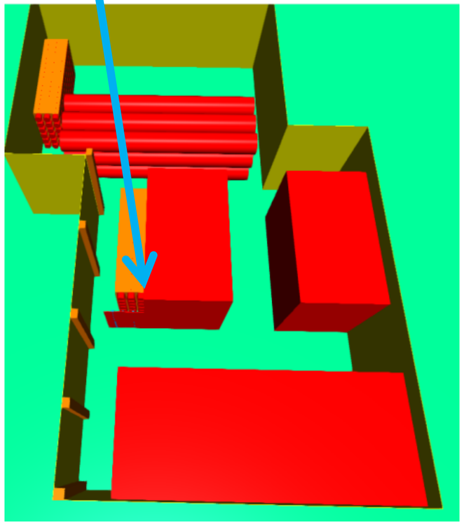
All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

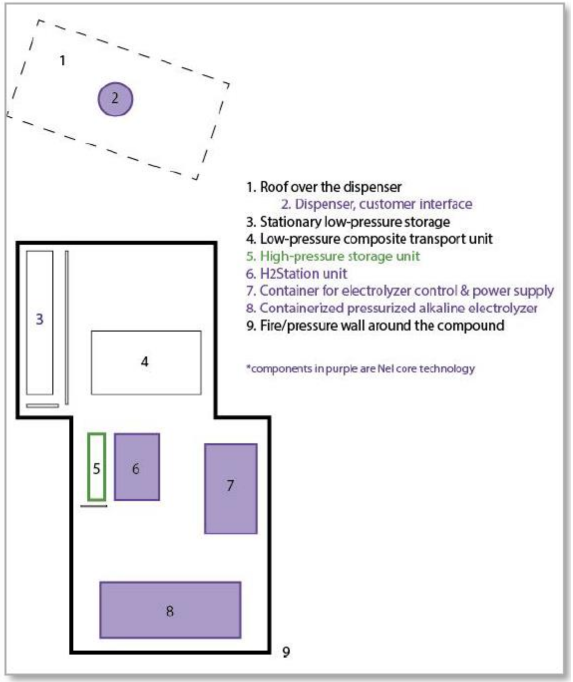
3D model for CFD-simulations

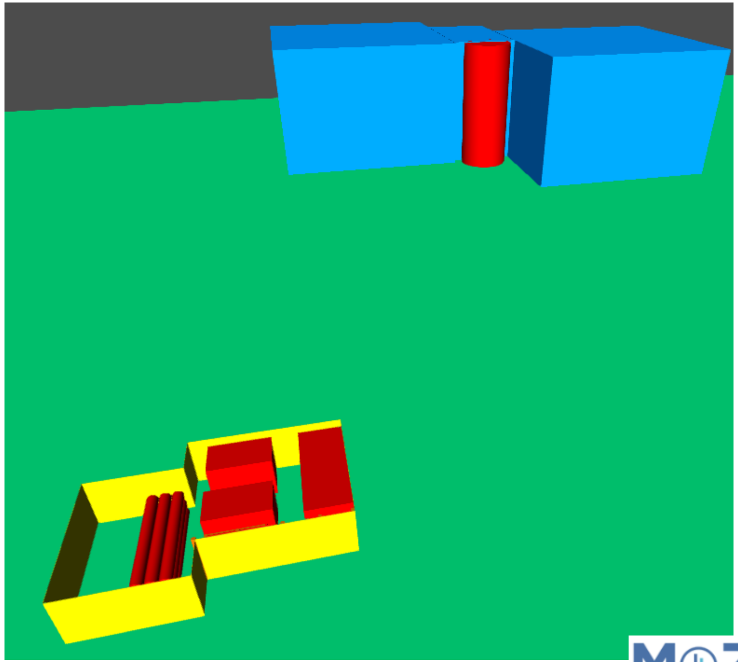
Simplified 3D model based on sketch from NEL and photos from accident

Fences are more rectangular than in reality, exact dimensions not known

Assumed leak location (at ground level)







All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

What was the release rate profile?

Uncertainty of leak rate/profile and geometry, thus expectations of precise CFD dispersion estimates low

Gexcon: 1.5-3.0 kg was released and exploded [Full bottle 2.5 kg?]

Maximum opening cross-section 22mm => bottle could empty in less than a second

Release profile 7mm hole (38.5mm^2)

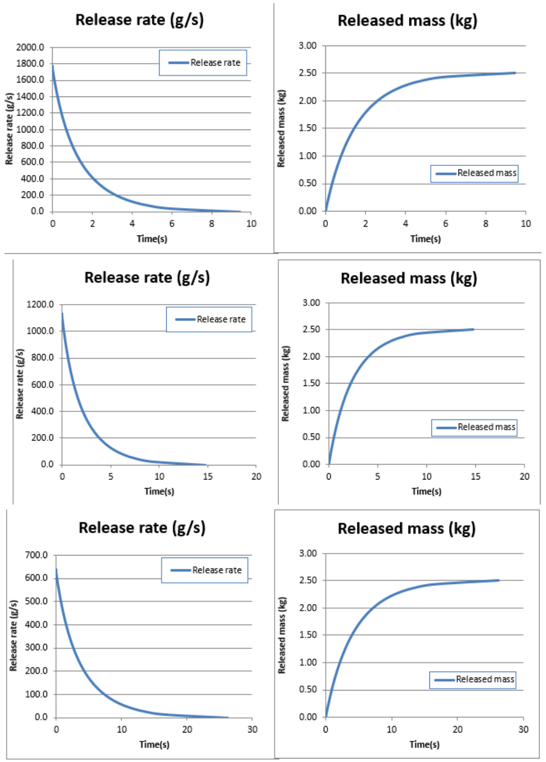
- 1650 g/s to 237 g/s in 3s
- 2.0 kg released

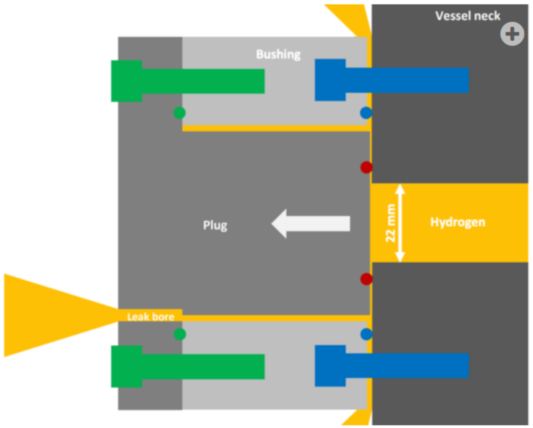
Release profile 5.5mm hole (23.7mm^2)

- 1000 g/s to 285 g/s in 3s
- 1.7 kg released

Release profile 4.4mm hole (15.2mm^2)

- 640 g/s to 275 g/s in 3s
- 1.3 kg released





Simulated 3 rate profiles plus some geometry variations with CFD

All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

MOZEES Mobility Zero Emission Energy Systems

How frequently is such a release expected to happen?

