Session “Progress in Safety Research”

Topic: Low T (LH2/cryogenic) related

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Chair: Stuart Hawksworth, Jay Keller

Research Priorities Workshop – 26-30 October 2020

The Focal Point on Integrated Research and Information for Hydrogen Safety

Topic: Low T (LH2/cryogenic) related

Acknowledgements

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- United States Department of Energy, Energy Efficiency &Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Laura Hill
- Industry support including the OEM Group at the California Fuel Cell Partnership, Linde, and Shell
- Air Liquide and partners

The PRESLHY project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under the grant agreement No 779613.
The project members thank all further contributors (e.g. Equinor, SHELL, …)

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Topic: Low T (LH2/cryogenic) related

Status at the time of previous workshop

Topics for voting

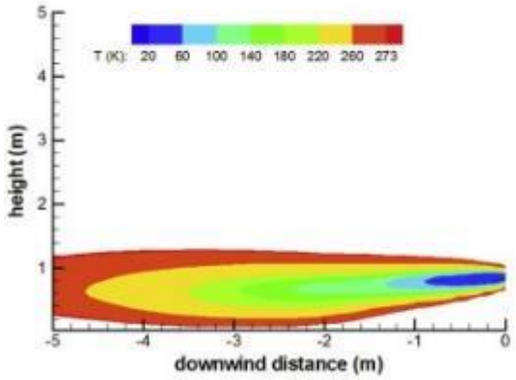
- Knowledge and experience related to indoor releases and dispersion
- Knowledge and experience related releases involving large quantities
- **Knowledge and experience related releases in congested areas**
- **Multi-phase accumulations with explosion potential (LH2 can condense and freeze oxygen. The resultant mixture can be made to detonate): conditions for occurrence and the consequences are not understood**
- BLEVE (Boiling Liquid Expanding Vapour Explosion or Fireball): knowledge on fire resistance and prediction of consequences are needed.
- Studies on humidity / air phase change during LH2 and cryogenic compressed hydrogen releases should be undertaken to inform modelling of these phenomena
- Correlations for accurately calculating the specific heat capacity of hydrogen at low temperatures and high pressures should be further investigated and incorporated into CFD codes.
- **CFD validation especially for complex obstructed industrial environments and various weather conditions (wind speed atmospheric stability class)**
- Modelling of the two-phase chocked releases, in particular for achieving a reasonable estimation of the mass flow rate
- Further development of pool spreading and evaporation models, coupled with vapour dispersion. Research should be directed at improving the modelling of ground heat flux in cases where a liquid pool is formed- for both solid and liquid (usually water) substrates. The radiative heat transfer and its contribution to the total heat transfer from the air and ground to the cold cloud should also be studied. Liquid hydrogen pool fire not well characterised
- Evaluation and comparison of the performance of the different Equation of States (EOS) in the two-phase chocked flow approaches should be attempted
- Ignition sensitivity & electrostatic hazards during venting / accident scenarios
- Combustion properties of cold gas clouds, especially in congested areas
- Rapid phase transition / response to water deluge etc
- High Pressure LH2 releases

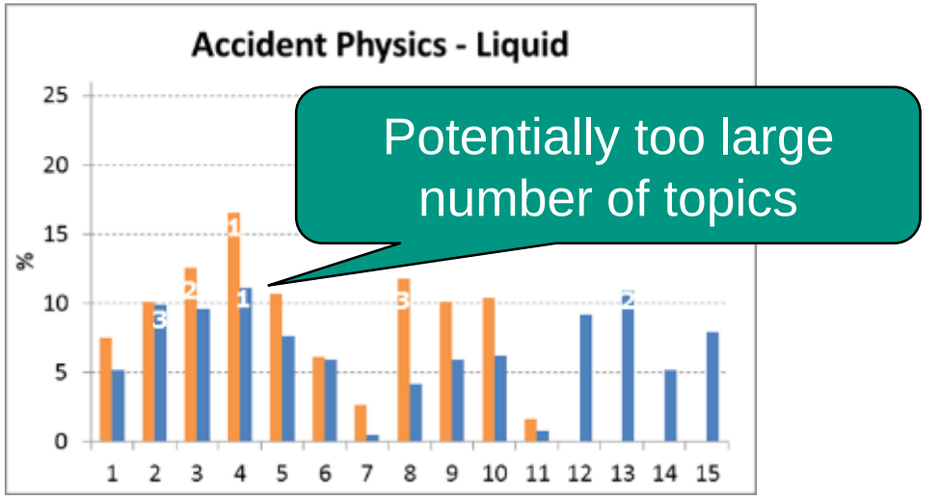
Topic: Low T (LH2/cryogenic) related

Status at the time of previous workshop

Topics with highest ranking

1. **Multi-phase accumulations** with explosion potential (LH2 can condense and freeze oxygen. The resultant mixture can be made to detonate): conditions for occurrence and their the consequences are not understood
2. Combustion properties of cold gas clouds, especially in **congested area**
3. Knowledge and experience related releases involving **large quantities**





