SAND2020-11941PE

European Commission · U.S. DEPARTMENT OF ENERGY · hySafe INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY

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

Status at the time of previous workshop

Topics for voting

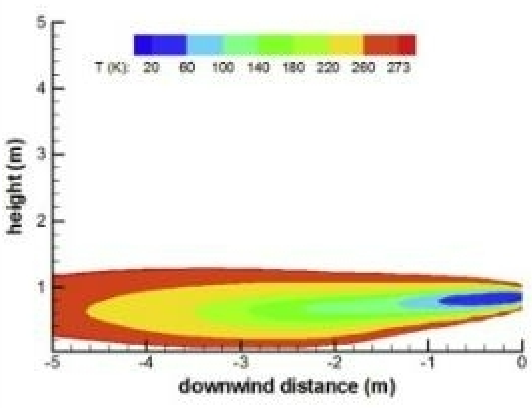
- Knowledge and experience related to indoor releases and dispersion
- Knowledge and experience related releases involving large quantities
- **Knowledge and experience related releases in congested areas**
- **Multi-phase accumulations with explosion potential (LH2 can condense and freeze oxygen. The 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

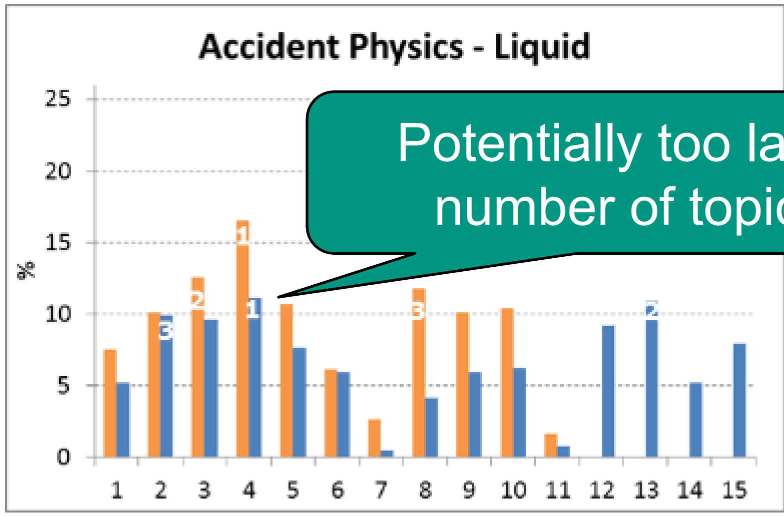
Topic: Low T (LH2/cryogenic) related

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**

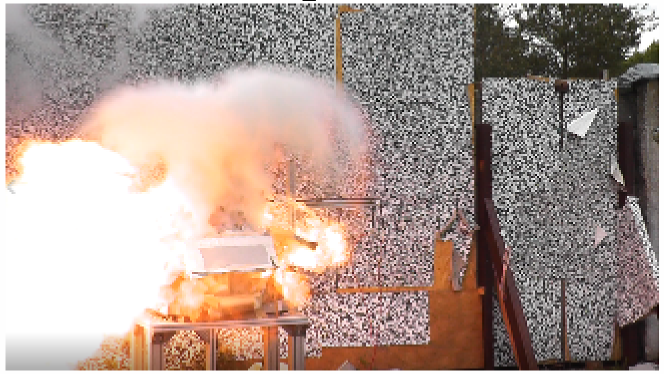




Potentially too large number of topics

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

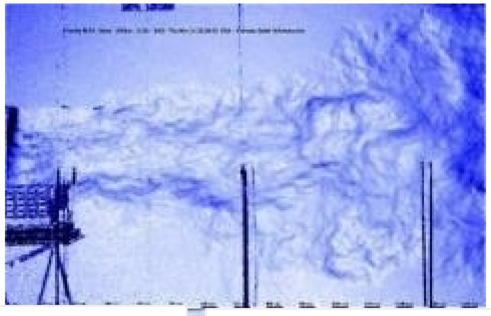
- **Higher expansion ratios come with higher critical expansion ratios**
- **Uncongested mixtures behave less critical**
- **Density effects might promote strong pressure effects in particular for congested areas**

