Modelling of hazards from LH_2 releases during bunkering operations

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ELVHyS Project – International Stakeholders Seminar

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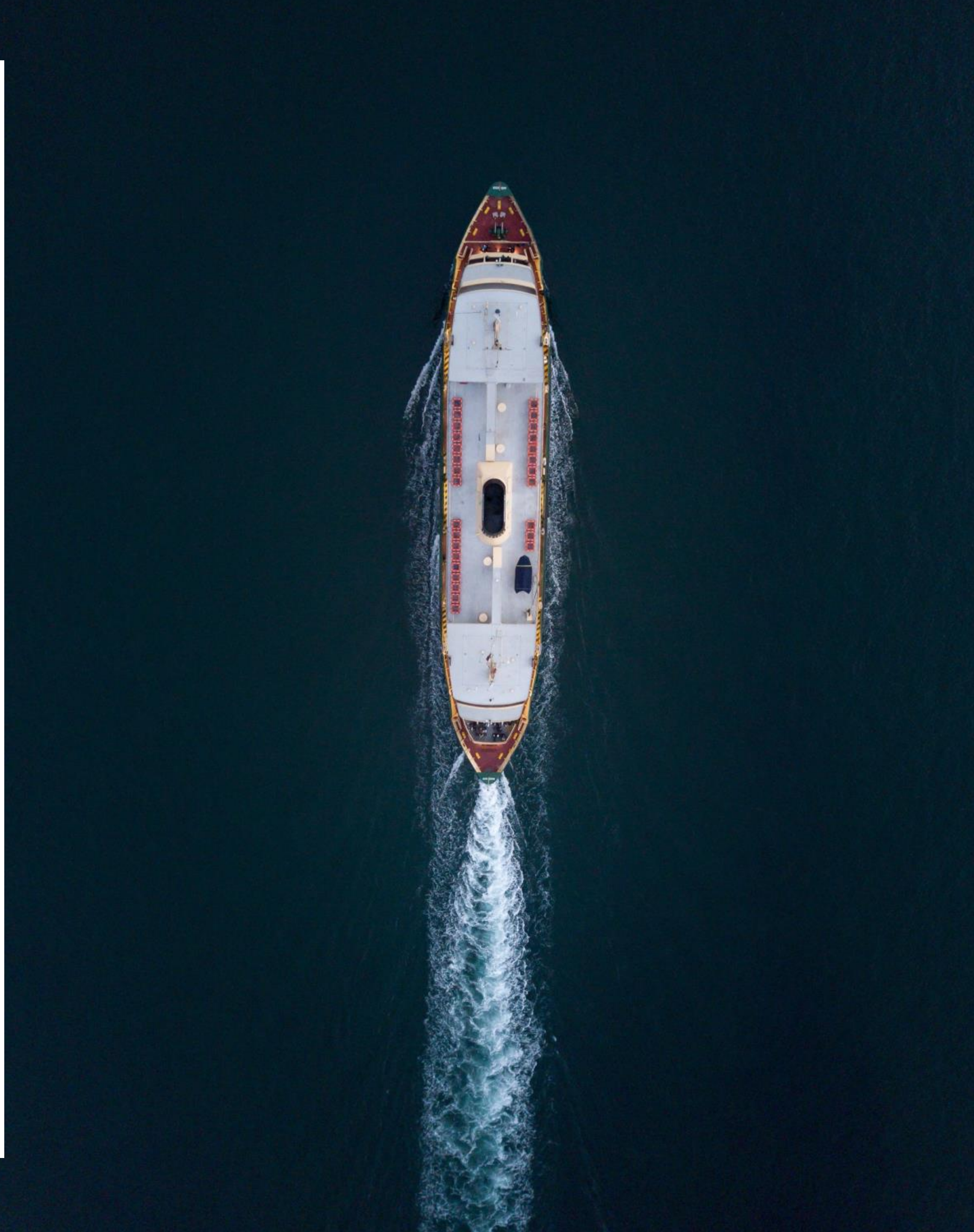
HYEX SAFETY



HYEX Safety

Safety advice and approval support within hydrogen/ammonia safety

Maritime vessels and facilities on land (> 100 clients in 10 countries since 2020)

Land facilities

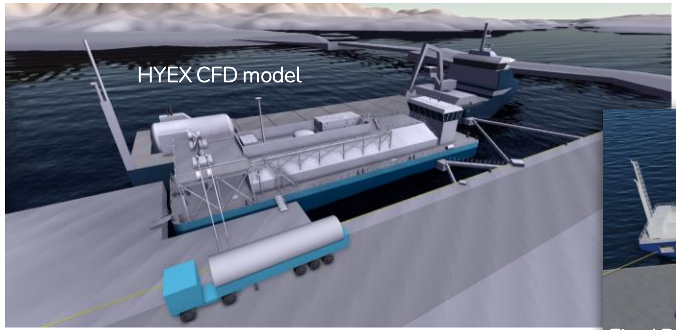
- Hydrogen production systems
- Power-to-X facilities
- Green steel & metals
- Green ammonia
- Hydrogen to gas network
- Pilot and R&D facilities
- Bunkering facilities

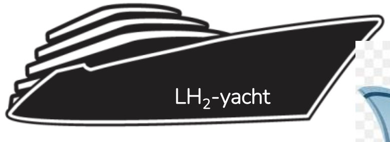
Ships/vessels (20+)

- Hydrogen vessels (LH_2, compressed H_2, NH_3 and other H_2-carriers)
- Bunkering and storage solutions

R&D-involvement

- Ammonia Fuel Bunkering Network, HYDROGENi





HYEX SAFETY

Gas bunkering concepts LNG, H_2, LH_2 and NH_3

TTS, STS, Shore-Ship and Swap

- Various gas bunkering concepts
- Optimal solutions vary with fuel

LNG – flexible (public quays & terminals)

⇒ Good availability, energy density and holding time

NH_3 – primarily refrigerated from terminals

⇒ Fair availability, moderate energy density, good holding time, toxicity concerns

LH_2 – trucks/swap (public quays & terminals)

⇒ Low availability, limited energy density and holding time

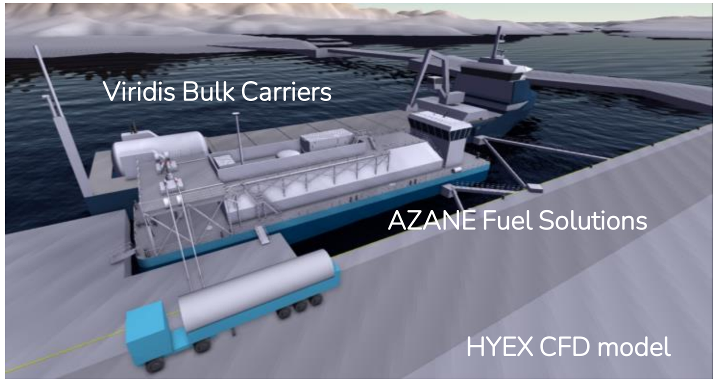
H_2 – truck/plant filling or swap (public quays & terminals)