LR generally uses Sandia HyRAM leak frequencies for hydrogen

Tank connections generally assumed to be “joint”, connection that leaked is more like a “flange”

Frequencies from “joint” and “flange” for e.g. 10 HP bottles and 22mm bottle opening shown

High pressure leaks		
Pressure	950	[bar]
Temperature	293	[K]
Volume	50	[L]
Compr (Z)	1.57	[-]
H2 mass	2.539	[kg]
Diameter	22	[mm]

Frequency estimates								
Hole size		[relative]	0.01%	0.10%	1%	10%	100%	Total
		[mm]	0.2	0.7	2.2	7.0	22.0	
Joints		[per unityear]	7.05E-05	3.56E-06	7.80E-06	6.96E-06	6.21E-06	9.50E-05
	10	joints [/year]	7.05E-04	3.56E-05	7.80E-05	6.96E-05	6.21E-05	9.50E-04
Flanges		[per unityear]	7.86E-02	4.82E-03	2.72E-03	3.74E-05	1.55E-05	8.62E-02
	10	joints [/year]	7.86E-01	4.82E-02	2.72E-02	3.74E-04	1.55E-04	8.62E-01
Leak rate		[g/s]	1.62	16.21	162.14	1621.45	9537.92	
Half-time		[s]	1096	110	11	1	0	

Major joint leak every 7500y

One joint leak every 1050y

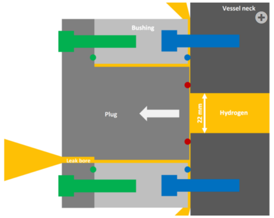
One flange leak almost every year

Major flange leak every 1900y

PS: Leak frequencies must always be considered to have large uncertainties

Table 4. Parameters for frequency of random leaks for individual components

Component	Release size	μ	σ	Mean (Calculated)	Variance (Calculated)
Compressors	0.01%	−1.72	0.21	1.83×10^{-1}	1.58×10^{-3}
	0.1%	−3.92	0.48	2.23×10^{-2}	1.32×10^{-4}
	1%	−5.14	0.79	8.01×10^{-3}	5.55×10^{-5}
	10%	−8.84	0.84	2.06×10^{-4}	4.31×10^{-8}
	100%	−11.34	1.37	3.04×10^{-5}	5.11×10^{-9}
Cylinders	0.01%	−13.84	0.62	1.18×10^{-6}	6.46×10^{-13}
	0.1%	−14.00	0.61	9.98×10^{-7}	4.43×10^{-13}
	1%	−14.40	0.62	6.80×10^{-7}	2.19×10^{-13}
	10%	−14.96	0.63	3.90×10^{-7}	7.36×10^{-14}
	100%	−15.60	0.67	2.09×10^{-7}	2.47×10^{-14}
Filters	0.01%	−5.25	1.98	3.77×10^{-2}	7.18×10^{-2}
	0.1%	−5.29	1.52	1.60×10^{-2}	2.30×10^{-3}
	1%	−5.34	1.48	1.44×10^{-2}	1.64×10^{-3}
	10%	−5.38	0.89	6.87×10^{-3}	5.67×10^{-5}
	100%	−5.43	0.95	6.94×10^{-3}	7.16×10^{-5}
Flanges	0.01%	−3.92	1.66	7.86×10^{-2}	9.13×10^{-2}
	0.1%	−6.12	1.25	4.82×10^{-3}	8.84×10^{-5}
	1%	−8.33	2.20	2.72×10^{-3}	9.41×10^{-4}
	10%	−10.54	0.83	3.74×10^{-5}	1.41×10^{-9}
	100%	−12.75	1.83	1.55×10^{-5}	6.53×10^{-9}
Hoses	0.01%	−6.81	0.27	1.15×10^{-3}	9.82×10^{-8}
	0.1%	−8.64	0.55	2.06×10^{-4}	1.51×10^{-8}
	1%	−8.77	0.54	1.79×10^{-4}	1.11×10^{-8}
	10%	−8.89	0.55	1.60×10^{-4}	8.92×10^{-9}
	100%	−9.86	0.85	7.47×10^{-5}	5.82×10^{-9}
Joints	0.01%	−9.57	0.16	7.05×10^{-5}	1.35×10^{-10}
	0.1%	−12.83	0.76	3.56×10^{-6}	9.84×10^{-12}
	1%	−11.87	0.48	7.80×10^{-6}	1.54×10^{-11}
	10%	−12.02	0.53	6.96×10^{-6}	1.57×10^{-11}
	100%	−12.15	0.57	6.21×10^{-6}	1.45×10^{-11}
Pipes	0.01%	−11.86	0.66	8.78×10^{-6}	4.16×10^{-11}
	0.1%	−12.53	0.69	4.57×10^{-6}	1.26×10^{-11}
	1%	−13.87	1.13	1.80×10^{-6}	8.27×10^{-12}
	10%	−14.58	1.16	9.12×10^{-7}	2.33×10^{-12}
	100%	−15.73	1.71	6.43×10^{-7}	7.39×10^{-12}
Valves	0.01%	−5.18	0.17	5.71×10^{-3}	9.90×10^{-7}
	0.1%	−7.27	0.40	7.50×10^{-4}	9.67×10^{-8}
	1%	−9.68	0.96	9.92×10^{-5}	1.49×10^{-8}
	10%	−10.32	0.68	4.13×10^{-5}	9.86×10^{-10}
	100%	−12.00	1.33	1.49×10^{-5}	1.09×10^{-9}
Instruments	0.01%	−7.32	0.68	8.31×10^{-4}	4.00×10^{-7}
	0.1%	−8.50	0.79	2.78×10^{-4}	6.80×10^{-8}
	1%	−9.06	0.90	1.73×10^{-4}	3.68×10^{-8}
	10%	−9.17	1.07	1.84×10^{-4}	7.18×10^{-8}
	100%	−10.20	1.48	1.11×10^{-4}	9.85×10^{-8}



“Flange” versus “joint”

- 4x higher catastrophic (>0.5 kg/s) frequency and 1000x higher total frequency
- Smaller releases MUST not be allowed to escalate

It should be considered:

- To reduce channel diameter (22mm) significantly to limit leak rate potential
- To avoid dependency on tightening of bolts and seals that may deteriorate

Plug design, unique to Europe

Certified by third parties

Kjørbo incident

US stations | European stations | Korean stations

Number of stations:

- Norway – 3
- Iceland – 3
- Germany – 3
- ASKO – 1

nel•

MOZEES Mobility Zero Emission Energy Systems

All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

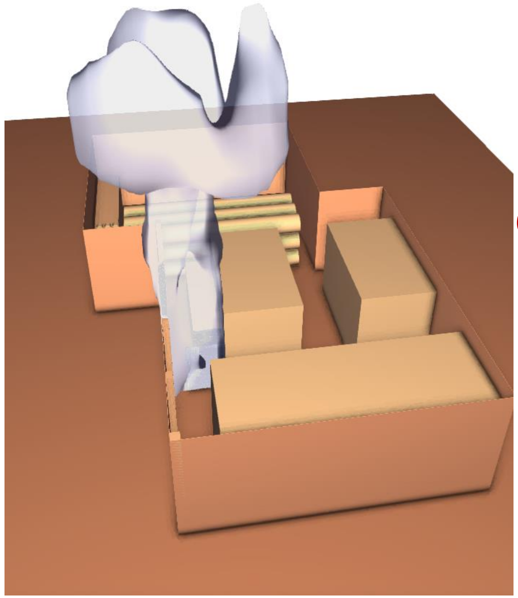
Dispersion simulation results were all very similar