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

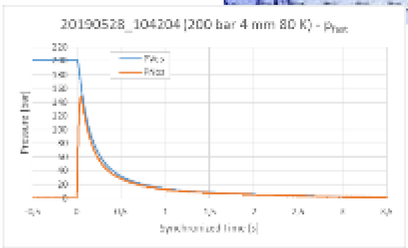
- **Large discharges do not generate static electricity or promote spontaneous ignition under normal weather conditions**
- **Spills shall be trenched and kept in a pool with low release rates**

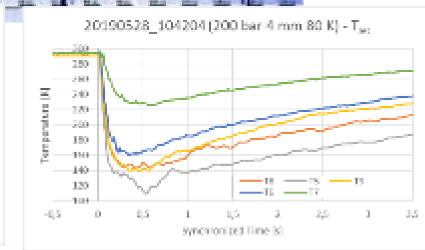
Topic: Low T (LH2/cryogenic) related

Further progress, closed gaps - Release

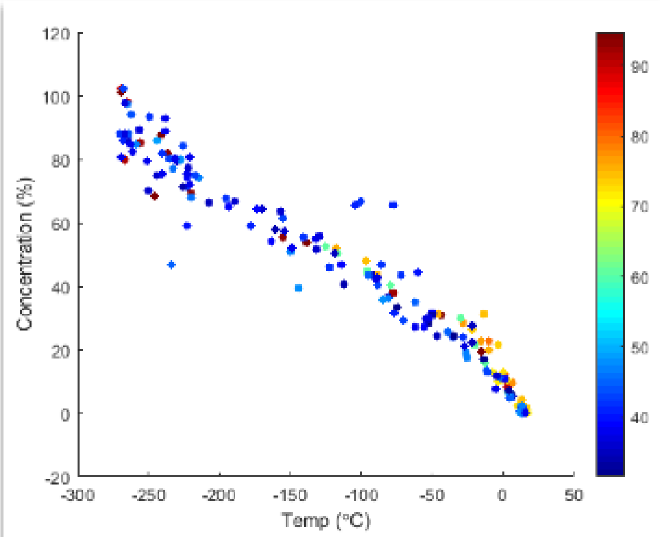


- 1 D model for multi-phase release developed (NCSRD)
- Discharge coefficients for circular nozzles D=0.5-4 mm
  5 - 200 bar; 20 – 300K (PRESLHY KIT/PS E3.1 DISCHA tests)
  see https://doi.org/10.5445/IR/1000096833





- No rainout for large scale above ground horizontal releases (PRESLHY HSE E3.5: rainout tests)
- Correlation of T and concentration of mixtures of H_2 with cryogenic origin and air