⇒ Limited availability and low energy density

LNG shore-ship

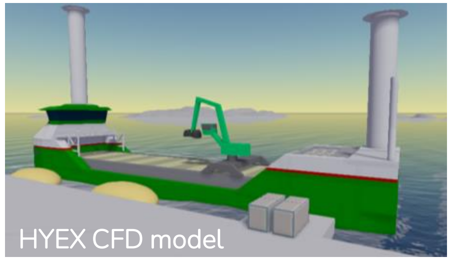
LNG ship-to-ship

LNG truck-to-ship

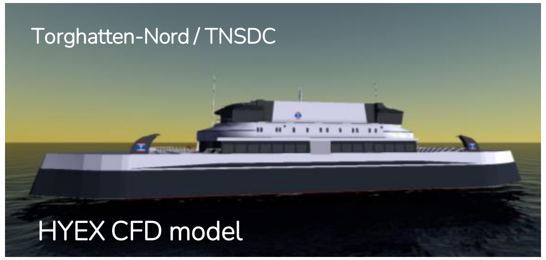


NH_3 bunkering barge

MF Hydra– LH_2 bunkering truck through tower

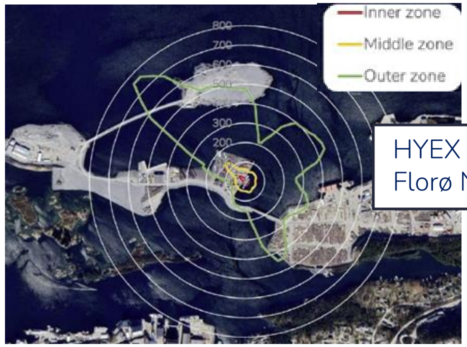


With Orca vessel concept
Bunkering by container swap



Bodø-Moskenes – 3h crossing of open sea
2 ferries to bunker several tonnes compressed H_2 daily

Land versus sea – regulations



HYEX risk contours
Florø NH_3 bunkering facility

Land facilities (Port/municipality or National regulator)

- Hydrogen & Ammonia - two out of many hazardous substances
- National regulations based on various EU-directives (Seveso / ATEX ++)
- Differences within Europe (NO/DK/UK/NL, SE and FR/IT)

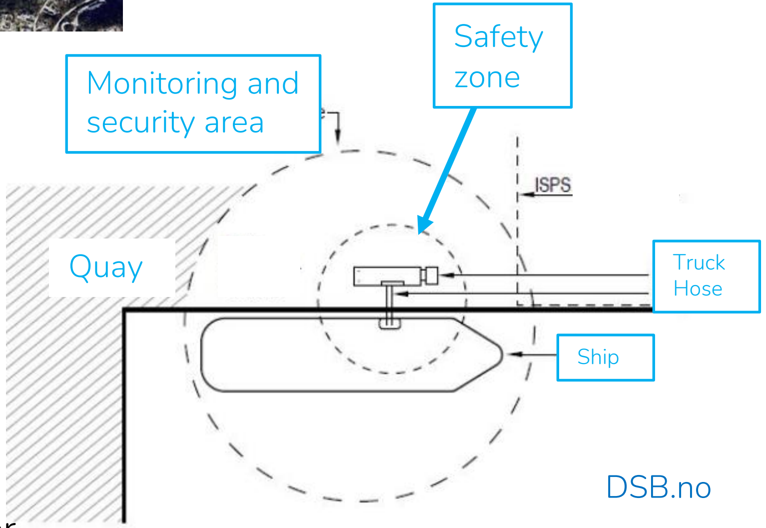
Norway – **risk contours** (probabilistic) + **bunkering zones** - similar to ISO 20519 (LNG)

⇒ **Safety zone**: Credible leak (HAZID) – e.g. hose rupture with mitigation, instrument connection

– LFL-distance + 1% fatality probability (toxicity or fire radiation) proposed in new regulation

– Norway: Expected to depower non-Ex equipment and ventilation intakes (may impact ship design)

⇒ **Monitoring & security area** (prevent violation of safety zone)



Norway: Swap not bunkering (IMO – yes, it is)! **Consent process** for bunkering LNG (passenger ships), H_2 and NH_3, (STS, TTS and Shore-ship) + Swap from ship (not Swap from quay)

Ship/Vessels (National Maritime Administrations / IMO)

- Hydrogen & Ammonia – new fuels with very different (hazardous) properties
- IMO – UN organisation – consensus-driven rules processes
- Interim guidelines for NH_3 expected 2024 (?) and H_2 (2025+) – rules additional years
- Conventional design by prescriptive rules "do this-do that"
- H_2 & NH_3-vessels follow IGF Part A "Alternative design"
- Requires QRA and safety studies

Member of NGO ZESTA's delegation at IMO CCC London, 2023/2024, contributing to the development of interim guidance for hydrogen ships

HYEX SAFETY

What are the main hazards from LH_2 releases?

Explosion hazards

- Explosion risk (DDT) from accumulation inside semiconfined bunker station, below quay or along ship side
- Flashfire/explosion hazards from denser than air plumes along quay or shipside

⇒ Assess using CFD-modelling, limit by design, ignition control, detection/ESD and safety zone

Thermal hazards jet-fire/cryogenic

- Jet-fires or cold LH_2 releases exposing bunker station or shipside
- Detonation in solid/condensed oxygen-enriched air deposits

⇒ Fast detection/ESD, robust thermal design, and safety zone, consider (!) water mitigation

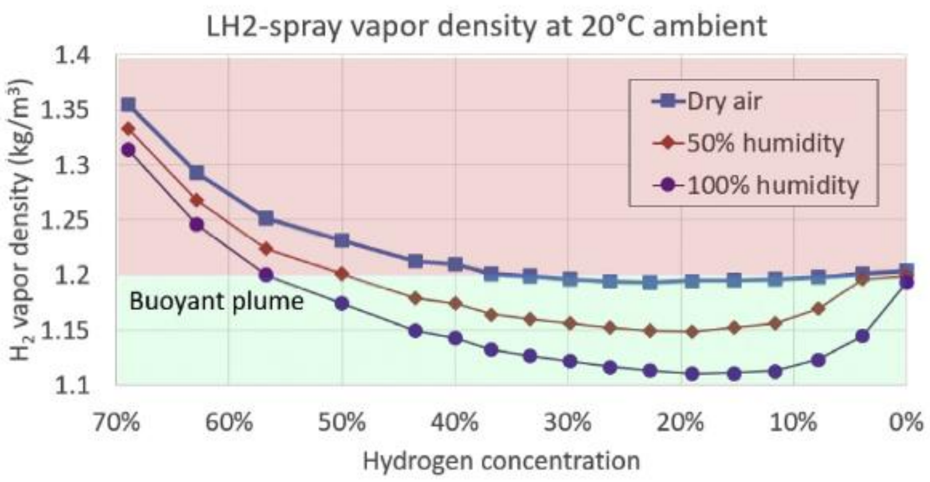
Other aspects

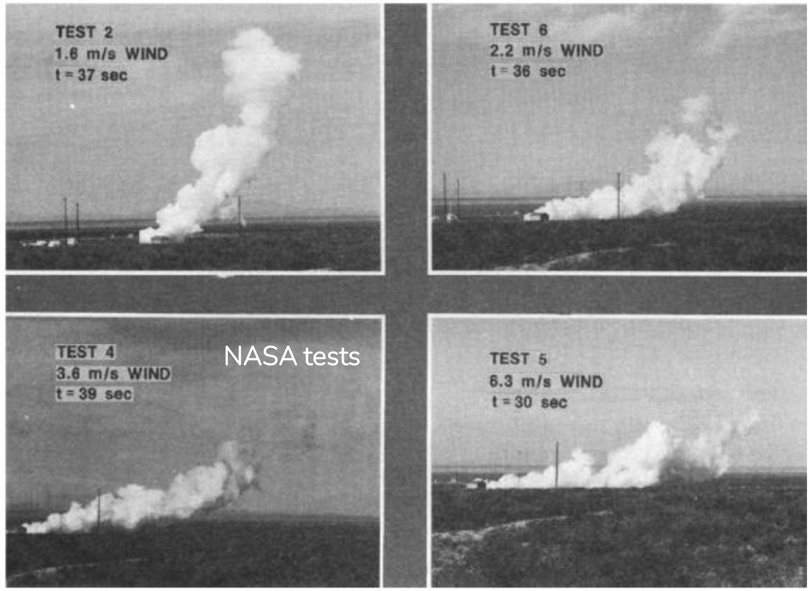
- Venting during flushing/purging or prior to truck departure – to be minimised and ensured safe even if igniting
- BLEVE – avoid LH_2 truck falling off jetty upside down into mud blocking PSVs while losing vacuum …
- LH_2 releases entrained into water frequently ignite – not normally expected to be a concern
- Cryogenic burns from LH_2-leaks a hazard – ignition considered much more severe …
- LH_2-spray two-phase region is limited, cooling of structures is expected less of concern than for LNG-sprays