7 simulations with 3 different release profiles and geometry modifications all predicted plume to rise quickly

PS! Release velocity of 0.9 C_{sound} used (FLACS guidance 0.5 C_{sound} is not considered accurate enough)

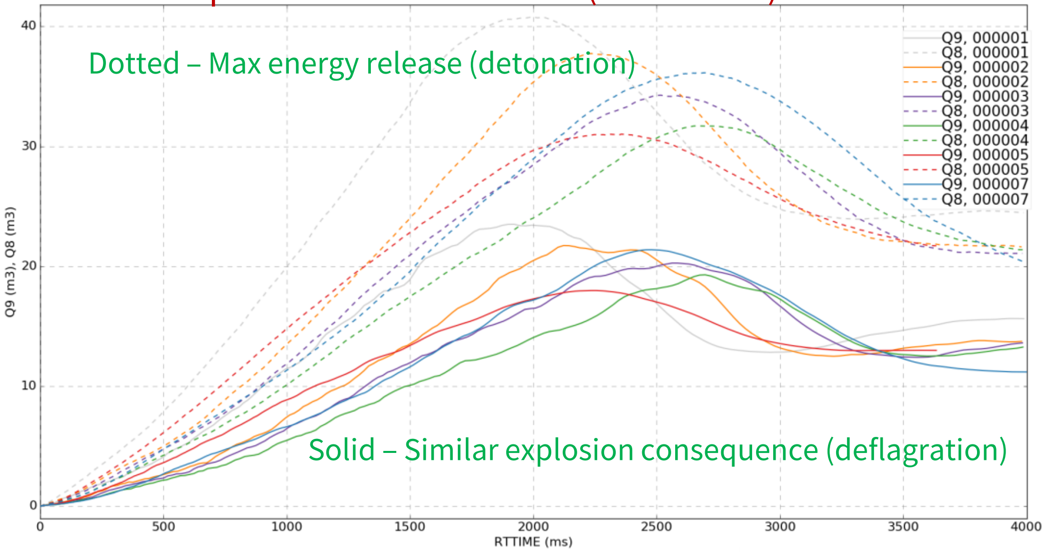
Maximum explosion energy (Q8) from 25m^3 to 34m^3 (0.63-0.85 kg hydrogen) at 3s

Equivalent stoichiometric cloud (Q9) was predicted to 13-18m^3 (0.33-0.45 kg hydrogen)



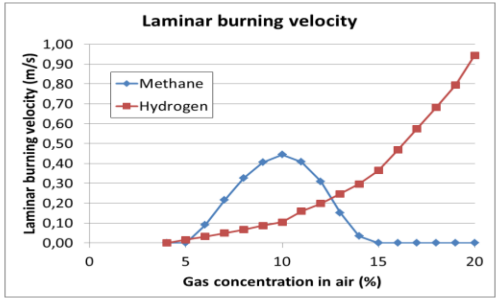
640 g/s initial rate used
(worst case at 3s)
Reactive plume
15-60% shown

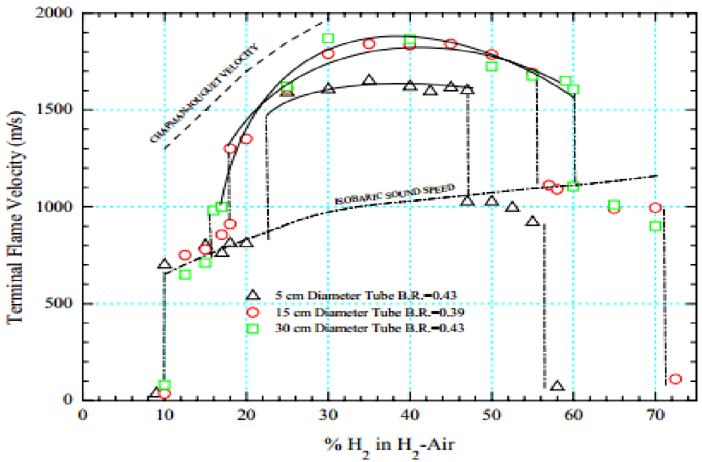
Equivalent stoichiometric (worst-case) cloud size

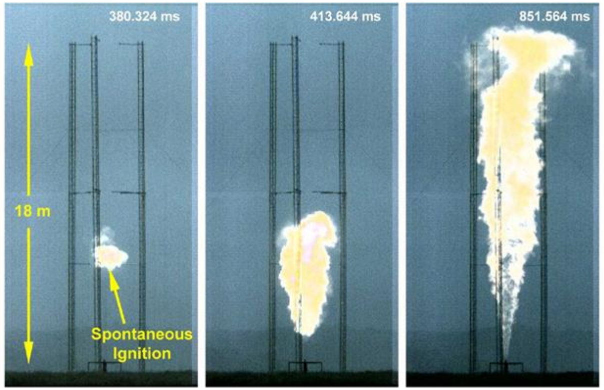


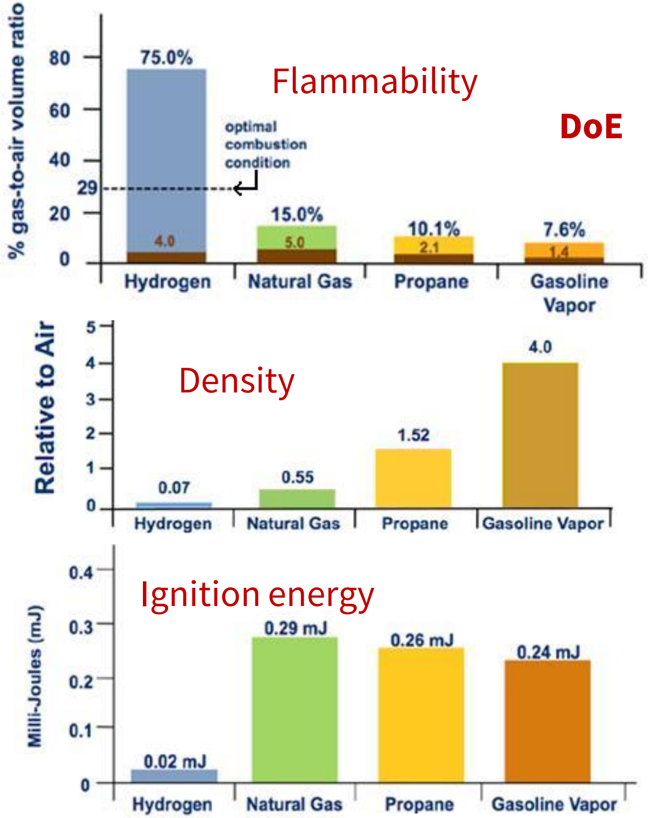
Hydrogen properties extreme

Property	Hydrogen	Methane
Flammability in air	4%-75%	5%-15%
Burning velocity	~ 3 m/s	~0.4 m/s
Detonation energy	1 g TNT	1 kg TNT