Topic: Low T (LH2/cryogenic) related

Where we are today wrt highly ranked topics

Ad Priority 1: Multi-phase accumulations with explosion potential

- ✓ **Repeated spill in gravel bed might generate dangerous condensed phase mixtures; not for other substrates**
- ✓ **Water sprays on LH2 and LH2 spill on small water pool seem to be non critical**

Ad Priority 2: Combustion properties of cold gas clouds, especially in congested area

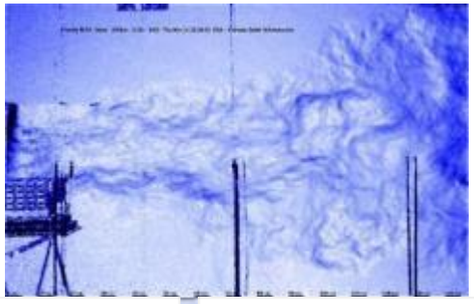
- ✓ **Higher expansion ratios come with higher critical expansion ratios**
- ✓ **Uncongested mixtures behave less critical**
- ✓ **Density effects might promote strong pressure effects in particular for congested areas**

Ad Priority 3: Knowledge and experience related releases involving large quantities

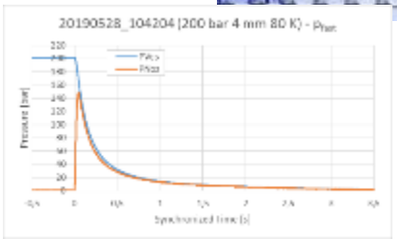
- ✓ **Large discharges do not generate static electricity or promote spontaneous ignition under normal weather conditions**
- ✓ **Spills shall be trenched and kept in a pool with low release rates**

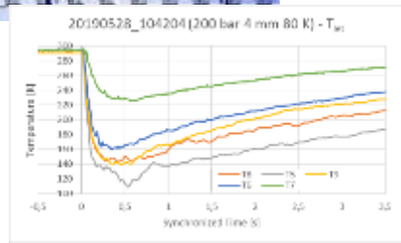
Topic: Low T (LH2/cryogenic) related

Further progress, closed gaps - Release

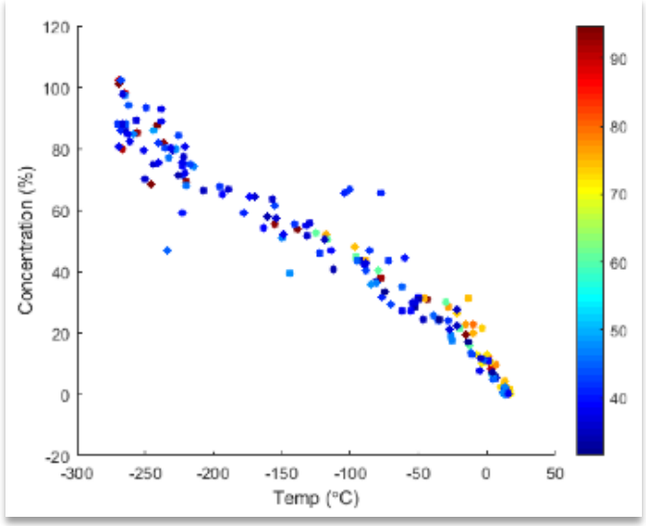


- 1 D model for multi-phase release developed (NCSRD)
- Discharge coefficients for circular nozzles D=0.5-4 mm
  5 - 200 bar; 20 – 300K (PRESLHY KIT/PS E3.1 DISCHA tests)
  see https://doi.org/10.5445/IR/1000096833





- No rainout for large scale above ground horizontal releases
  (PRESLHY HSE E3.5: rainout tests)
- Correlation of T and concentration of mixtures of H2
  with cryogenic origin and air