How best to model dispersion from LH_2 releases

Main challenges

- What is the leak rate? - P, T, hose friction, boiling upstream leak
- Source term? - LH_2 flashing, air multiphase zone, gas zone
- Will pools form? - Not for momentum leaks with suffiicent air
- Plume buoyancy? - With dilution and some air humidity/fog

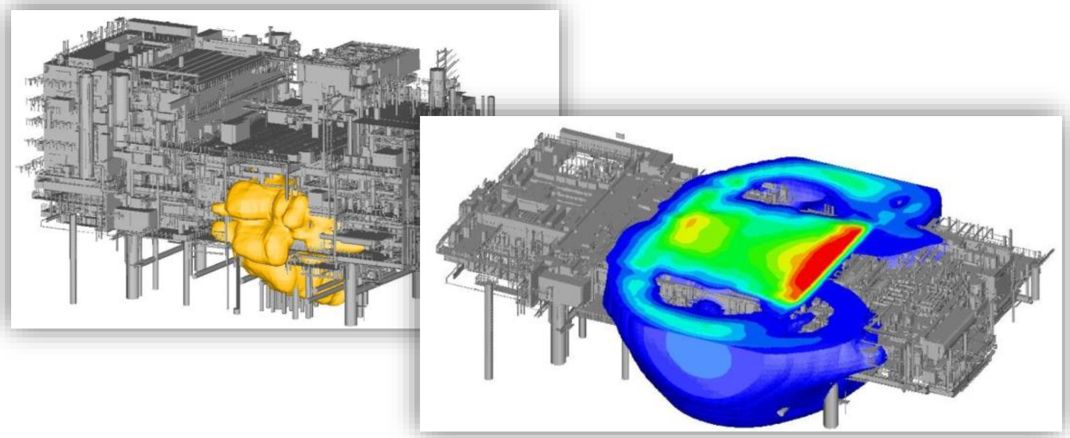


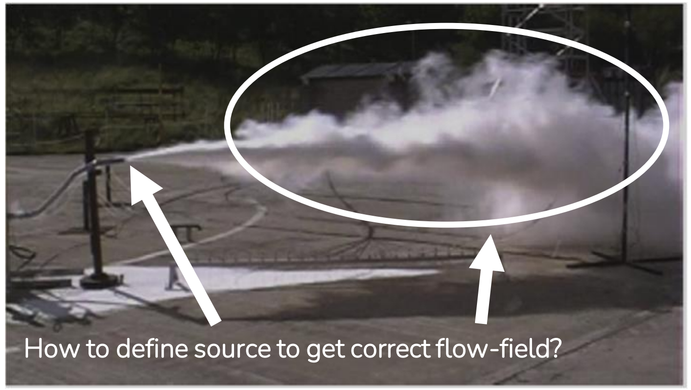


How best to model dispersion from LH_2 releases

Option 1 – try model the complex physics in detail [Not recommended - we tried with FLACS CFD for oil mists 25 y ago]

- Heat transfer (line/structures), flashboiling, droplet distribution, break-up/agglomeration, phase changes, pools ...





Option 2 – find a simplified modelling approach [FLACS CFD is gas-phase tool]

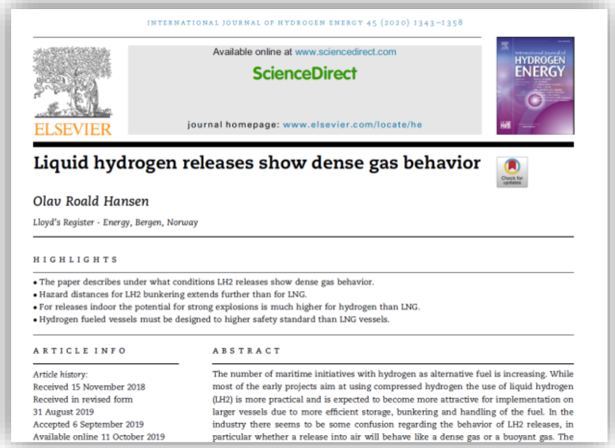
- **Estimate leak rate** (pressure drop, flashing upstream leak?] V ~100 m/s – reduce slightly with 10% v/v ambient air entrained
- **Assume no pool** (momentum leaks with excess air)
- **Ignore multiphase region** (< 90 K) - Optimise pseudo-source **22-25 K** LH_2/mist => evaporate to H_2 at **-15 K** => mix 10% air to **25 K**
- **Model humidty/fog** – Necessary for plume buoyancy at dilution Possible to activate **fog model** in FLACS

Approximation - Not critical whether parahydrogen or normal hydrogen properties are assumed

FLACS simulations to support NPRA advisory board May 2020

Simulation parameters

- Pseudo-source term as described in [Hansen, 2020] (cold H_2+air – mixture)
- Multi-phase region (LH_2, frozen/condensed air) simulated as gas phase
- No pool assumed (outdoor releases)
- Pressure near orifice used to estimate outflow velocity (~100 m/s)
- Average wind and ambient conditions used as specified
- Air humidity (90%) simulated => plume lift-off at diluted concentrations for low wind
- Geometry model made based on photos and reports
- Instrumentation as described in reports



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Liquid hydrogen releases show dense gas behavior

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HIGHLIGHTS

- The paper describes under what conditions LH2 releases show dense gas behavior.
- Hazard distances for LH2 bunkering extends further than for LNG.
- For releases indoor the potential for strong explosions is much higher for hydrogen than LNG.
- Hydrogen fueled vessels must be designed to higher safety standard than LNG vessels.

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ABSTRACT

The number of maritime initiatives with hydrogen as alternative fuel is increasing. While most of the early projects aim at using compressed hydrogen the use of liquid hydrogen (LH2) is more practical and is expected to become more attractive for implementation on larger vessels due to more efficient storage, bunkering and handling of the fuel. In the industry there seems to be some confusion regarding the behavior of LH2 releases, in particular whether a release into air will behave like a dense gas or a buoyant gas. The

Simulations were presented at advisory board meeting less than 1 week after receiving first draft reports

[NPRA – Norwegian Public Road Authority]

NPRA LH_2 tests at DNV Spadeadam site 2019/2020

DNV large scale LH_2 experiments for NPRA/FFI

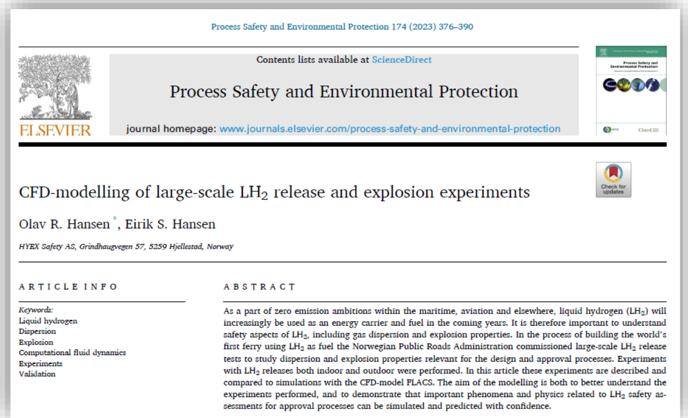
Outdoor (Tests 1-7): Releases 0.7-0.8 kg/s relevant for vessel bunkering safety

- NPRA stated goal => Study pool spread, dispersion and ignition
- My advisory board input => No outdoor pool expected, should focus on far-field concentrations

Indoor (Tests 8-15): Releases 0.4-0.5 kg/s inside TCS – tank connection space [Not covered in this presentation]