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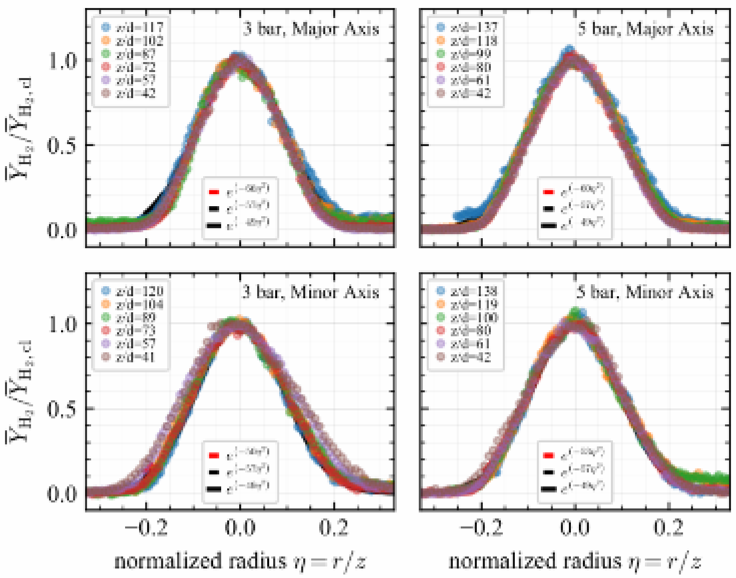
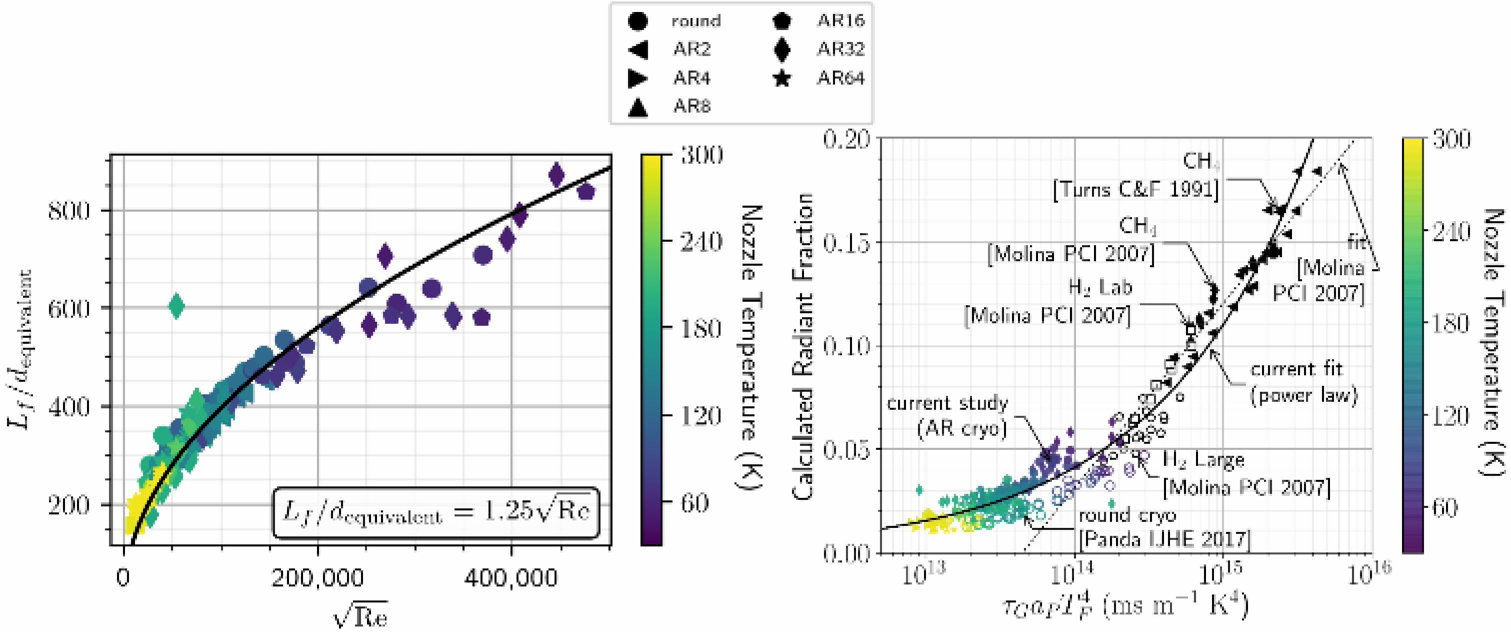
Further progress, closed gaps– Jet Fires