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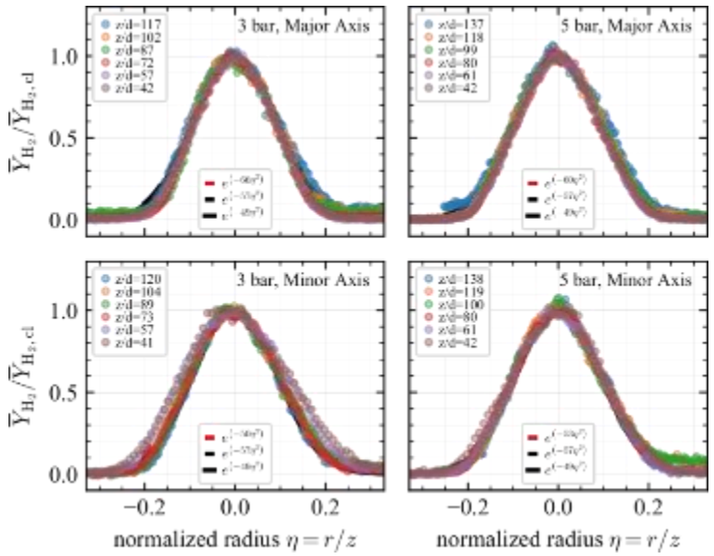
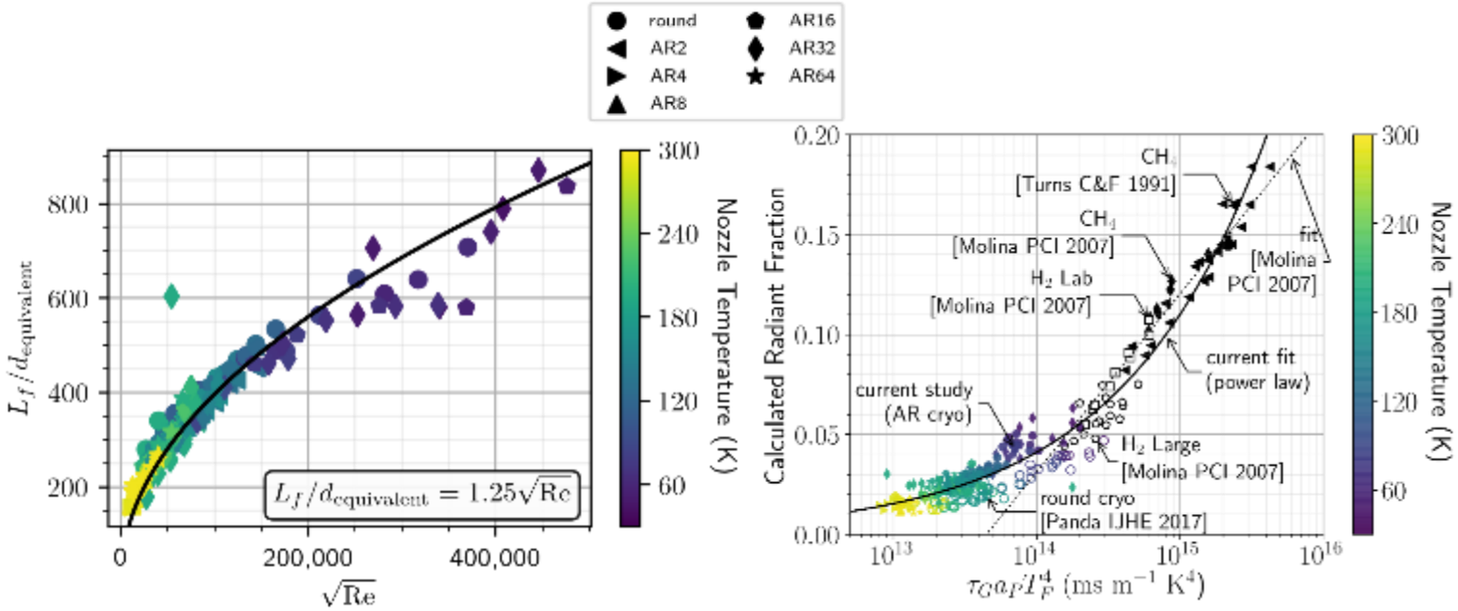
Further progress, closed gaps– Jet Fires