- NPRA stated goal => Study indoor dispersion, ventilation, N_2-dilution, explosion, venting
- My advisory board input => Too high release rates – hazards more severe with 0.05 kg/s release

=> Nitrogen dilution/venting poor safety strategy – major LH_2 indoor leaks not tolerable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CFD-modelling of large-scale LH_2 release and explosion experiments

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ABSTRACT

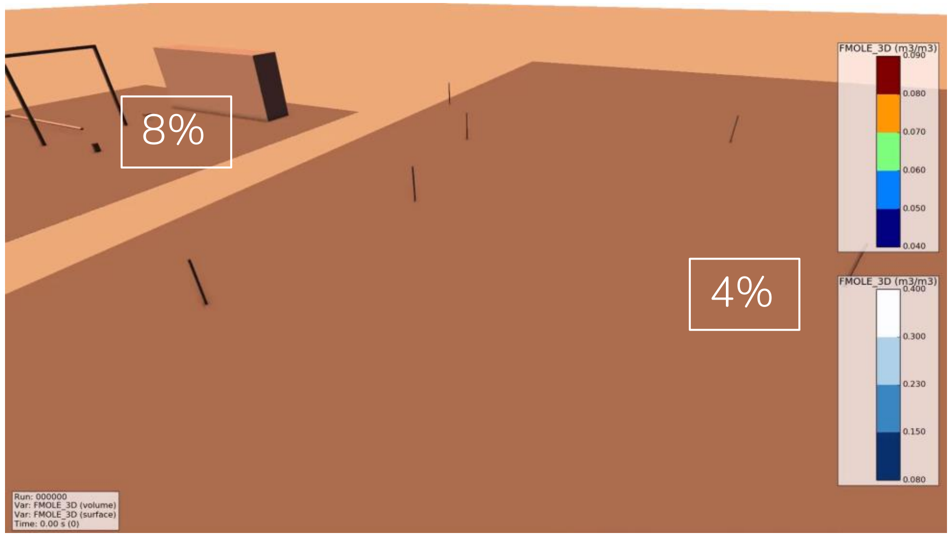
As a part of zero emission ambitions within the maritime, aviation and elsewhere, liquid hydrogen (LH_2) will increasingly be used as an energy carrier and fuel in the coming years. It is therefore important to understand safety aspects of LH_2, including gas dispersion and explosion properties. In the process of building the world's first ferry using LH_2 as fuel the Norwegian Public Roads Administration commissioned large-scale LH_2 release tests to study dispersion and explosion properties relevant for the design and approval processes. Experiments with LH_2 releases both indoor and outdoor were performed. In this article these experiments are described and compared to simulations with the CFD-model FLACS. The aim of the modelling is both to better understand the experiments performed, and to demonstrate that important phenomena and physics related to LH_2 safety assessments for approval processes can be simulated and predicted with confidence.

Test 5 (and Test 3) – 0.74 kg/s downwards

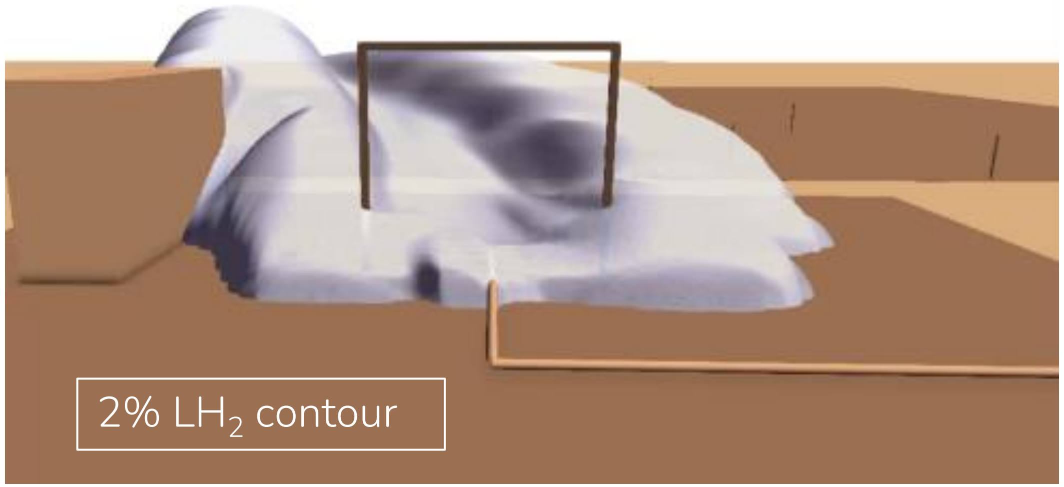
Temperature 4 °C (90% humidity assumed – 0.75% v/v)