All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

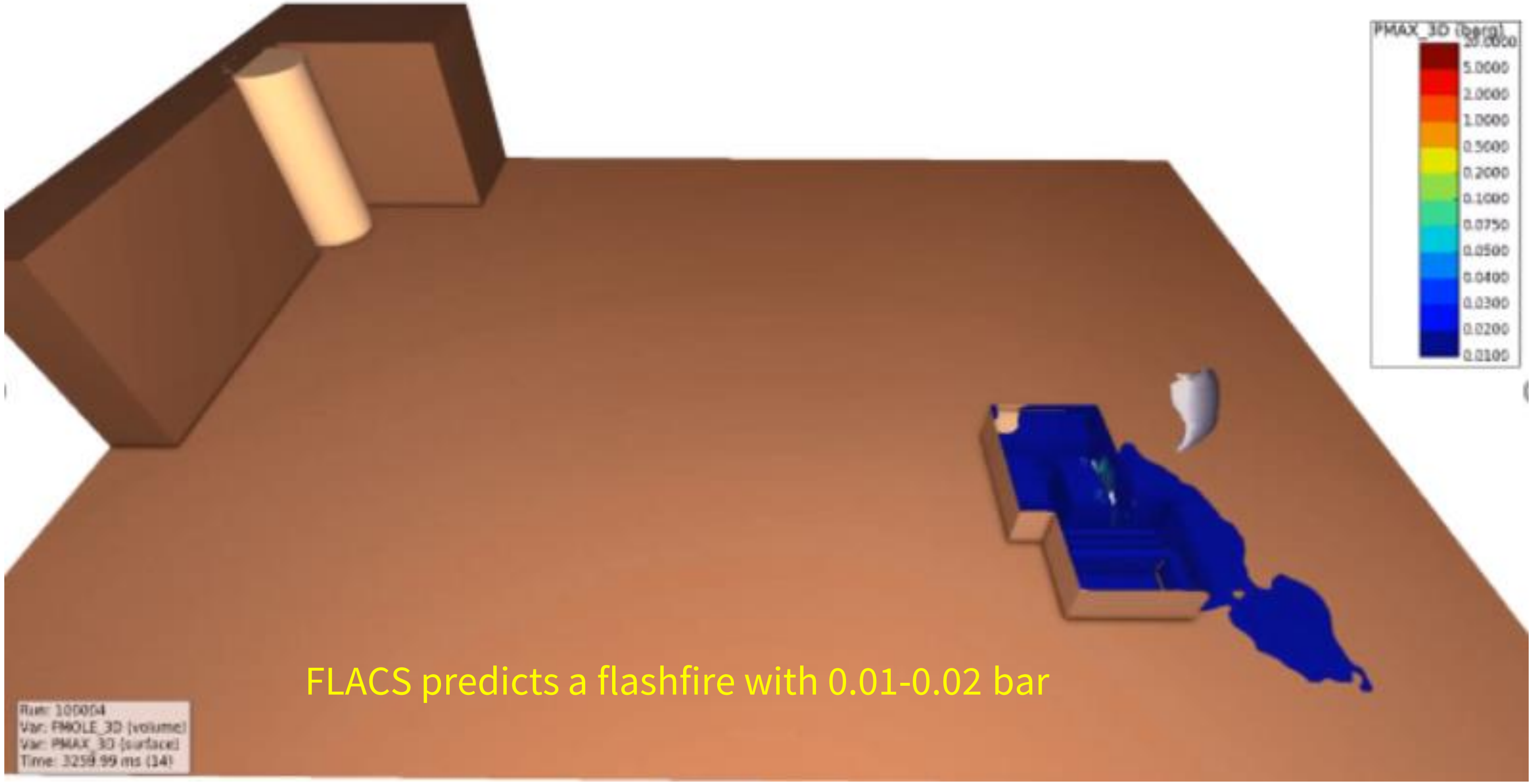
Visible building damage (6 weeks after explosion)

A few scattered windows, indication of more severe impact in corner

All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

What if we explode the cloud with FLACS?

640 g/s initial release rate exploded (most reactive gas cloud at 3s, 0.45-0.85 kg hydrogen)



All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

Can observed damage be explained by deflagration?

Lloyd's Register

Slow explosion (~300-500ms)
No significant pressures (fuel-rich plume)
How to explain major explosion effects???

FLACS is a deflagration model only

- Strong deflagration requires very reactive gas cloud and high turbulence
- Questionable if unconfined part of cloud will burn fast to generate pressures

Could it be a detonation?

- Detonation propagate by autoignition in shockwaves ahead of flames
- This may "immediately" explode all H_2 within 15-60%
- DDT (deflagration-to-detonation-transition) or direct initiation (energy ~1 g TNT)

Lets try model detonation with FLACS!
(possible by tweaking input parameters, see journal article below for validation)

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

ELSEVIER

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

CrossMark

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

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

Tests by British Gas 1980s (now DNV GL)

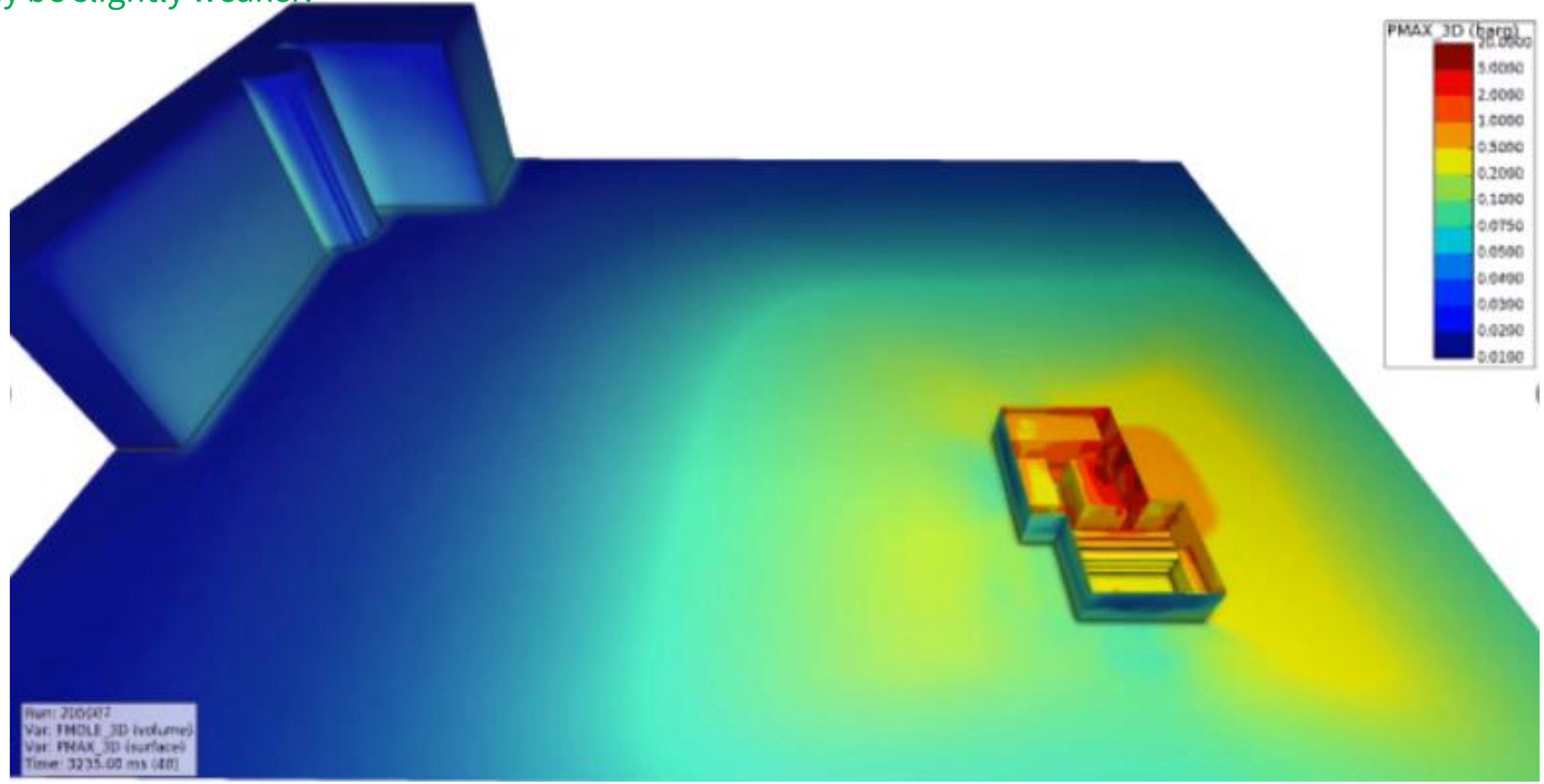
All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