Aspect ratio 32



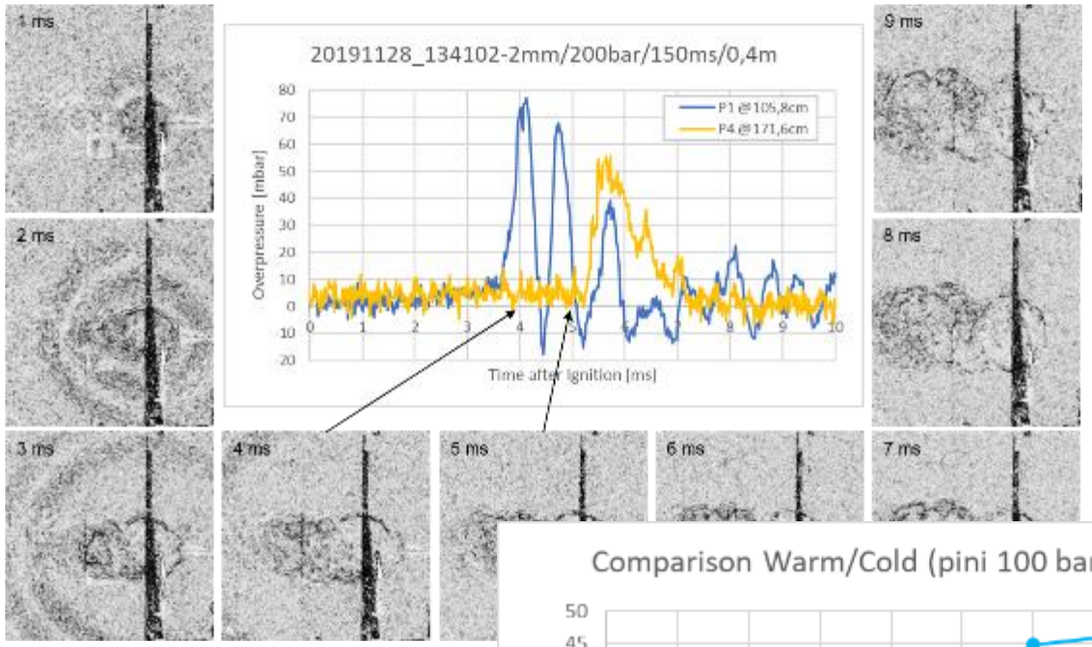


- Profiles are self-similar and the same along the major and minor axes
- High aspect-ratio data for flame length and radiant fraction fall on same correlations as round data
- Small (~1mm effective diameter), non-round (high aspect-ratio) leaks at LH2 storage pressures (5 bar) have the same dispersion and flame properties as round leaks

Topic: Low T (LH2/cryogenic) related

Further progress, closed gaps – Max. overpressures of small inventories

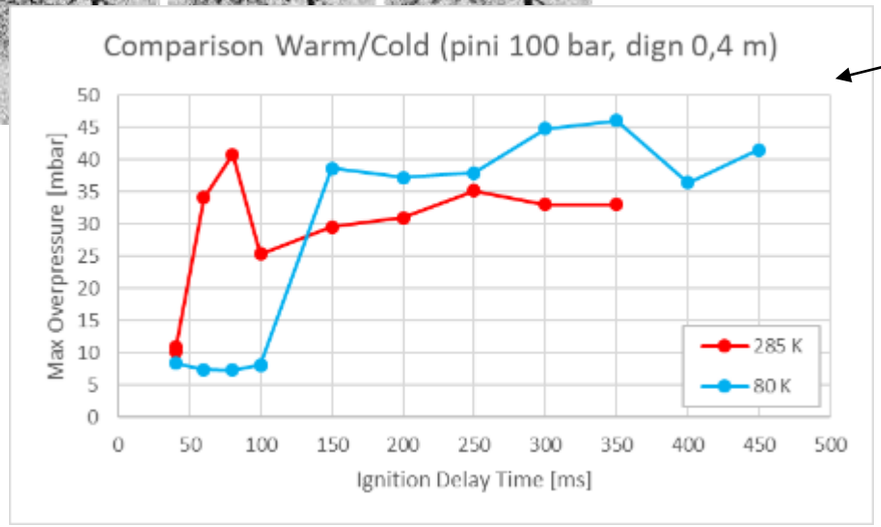
PRESLHY E5.1: Ignited jet test series



> 100 experiments based on unignited discharge tests E3.1 with reduced parameters variation:
T = 80K, ~285K
p = 5, 100, 200 bar
D_{nozzle}= 1, 2, 4mm

Iterative procedure for identifying most critical ignition time and location

e.g.