Wind 4 m/s

Release down from 0.32 m elevation

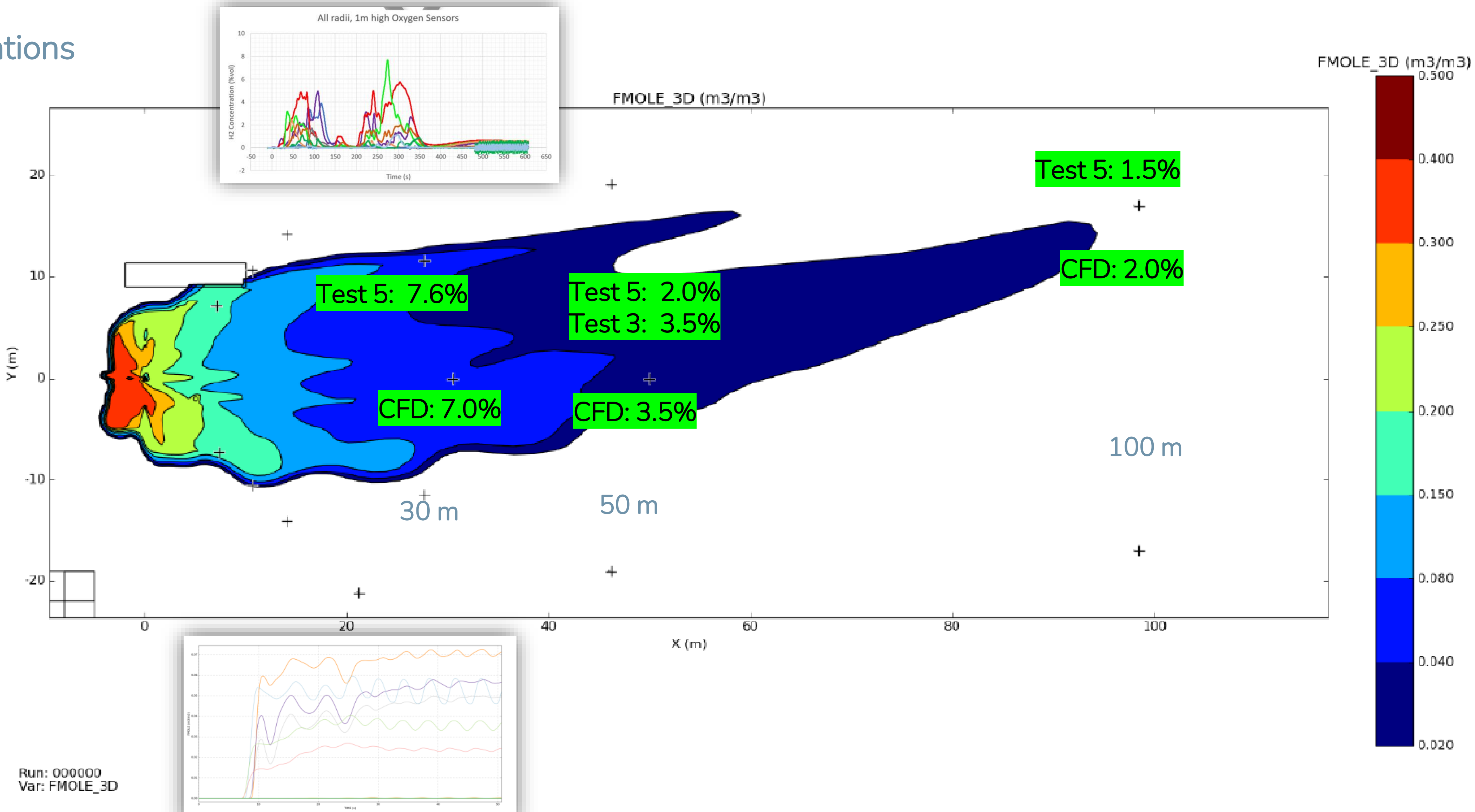


Test 5 – ignited at 18 m - 2nd attempt, 1st try failed to ignite at 24 & 18 m



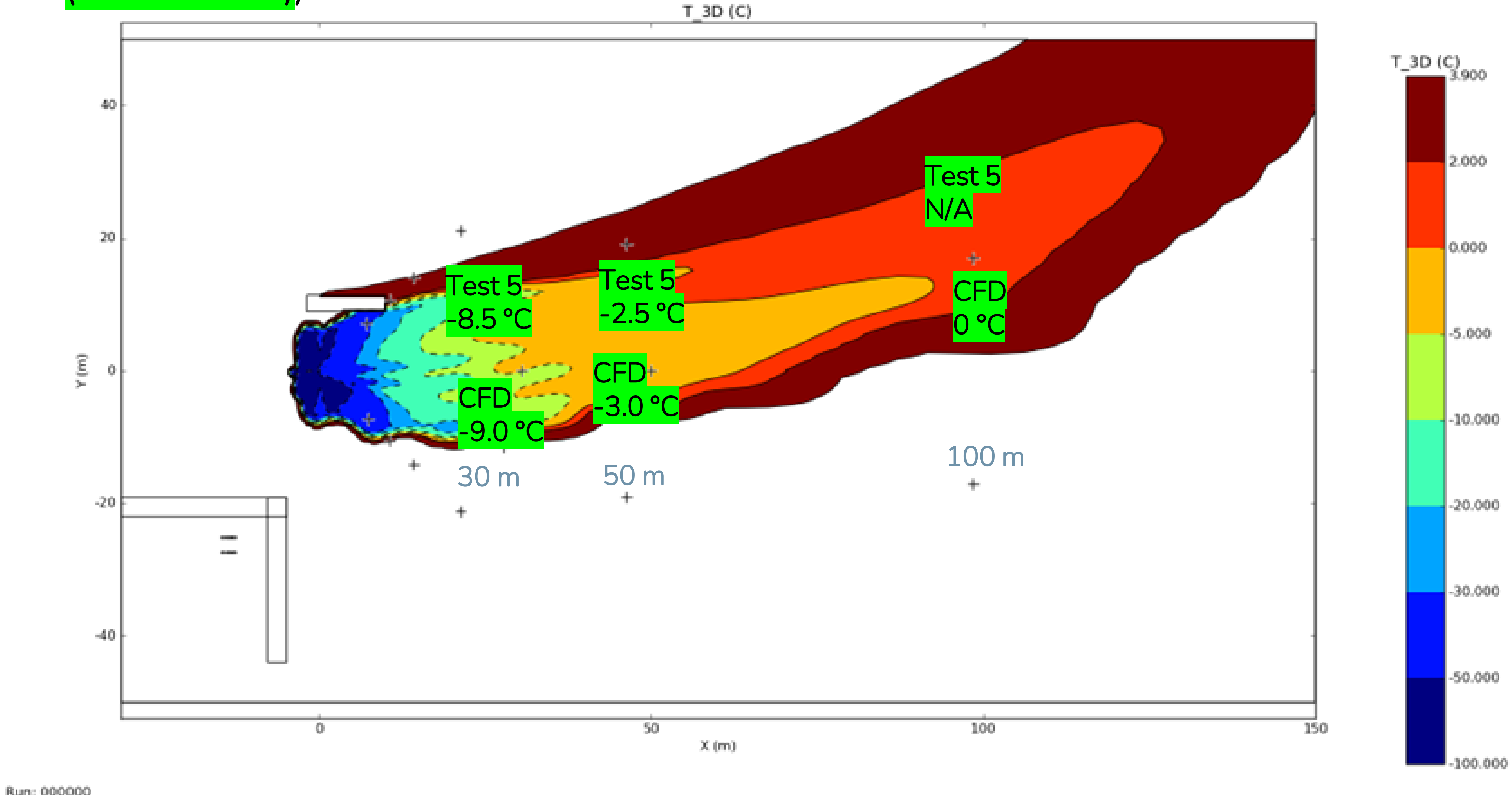
Test 5 (and Test 3) – 0.74 kg/s downwards

Concentrations



Test 5 (and Test 3) – 0.74 kg/s downwards

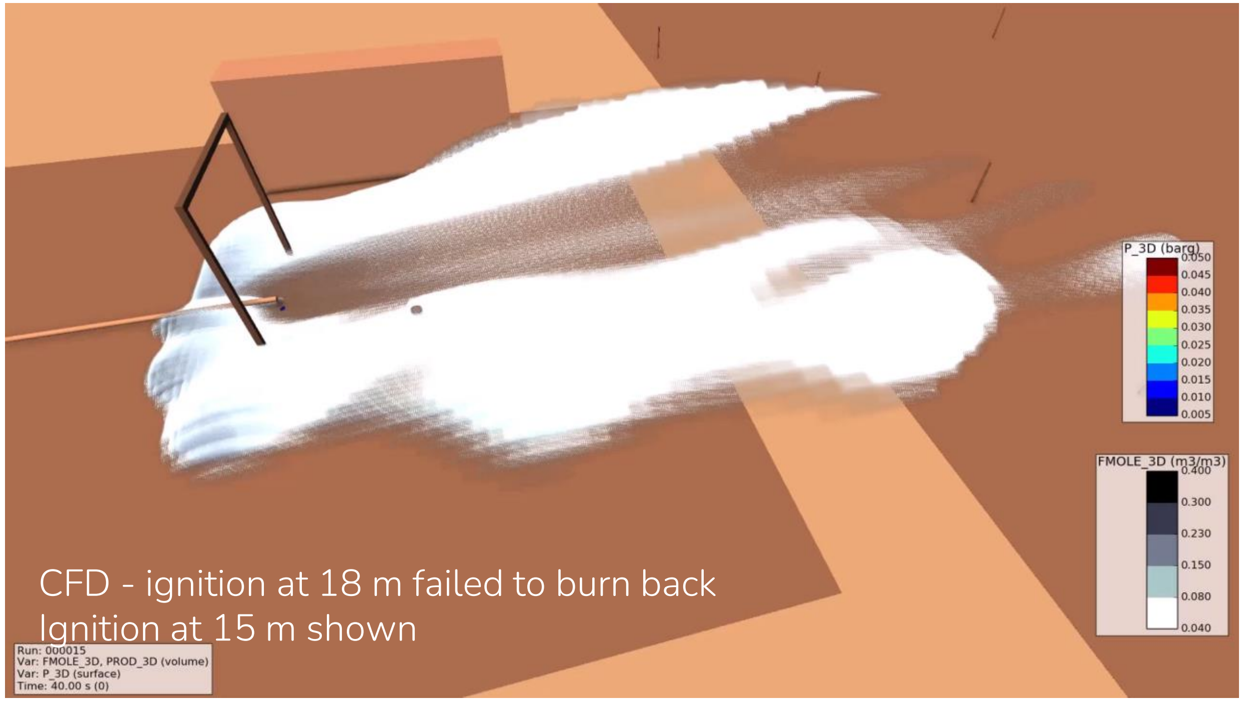
Temperatures (Ambient 4 °C))