MOZEES
Mobility Zero Emission Energy Systems

What if we detonate the cloud with FLACS?

640 g/s initial release rate exploded (most reactive gas cloud at 3s, 0.45-0.85 kg hydrogen)

PS! Simulation is based inaccurate description of event and on worst-case dispersion scenario evaluated. Actual blast waves may be slightly weaker.

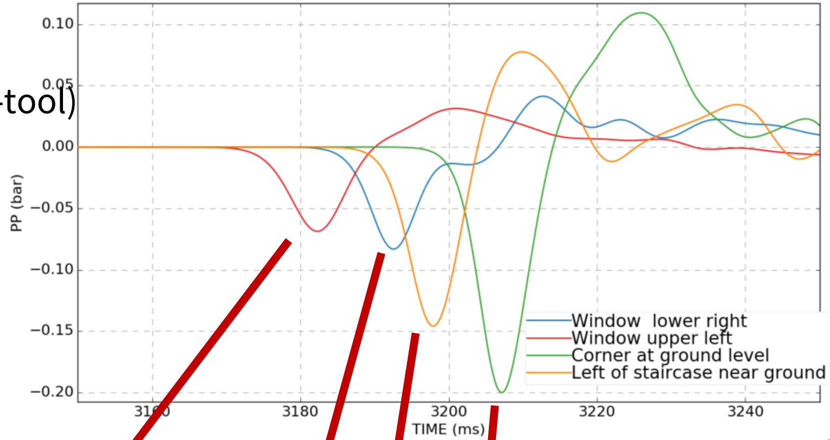


All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

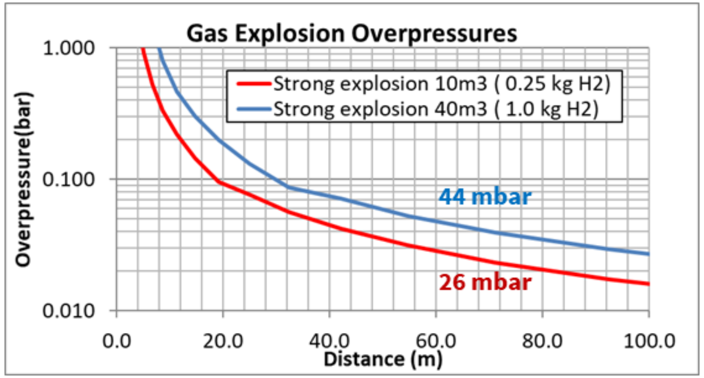
What if we detonate the cloud with FLACS?

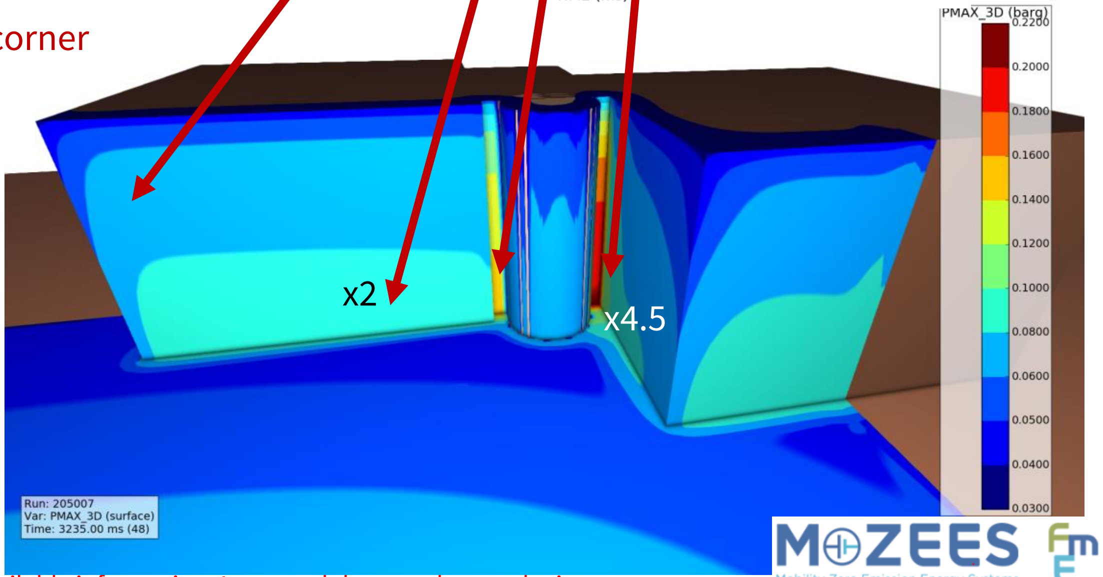
Blast onto building

- Side-on pressure ground ~45 mbar (consistent with LR screening-tool)
- Reflection x2 at front of building (90 mbar)
- Focused/reflected pressure 4-5 times higher in corner (200 mbar)



Due to shape of building, high pressures to be expected in corner





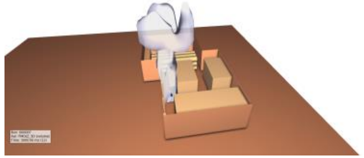
All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