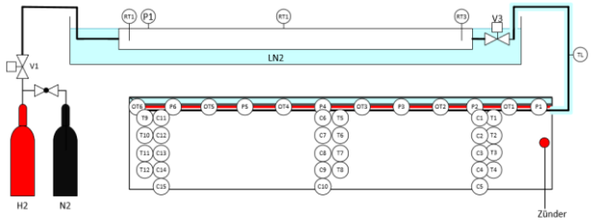


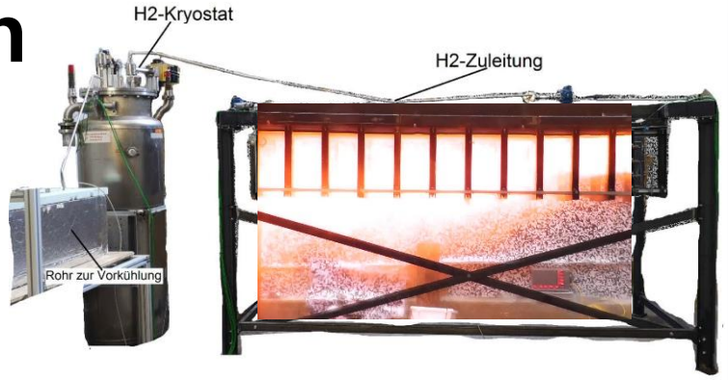
→
Better understanding of transient jets and combustion processes
→
to be extrapolated to large inventories for RCS

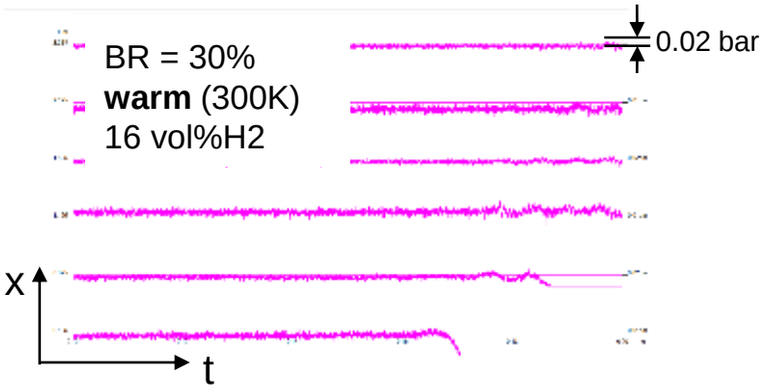
Topic: Low T (LH2/cryogenic) related

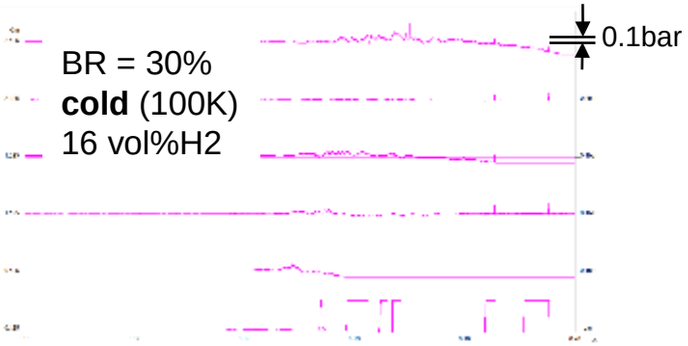
Further progress, closed gaps– Explosions in partially confined, obstructed domain