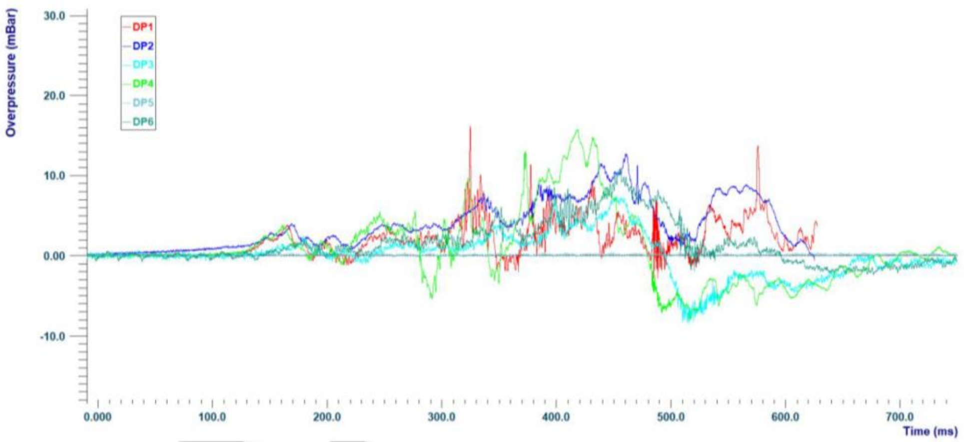
Test 5 (and Test 3) – 0.74 kg/s downwards

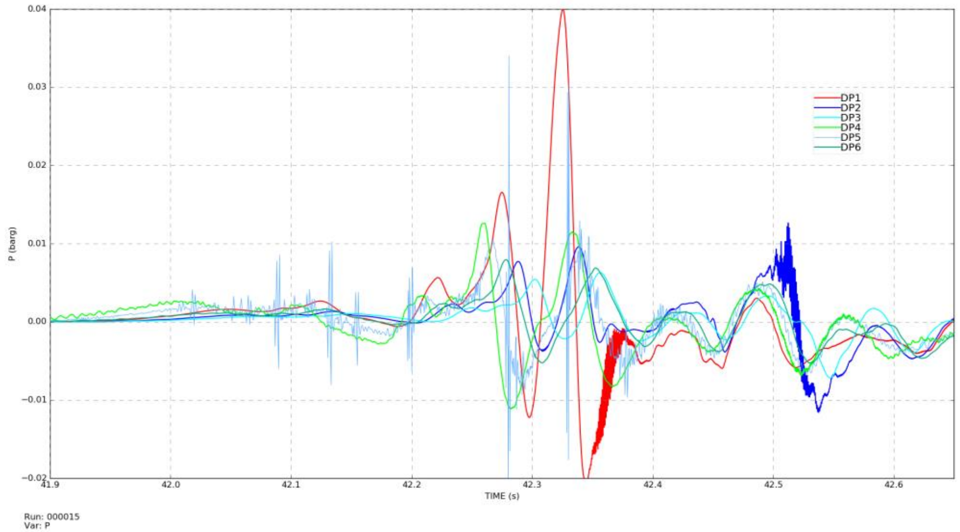
Test 5 – pressure 10-15 mbar

CFD – pressure 10-12 mbar (one detector 40 mbar)



CFD - ignition at 18 m failed to burn back
Ignition at 15 m shown





Test 5 (and Test 3) – 0.74 kg/s downwards

Test confirms no horizontal flashfire below 8% hydrogen

NPRA LH2 test 5 –
1st release – ignition at 24 m and 18 m failed

NPRA LH2 test 5 –
2nd release ignition 18 m successful –flame propagation stops >8%

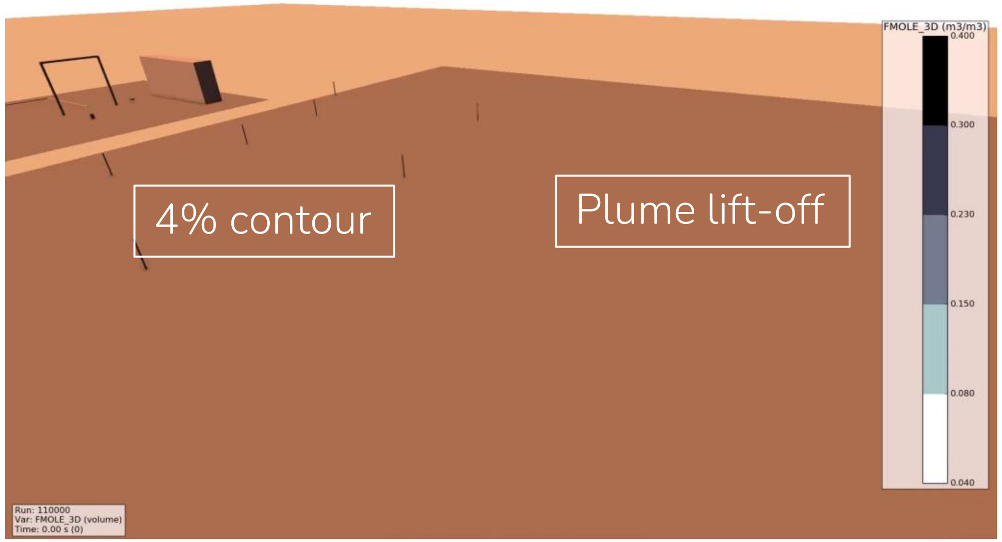
Test 6– 0.83 kg/s horizontally

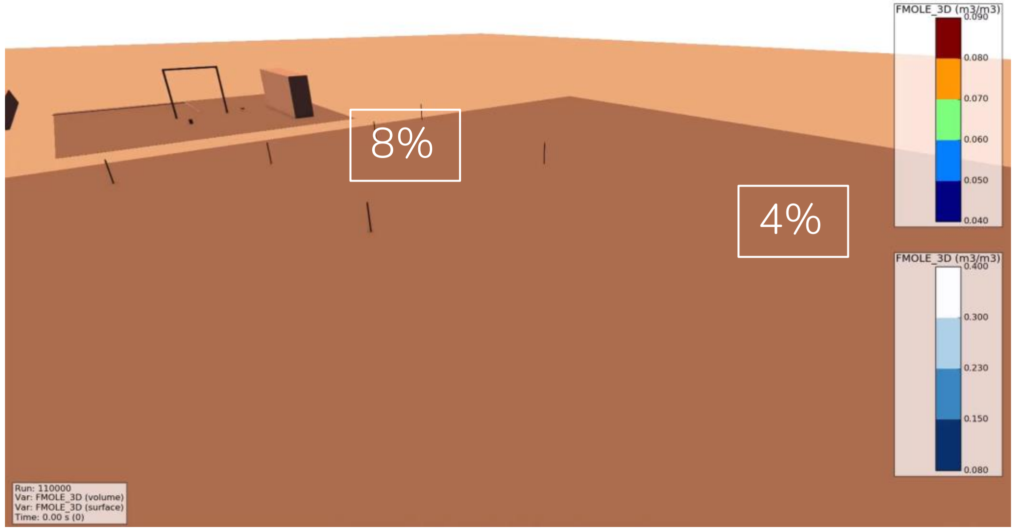
Temperature 4 °C (90% humidity assumed i.e. ~0.75% v/v H_2O (g))