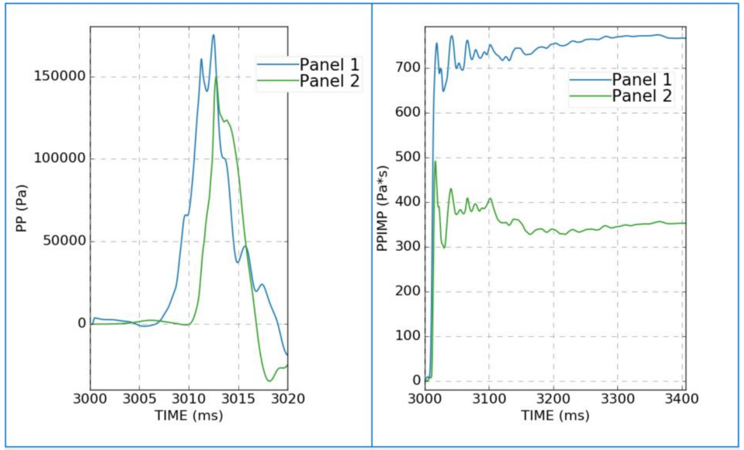
Wall projectiles

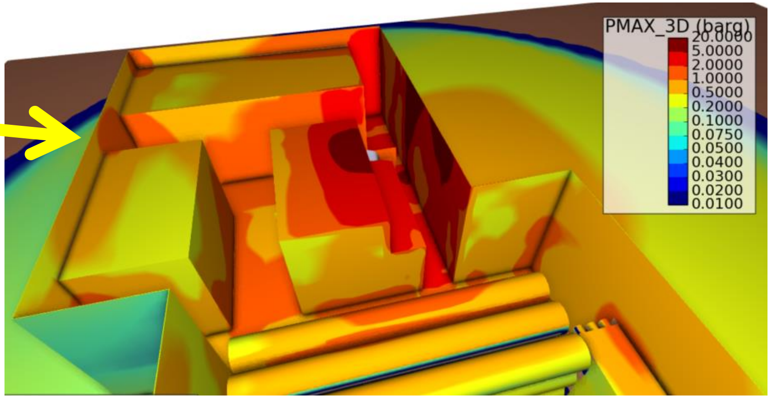
- Local pressure 10+ bar, average (2m x 3m panel) 1.5-1.8 bar
- Impulse 750 Pa s and 500 Pa s
- Weight of wall elements unknown
- 750 Pa s may throw 75 kg wall element (2m²) 41m

LR-tool simplified projectile estimate

"Loose brick"		
length	0.05	m
density	750	kg/m3
area	2	m2
side-on impulse	750	Pa s
projectile	Side-on blast	
ght	75	kg
city	20.00	m/s
gy	15.00	kJ
distance	40.77	m







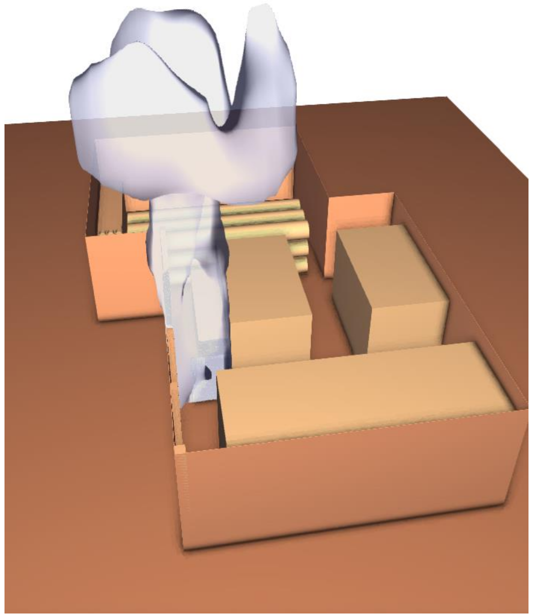
All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

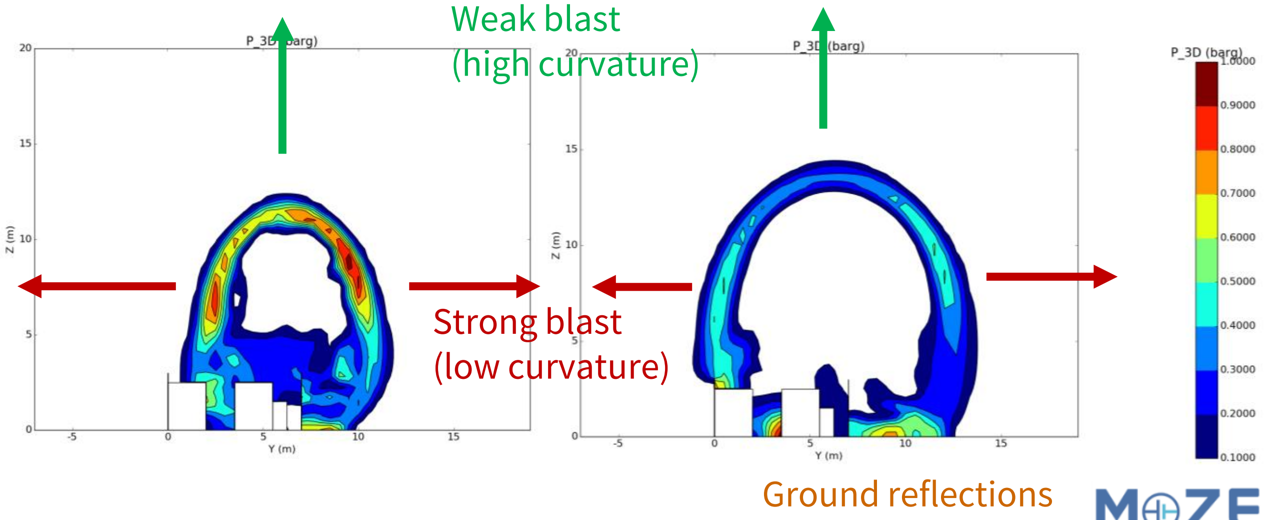
Blast exposure onto highway (E18)

Vertical elongated cloud may explain significant blast onto nearby elevated road

- Direct line of sight
- Shape of cloud would enhance horizontal blast strength

Prediction is supported by detonation experiments of elongated gas clouds giving double blast pressures across axis vs along



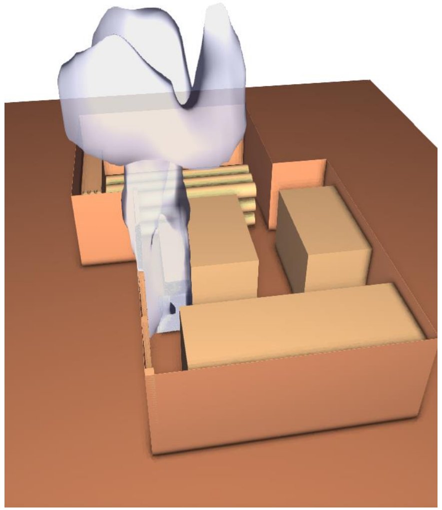


All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

Second explosion in compressor module?