Aspect ratio 32





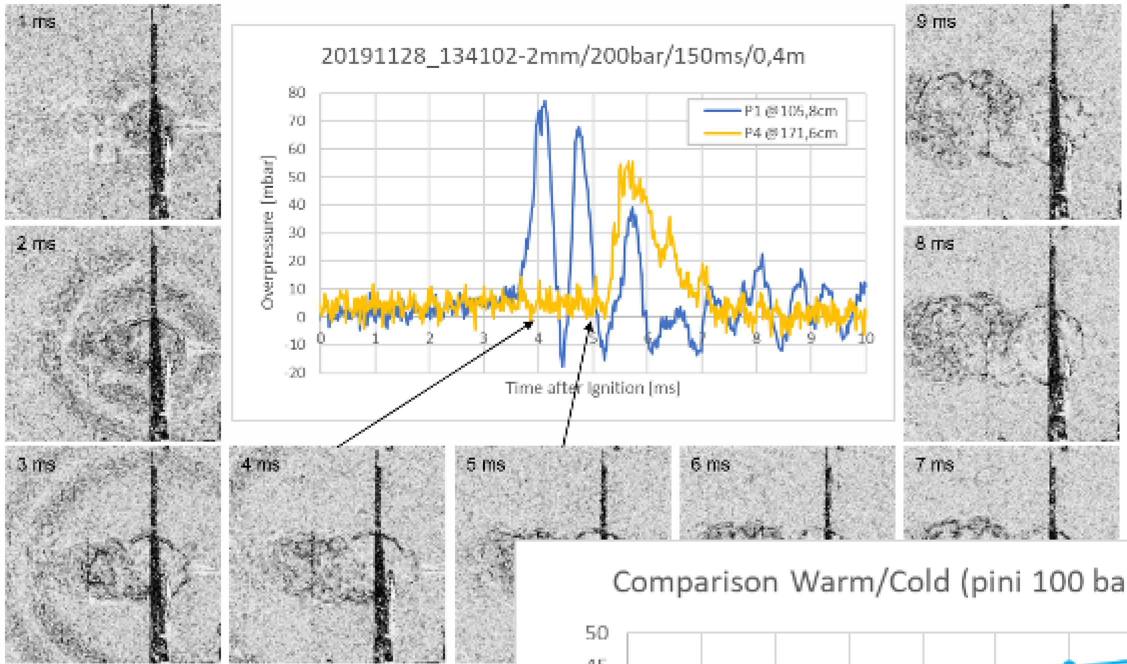
- Profiles are self-similar and the same along the major and minor axes
- High aspect-ratio data for flame length and radiant fraction fall on same correlations as round data

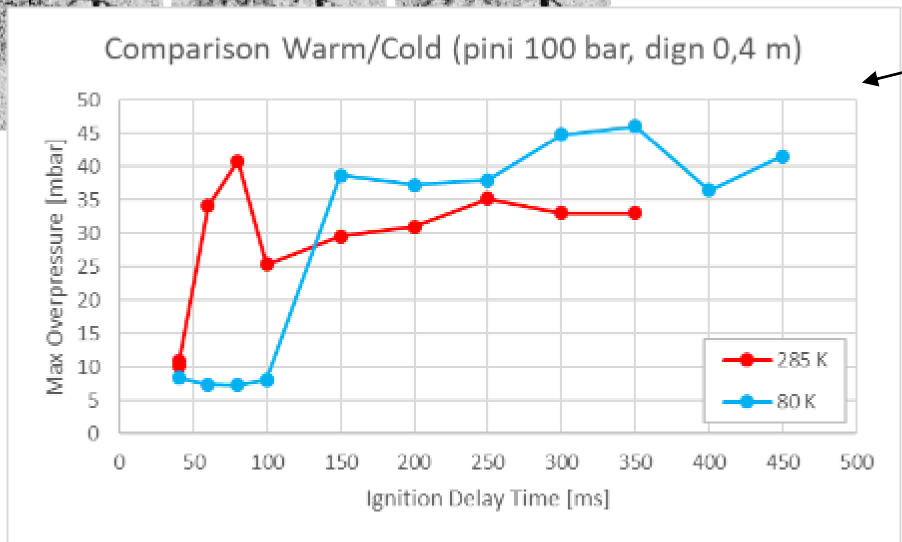
- Small (~1mm effective diameter), non-round (high aspect-ratio) leaks at LH2 storage pressures (5 bar) have the same dispersion and flame properties as round leaks

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

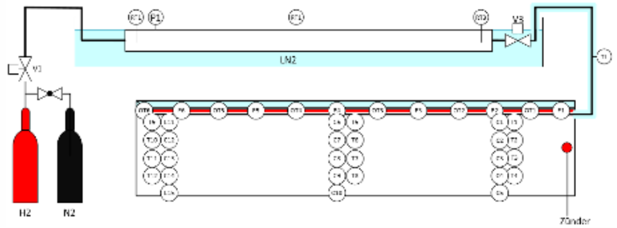
e.g.