Wind 2.5 m/s

Horizontal release at 0.50 m elevation

Low wind + humidity => plume lift-off at concentration ~6-7%





Test 6– 0.83 kg/s horizontally

Concentrations

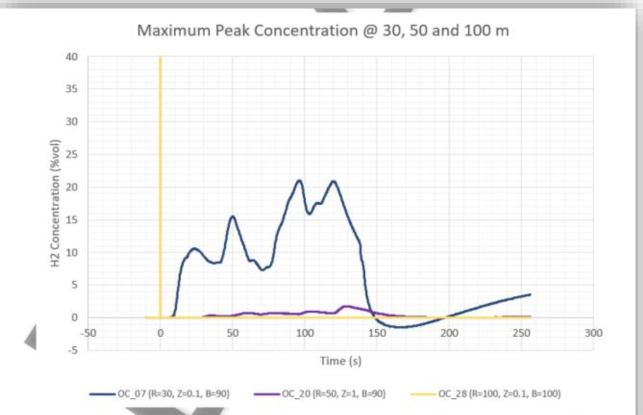
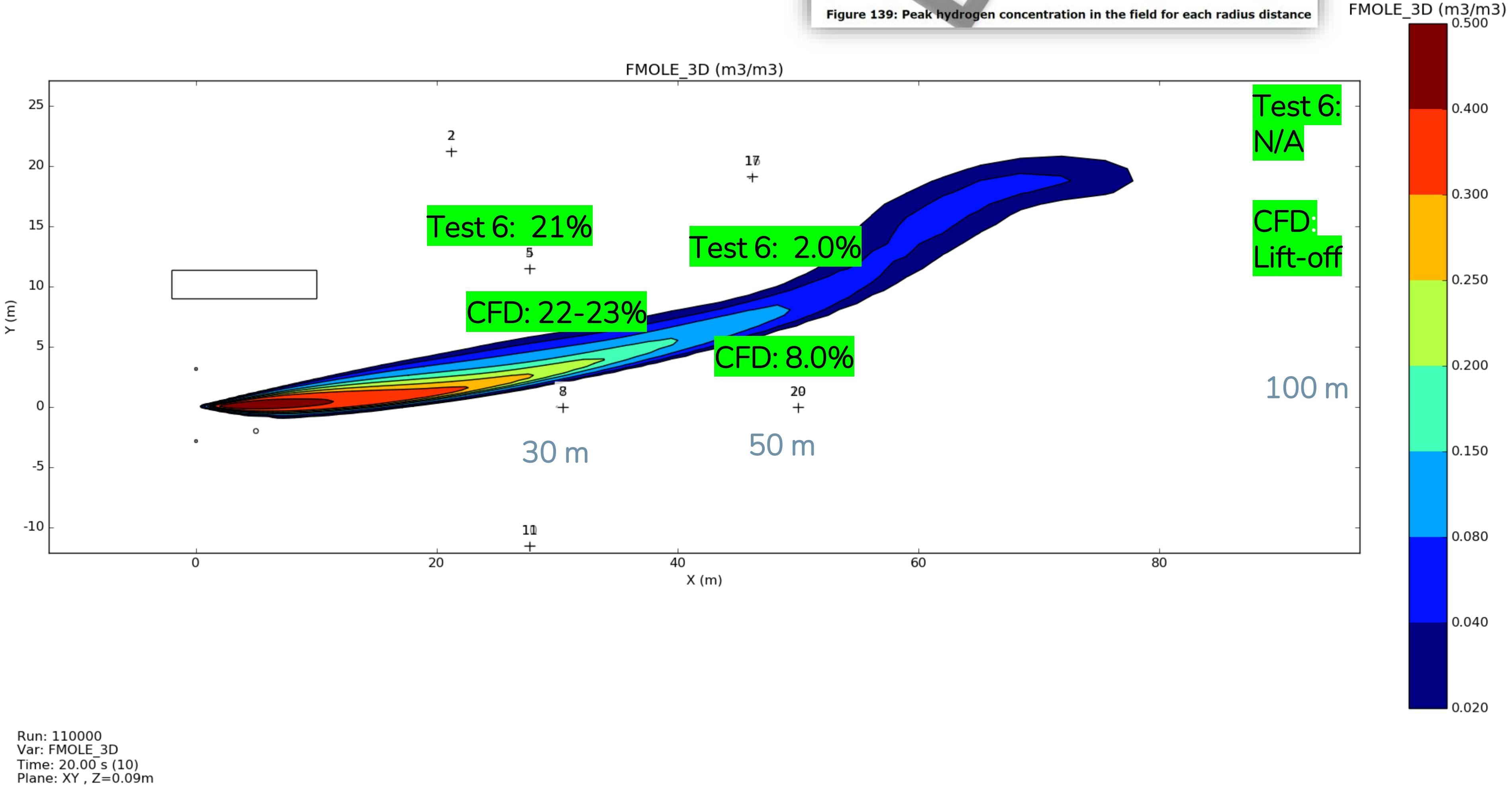
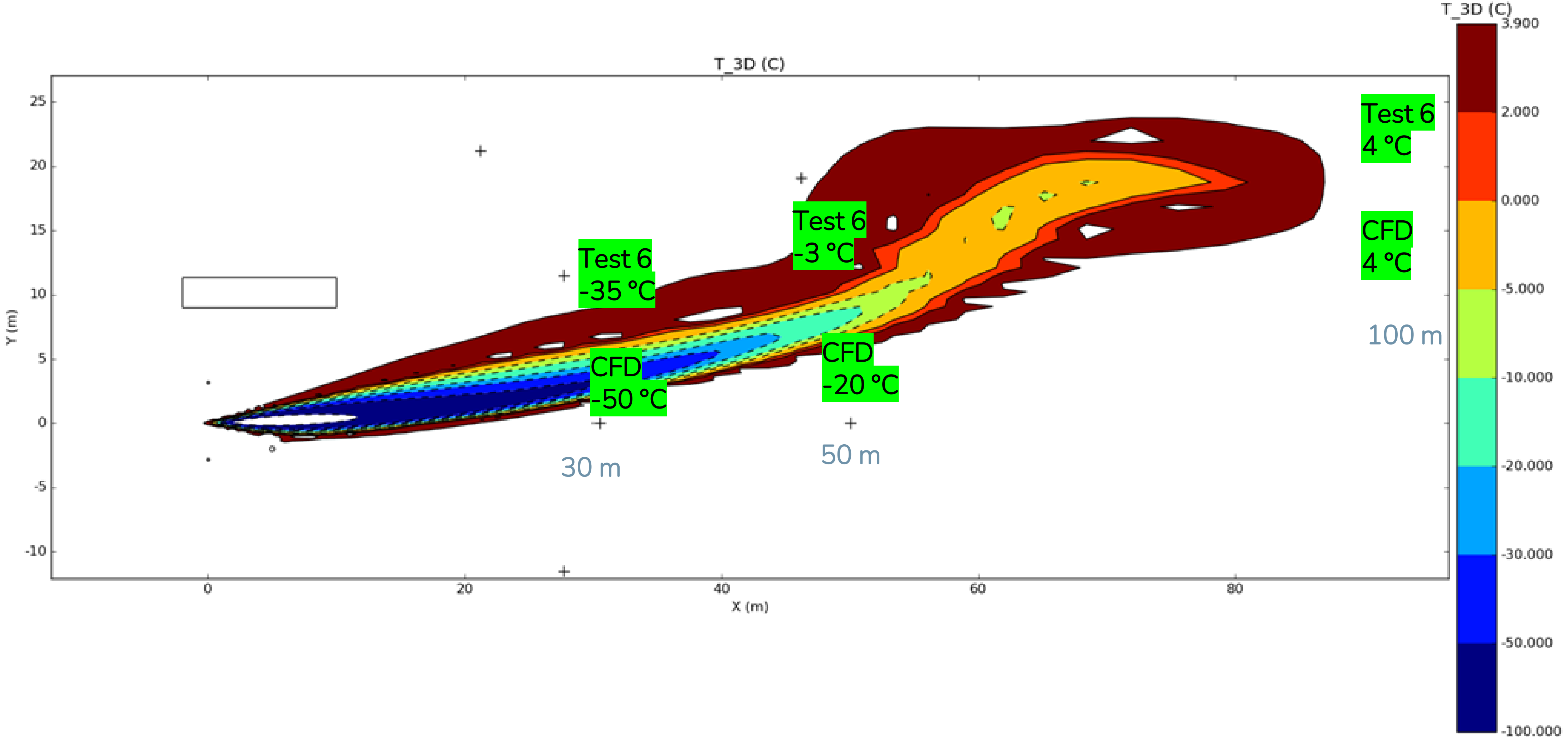