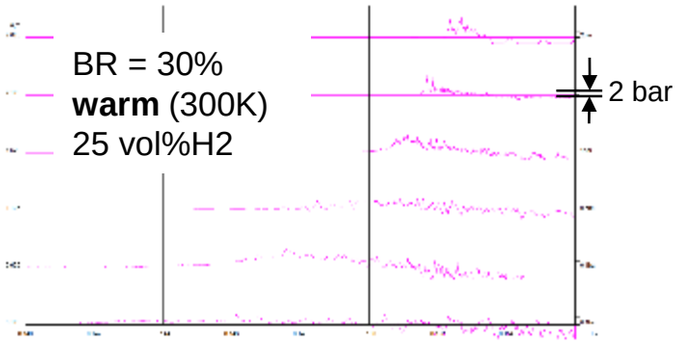
PRESLHY E5.5 Test series

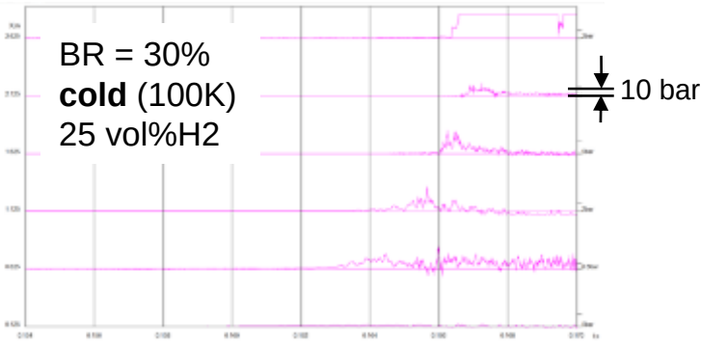












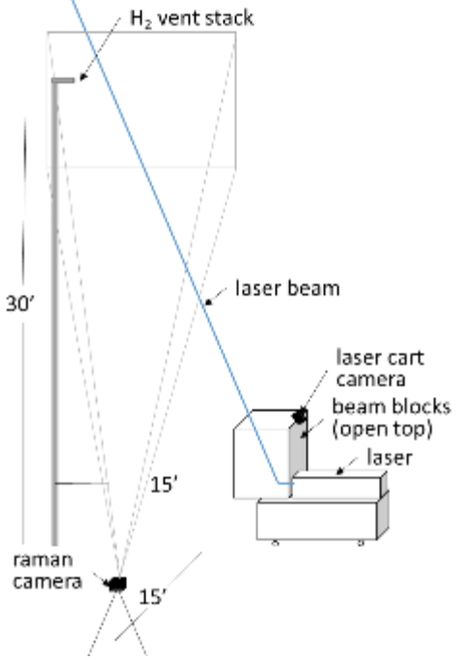
- Stronger pressure loads for cold tests in comparison with warm tests with the same hydrogen concentration and BR (to be inventory related)
- Difference increases with increasing hydrogen concentration

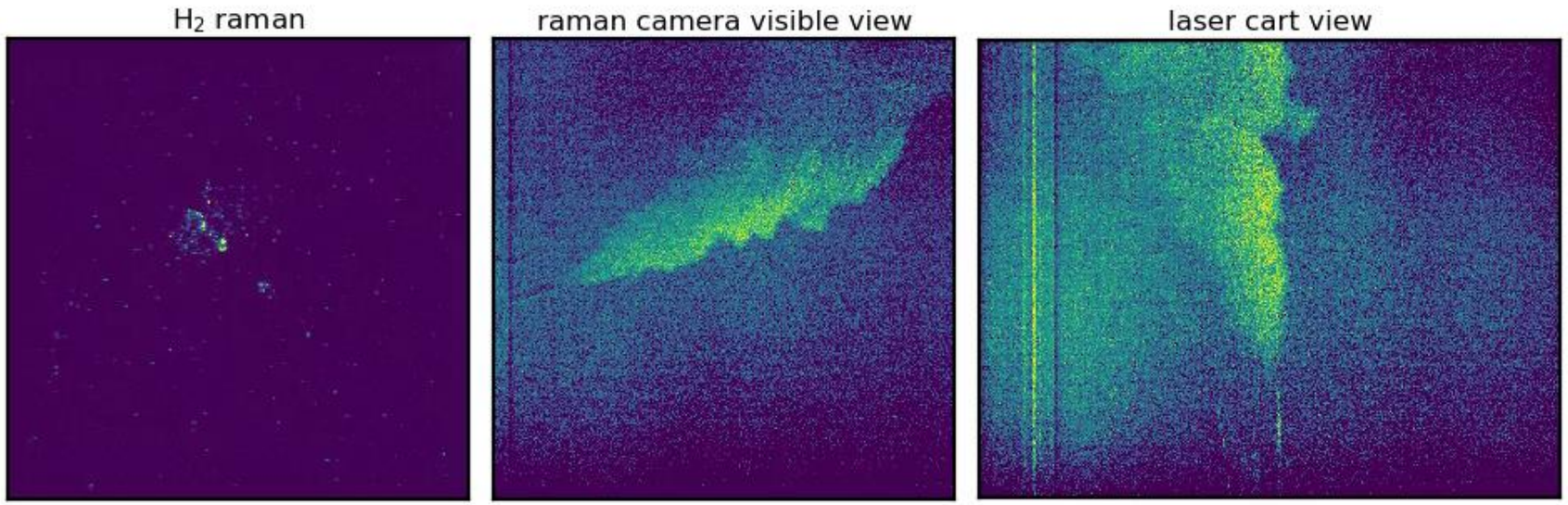
Topic: Low T (LH2/cryogenic) related

Ongoing work to close knowledge gaps of highly ranked topics

Ad Priority 3: Knowledge and experience related releases involving large quantities

Experiments underway using Sandia developed diagnostic to study ambient effects on large vent stack releases

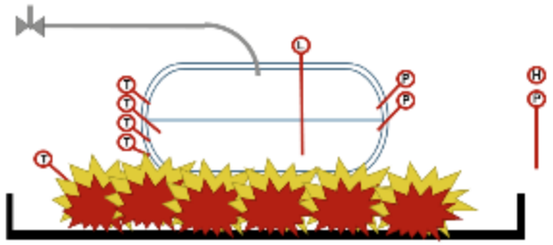




- Mapping out whether hydrogen is concurrent with condensed moisture
- Performing releases in low and high wind conditions