Gexcon mentioned “possible local DDT inside compressor module” & witness reported 1 strong +3 weak explosions

- Very strong outdoor explosion may have shaken compressor module and led to leak inside (?)
- With leak inside, and fires outside, ignition and explosion no surprise
- Pressure likely vented through doors and vent in roof
- Limited cloud volume (worst-case ~10m^3), fences would mitigate blast outside
- I doubt this scenario can explain failing fence or strong blast onto road/offices



All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

3rd and 4th explosion scenario that never happened

“Low pressure composite transport unit” was exposed to blast/fires and damaged

Significant flame exposure can lead to tank rupture

- Safeguards are fire protection, robust design against fire and emergency venting of hydrogen
- Safeguards may have contributed to preventing further severe explosions

25-40 kg hydrogen may be stored in each tank (depending on chosen pressure level 200-350 bar)

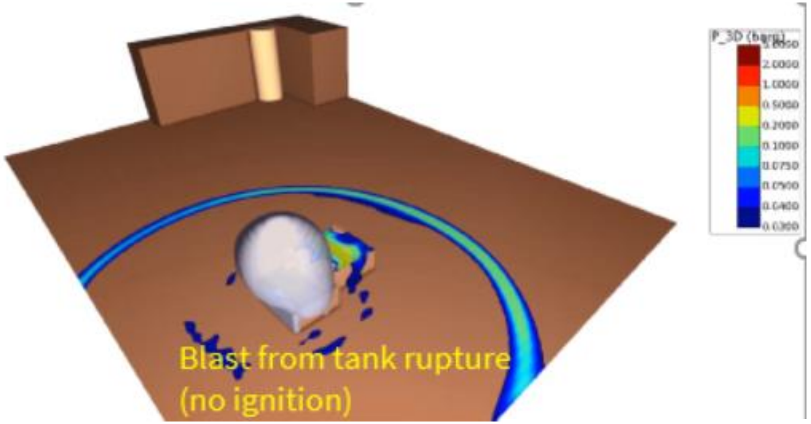
- Rupture could give 33-45 mbar at 65m distance (CFD predicted ~10% weaker than first explosion)

Explosion of released hydrogen could give even worse scenario with delayed ignition

- Immediate ignition due to fire or tank rupture, delayed ignition less likely
- Car tank rupture tests in fires indicate combustion effect is limited

These scenarios must be prevented by tank design and protection

Vessel burst	Distance to pressure level						Pressure level			Distance	
Safety distances and loads	1 barg		0.2 barg		0.05 barg		0.1	bar		65	m
Distance	10.68	m	26.65	m	61.66	m	39.04	m	Pressure	0.045	barg
Pressure impulse	270.2	Pa s	120.2	Pa s	56.25	Pa s	81.7	Pa s		54.0	Pa s
Pressure duration	5.80	ms	12.91	ms	23.21	ms	16.52	ms		24.20	ms



All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

Proposed actions will mostly improve safety, however ...

Actions 1 and 2 are routines and checks

⇒ Despite effort and costs, safety will still depend on peoples precision

⇒ Safety also depends on numerous bolts and soft seals that may deteriorate

Action 3 will detect small initiating releases and limit escalation risk

⇒ Necessary measure, not acceptable that initiating event can escalate

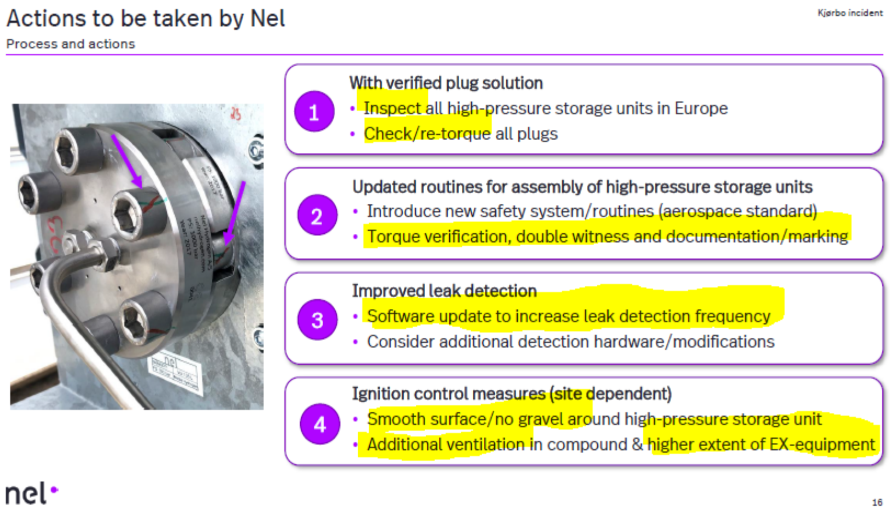
⇒ Still a residual risk as escalation can go fast

If channel/orifice diameter < 4mm would be feasible (instead of 22mm), neither of the actions 1, 2 or 3 may be critical.

If flange solution is necessary, consider possibility to use more robust metal rings

Action 4(a) considers ignition source control

⇒ Ignition source control has a value, but primarily inside confinement. Outdoor events of concern are all very energetic (high release rates, vessel bursts etc.) and self-ignition is likely. Thus the value of Ex-equipment may be limited.

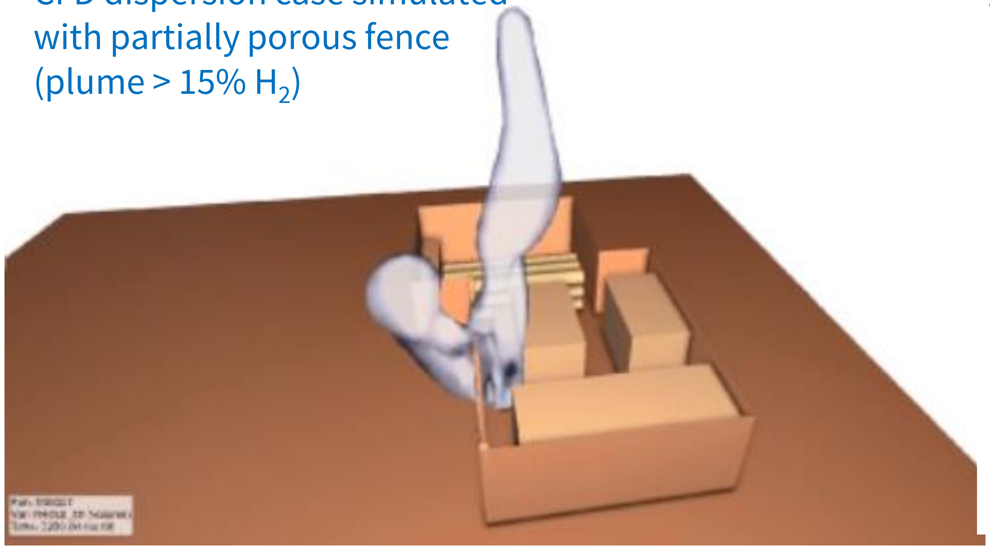


Proposed actions will mostly improve safety, however ...