Figure 139: Peak hydrogen concentration in the field for each radius distance



Test 6– 0.83 kg/s horizontally

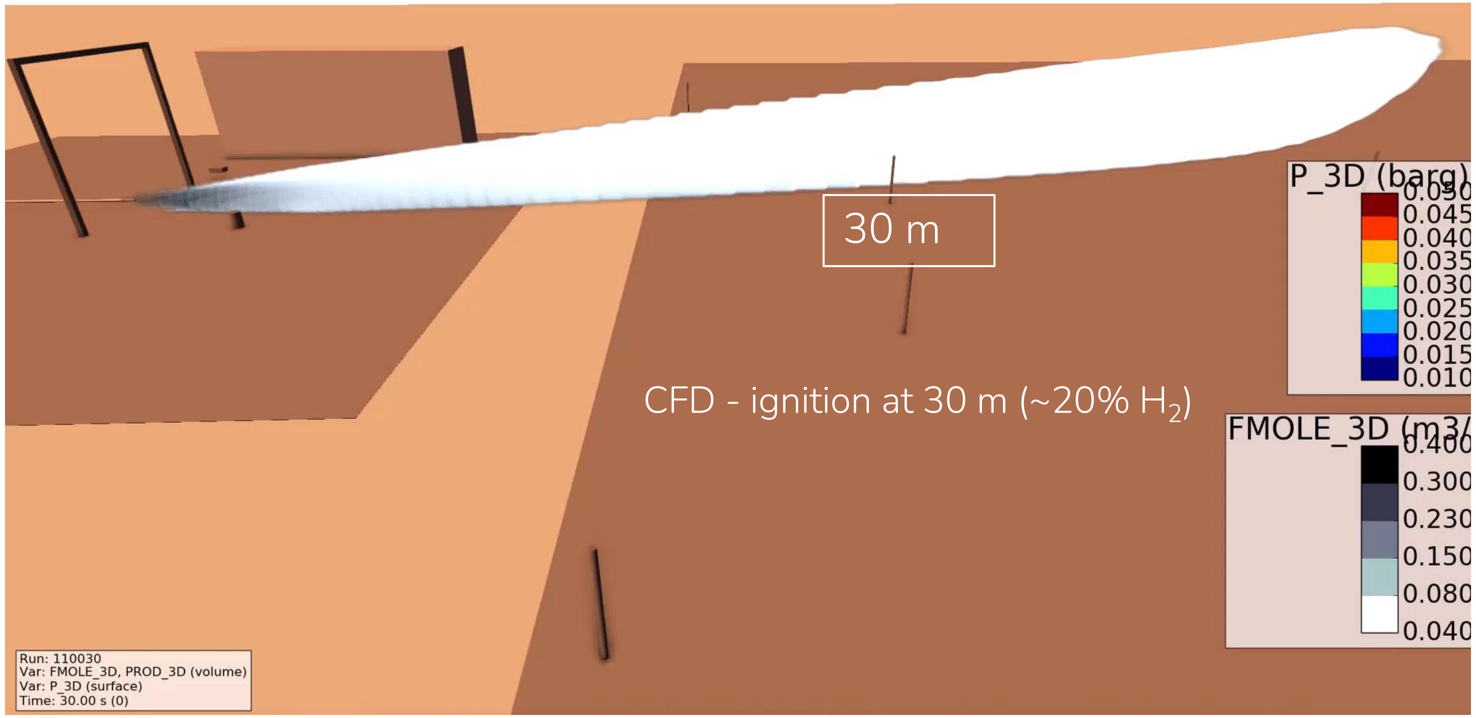
Temperatures (Ambient 4 °C))

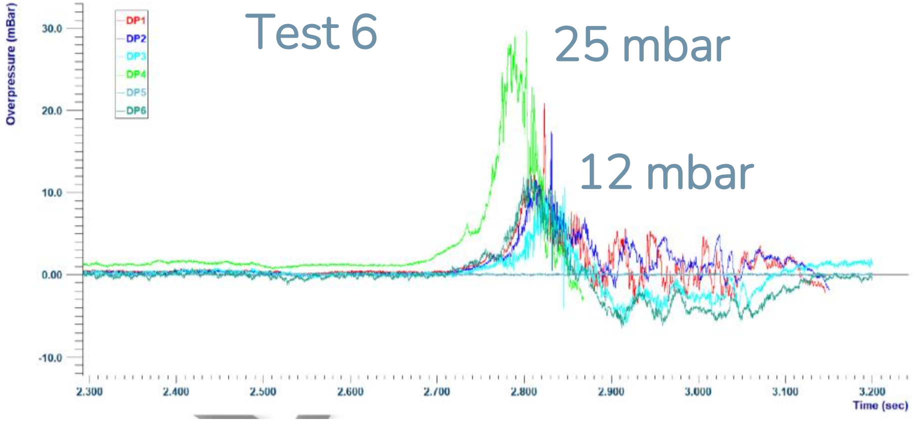


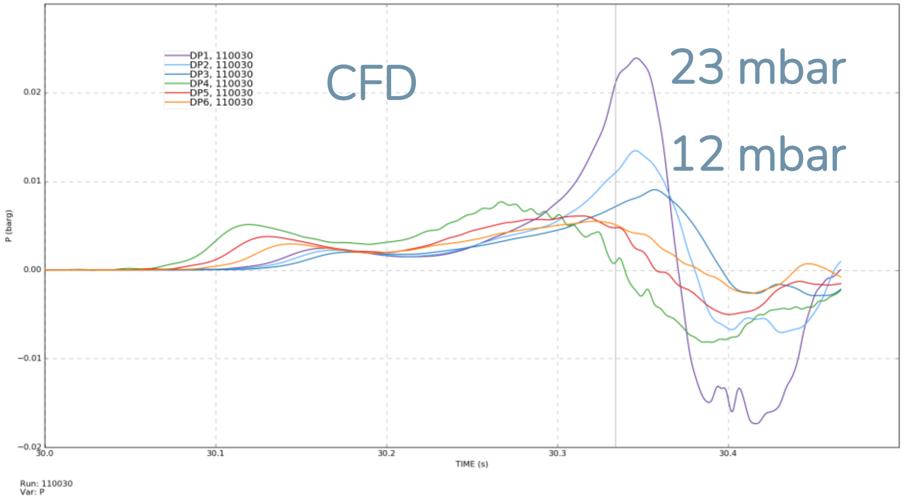
Test 6– 0.83 kg/s horizontally

Test 6 – Pressure 25 mbar (PD4) – rest 12 mbar

CFD – Pressure 23 mbar (PD1) – rest 12 mbar







Summary and conclusions

Interesting but challenging experiments were simulated surprisingly well

- Concentrations, temperatures, buoyancy and explosion seem well reproduced with CFD (FLACS) using pseudo-source approach
- Good confirmation of ability to predict LH_2 accident scenarios and applicability for bunkering assessments
- Simulation results valuable to help interpret and confirm quality of experiments

Main learnings from experiments

- LH_2 releases outdoor gave no pool formation (despite 0.74 kg/s released downwards from 0.32 m elevation)
- Indoors with lack of air, pools would form
- Plume lift-off when diluted for low winds
- Major LH_2 releases indoor not tolerable => very high pressures despite non-homogeneous clouds and large vent area

PS! Outdoor releases gave low pressures – with gas accumulation in partial confinement/congestion DDT to be feared

Thanks to NPRA and FFI for making tests publicly available and to DNV for good quality experiments

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