Topic: Low T (LH2/cryogenic) related

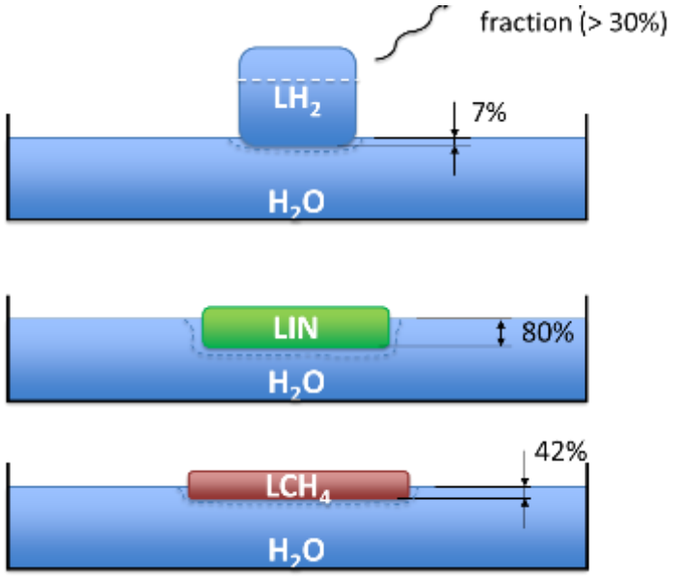
Ongoing work to close knowledge gaps related to BLEVE



to be performed Q1 2021

- **BLEVE** - **B**oiling **L**iquid **E**xpanding **V**apor **E**xplosion
  - 3 LH_2 vessels à 1 m^3

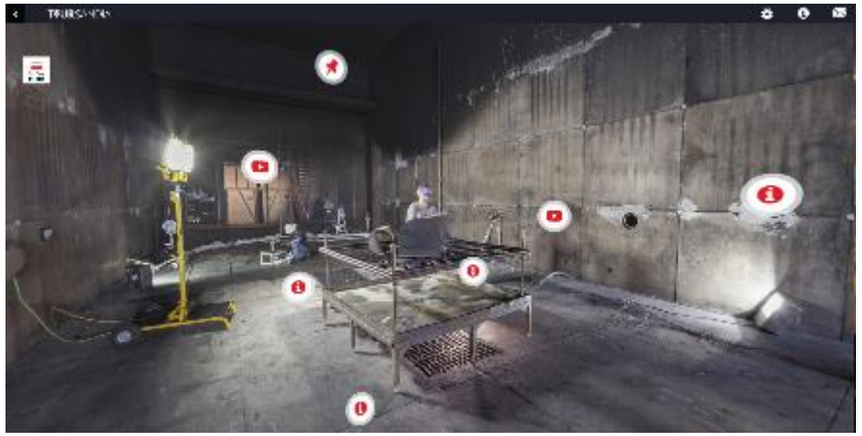
- **RPT** - **R**apid **P**hase **T**ransition
  - Basin 10 m x 10 m x 1.5 m



Topic: Low T (LH2/cryogenic) related

Work planned to improve fundamental knowledge of LH2 and validate models

- Carefully controlled pooling and vaporization experiments are being planned
  - Sandia's cross-wind test facility
  - Measure pooling rate
  - Measure evaporation rate
  - Measure dispersion in controlled cross-flow
- Future work to revisit mitigation from walls, including dispersion and mitigation of liquid hydrogen leaks/flames
  - Effects on unignited dispersion and accumulation
  - Reduction in heat flux/overpressure



Topic: Low T (LH2/cryogenic) related

Reorganization of the knowledge gaps

Ranked in priority order from 2018:

1. Multi-phase accumulations with explosion potential (LH2 can condense and freeze oxygen. The resultant mixture can be made to detonate): conditions for occurrence and the consequences are not understood
2. Combustion properties of cold gas clouds, especially in congested areas
3. Knowledge and experience related releases involving large quantities
4. Knowledge and experience related releases in congested areas
5. Ignition sensitivity & electrostatic hazards during venting / accident scenarios
6. High Pressure LH2 releases
7. BLEVE (Boiling Liquid Expanding Vapour Explosion or Fireball): knowledge on fire resistance and prediction of consequences are needed.
8. Further development of pool spreading and evaporation models, coupled with vapour dispersion. Research should be directed at improving the modelling of ground heat flux in cases where a liquid pool is formed- for both solid and liquid (usually water) substrates. The radiative heat transfer and its contribution to the total heat transfer from the air and ground to the cold cloud should also be studied. Liquid hydrogen pool fire not well characterised
9. Studies on humidity / air phase change during LH2 and cryogenic compressed hydrogen releases should be undertaken to inform modelling of these phenomena
10. Modelling of the two-phase choked releases, in particular for achieving a reasonable estimation of the mass flow rate
11. Rapid phase transition / response to water deluge etc.
12. Knowledge and experience related to indoor releases and dispersion
13. CFD validation especially for complex obstructed industrial environments and various weather conditions (wind speed atmospheric stability class)
14. Evaluation and comparison of the performance of the different Equation of States (EOS) in the two-phase choked flow approaches should be attempted
15. Correlations for accurately calculating the specific heat capacity of hydrogen at low temperatures and high pressures should be further investigated and incorporated into CFD codes.