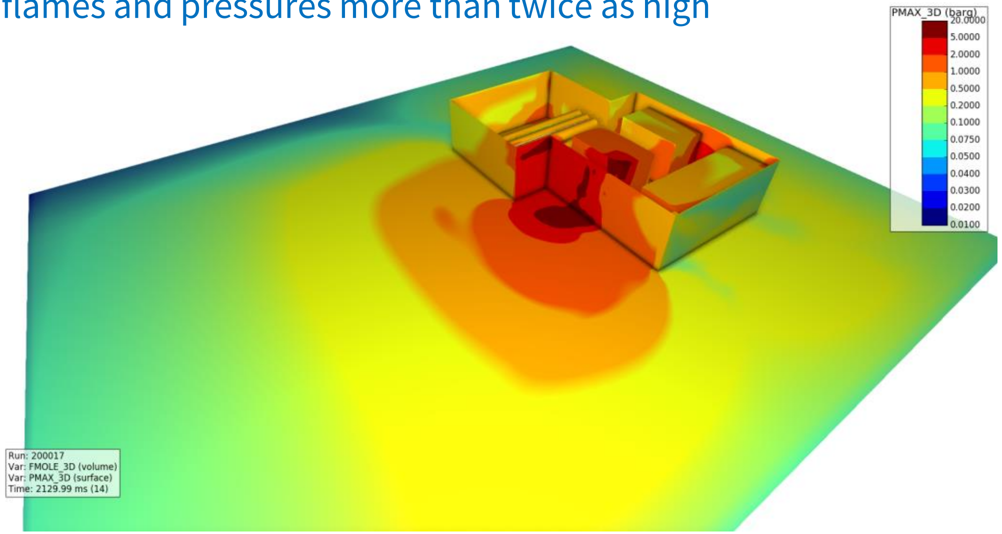
Action 4 (b) considers improved ventilation

- ⇒ Increased ventilation is an important measure for very confined modules where small releases of hydrogen can accumulate.
- ⇒ For a site like Kjørbo it is however NOT advised to replace solid fences with porous walls. This would potentially expose people outside the site to flames, projectiles and pressures, and will have an insignificant effect on risk for hydrogen scenarios as large releases outdoor will within moments seek upwards due to buoyancy.

CFD dispersion case simulated with partially porous fence (plume > 15% H_2)



People outside porous fence would be exposed to flames and pressures more than twice as high



All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

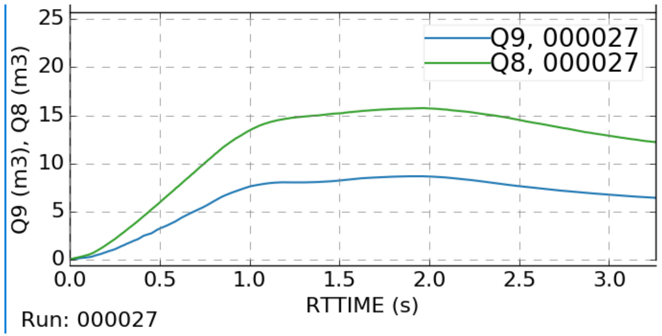
A further measure to consider to improve safety…

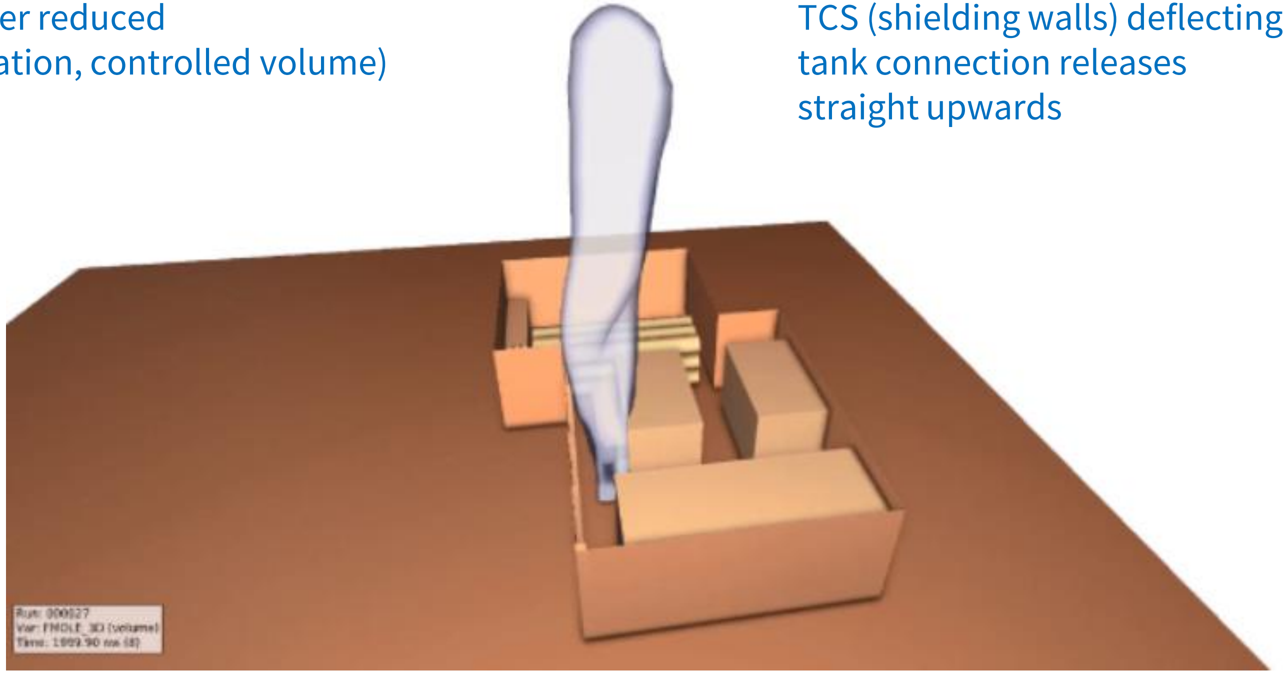
All outdoor releases with major accident potential are normally related to storage

⇒ Consider implementing a TCS (tank connection space) solution similar to what is standard on gas fuelled ships. This space shall safely collect and vent accidentally released gas. The simplest version of a TCS would be 4 vertical shields around tank connections and nearby instrument panel to deflect gas quickly upwards.

- Cloud sizes less than half, could be further reduced
- Ignition less likely in TCS (high concentration, controlled volume)
- Assumed very low likelihood for DDT

TCS (shielding walls) deflecting tank connection releases straight upwards





All input in this assessment is based on publicly available information. Input and thus results may be inaccurate

Summary and conclusions

With input from media and press releases I have tried to understand the dynamics of the Kjørbo incident.

- A CFD study indicated limited influence on the gas cloud of geometry details and initial release rate.
- Consequences of initial explosion can only be well understood if cloud detonated (DDT). This could explain damage to fence, loads onto highway and office building, plus possible escalation to compressor module.
- Proposed risk reducing measures are discussed, and others proposed. Physical measures preventing major incidents should be prioritized to procedures to reduce, but not eliminate, risk.
- For the bottle type that leaked one should consider reducing the maximum bottle orifice significantly (from 22mm) to limit the maximum leak. Complexity of connection may also be reduced (many bolts and soft seals)
- Increased ventilation of hydrogen enclosure, introducing porous fences, is not recommended. This is expected to increase risk to people around site, with no significant risk reduction to major scenarios.
- One measure to consider, in particular on sites with limited space, is “tank connection space” (TCS) solutions leading leaked hydrogen safely upwards and away. TCS is required on gas-fuelled ships.
- Continued focus should be on protection of storage tanks against fires/impact and ensure reliable depressurization when needed.

Questions?

For more information, please contact:

Olav Roald Hansen
+47 911 71 787

olav.hansen@lr.org