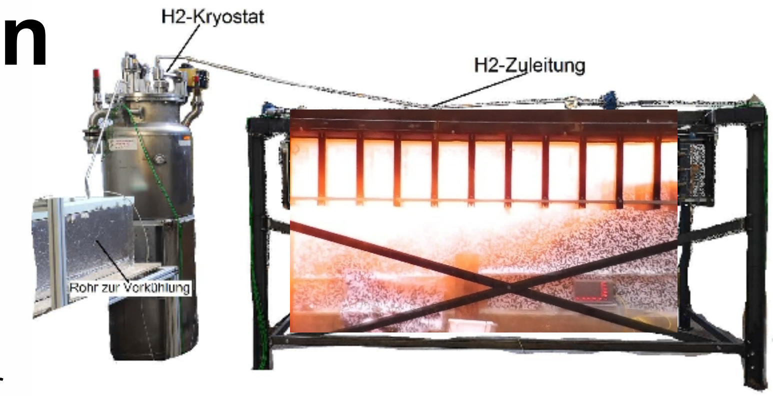
→
Better understanding of transient jets and combustion processes
→
to be extrapolated to large inventories for RCS

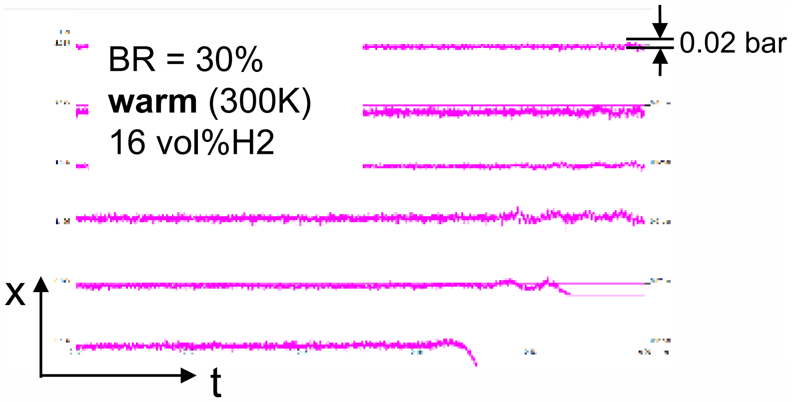
Topic: Low T (LH2/cryogenic) related

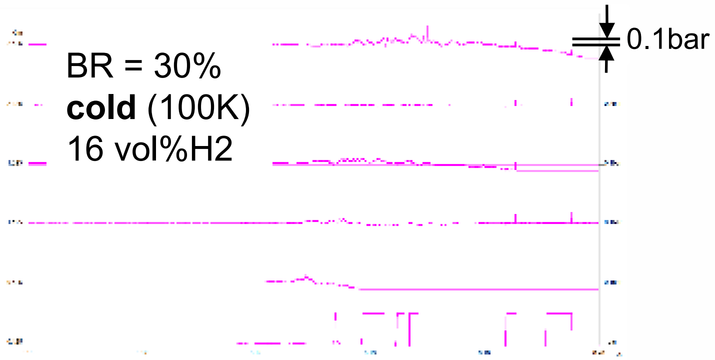
Further progress, closed gaps– Explosions in partially confined, obstructed domain