Topic: Low T (LH2/cryogenic) related

Reorganization of the knowledge gaps

A. Dispersion/unignited

1. Heat transfer to and dispersion from pools (on solid surfaces and water) (8)
2. Condensation rate of O2 into pools (1)
3. Rapid phase transition/response to water deluge (11)
4. Dispersion of cold mixtures in congested areas (4)
5. Dispersion of cold mixtures indoors (12)
6. Dispersion of cold mixtures from cryo-compressed sources
7. Effects of humidity on dispersion (9)

B. Ignition

1. Sensitivity (5)
2. Propensity for electrostatic build-up/discharge (5)
3. Weather conditions, in particular snow fall (19)

C. Combustion

1. LH2
2. Detonation potential with variations in solid O2 (1)
3. Overpressure during pool ignition
4. Heat flux from pool fires (8)
5. Effects of congestion (2)
6. Combustion of cryo-compressed sources
7. BLEVE/fireballs (7)

D. Modelling

1. Effect of humidity/air condensation (9)
2. Estimation of flowrate for two-phase choked flow (10)
3. Validation data for dispersion in complex environments (obstructions, different wind, etc.) (4, 13)
4. Equation of state effect on choked flow calculations (14)
5. Heat capacity at low temperatures/high pressures (15)

E. Material and Structural Issues

1. Compatibility of plastic materials (16)
2. Thermal shock on conventional structural elements (17)
3. Impact on cryostats (18)

(1) ~ previous ranking
(16)-(19) new identified gaps

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Where we are?

Topic: Low T (LH2/cryogenic) related

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Where we are?

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Proposal for future work

A. Dispersion/unignited

1. Heat transfer to and dispersion from pools (on solid surfaces and water) (8)
2. Condensation rate of O2 into pools (1)
3. Rapid phase transition/response to water deluge (11)
4. Dispersion of cold mixtures in congested areas (4)
5. Dispersion of cold mixtures indoors (12)
6. Dispersion of cold mixtures from cryo-compressed sources
7. **Effects of humidity on dispersion**

B. Ignition

1. Sensitivity (5)
2. Propensity for electrostatic build-up/discharge (5)
3. Weather conditions, in particular snow fall (19)

C. Combustion

1. **Detonation potential with variations in solid O2 in LH2 pools**
2. Overpressure during pool ignition
3. Heat flux from pool fires (8)
4. **Effects of congestion on FA, DDT and runup distance (Scaling…)**
5. **Investigation of instability effects on unconfined combustion**
6. Combustion of cryo-compressed sources
7. **BLEVE/fireballs (Scaling,…)**

D. Modelling

1. Effect of humidity/air condensation (9)
2. Estimation of flowrate for two-phase choked flow (10)
3. Validation data for dispersion in complex environments (obstructions, different wind, etc.) (4, 13)
4. **Thermodynamics - Equation of state** effect on choked flow calculations (14)
5. Heat capacity at low temperatures/high pressures
6. **Reaction kinetics below 200K (+ induction time and detonation cell size…)**

E. Material and Structural Issues

1. Compatibility of plastic materials (16)
2. Thermal shock on conventional structural elements (17)
3. Impact on cryostats (18)

Topic: Low T (LH2/cryogenic) related

Proposal for future work

In **Dispersion**:

- Multiphase effects on **large scale** dispersion with obstruction and/or (partial) confinement.

In **Combustion**:

- Still we have to understand better FA and DDT for different congestion and confinement (influence of low T on instabilities); all at large scale.
- Additionally the detonation potential of solid O2 in LH2 pools has to be evaluated.
- BLEVEs need attention. Here especially scaling should be addressed.

Integral (applied) tests (dispersion and combustion in closed rooms) for mitigation strategies

Fundamental/Modelling:

- improve **thermodynamic** modelling in multiphase, non-equilibrium domain and examinate **reaction kinetics** below 200K.
- determine **induction times** and **detonation cell sizes** at cryogenic conditions