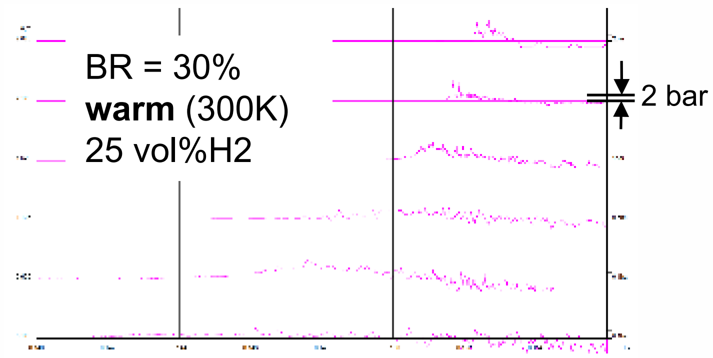
PRESLHY E5.5 Test series

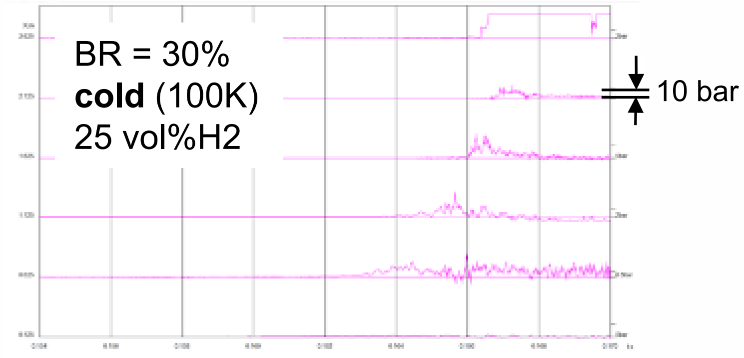












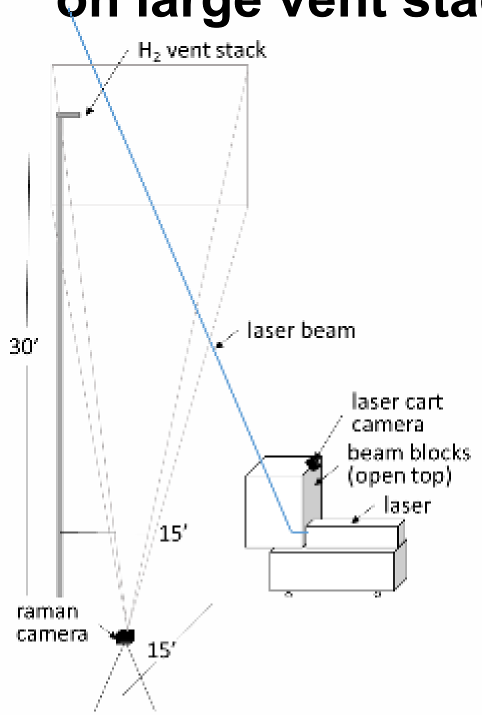
- Stronger pressure loads for cold tests in comparison with warm tests with the same hydrogen concentration and BR (to be inventory related)
- Difference increases with increasing hydrogen concentration

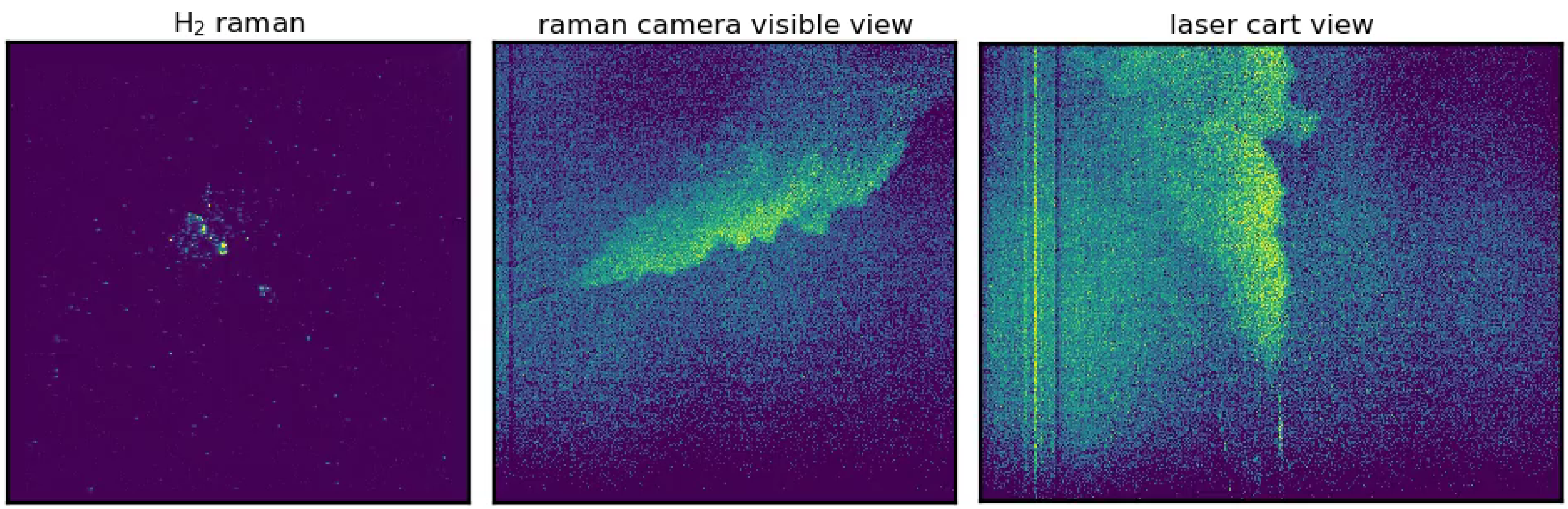
Topic: Low T (LH2/cryogenic) related

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





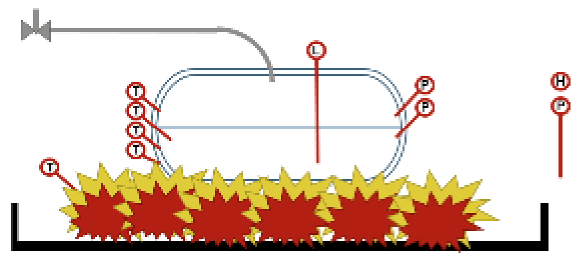
- Mapping out whether hydrogen is concurrent with condensed moisture
- Performing releases in low and high wind conditions

Topic: Low T (LH2/cryogenic) related

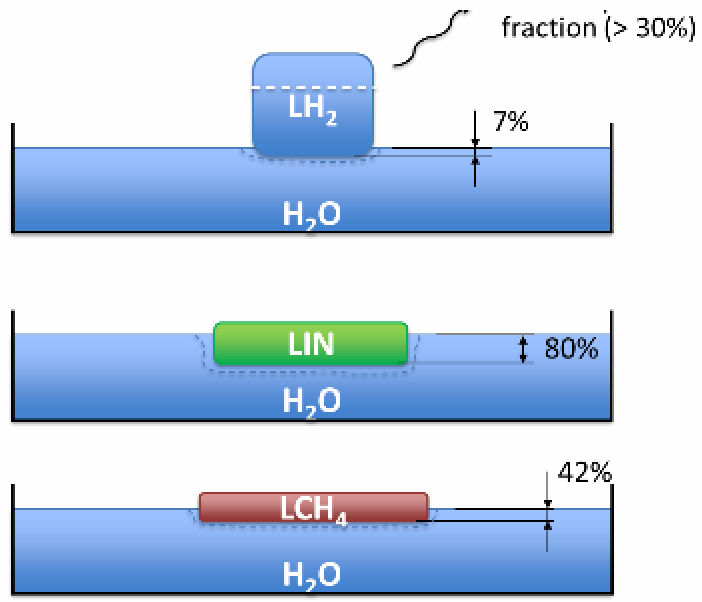
Ongoing work to close knowledge gaps related to BLEVE

to be performed Q1 2021

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



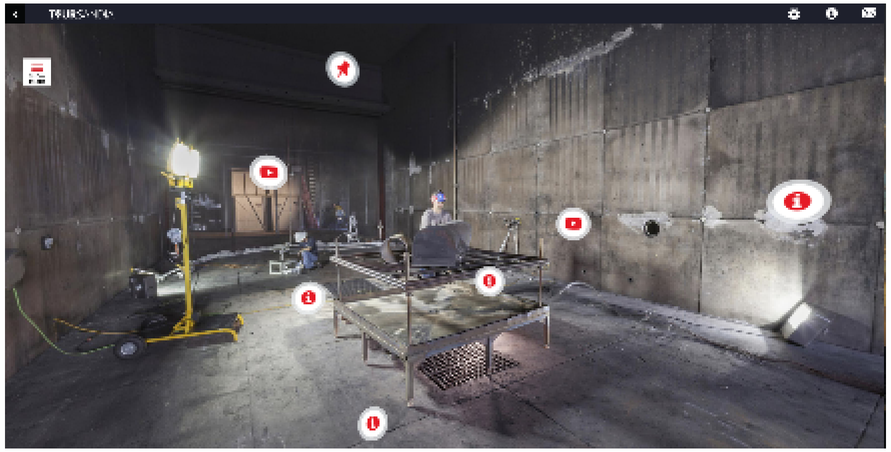
- **RPT** - **R**apid **P**hase **T**ransition
  - Basin 10 m x 10 m x 1.5 m



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



Sandia National Laboratories

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
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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

Topic: Low T (LH2/cryogenic) related

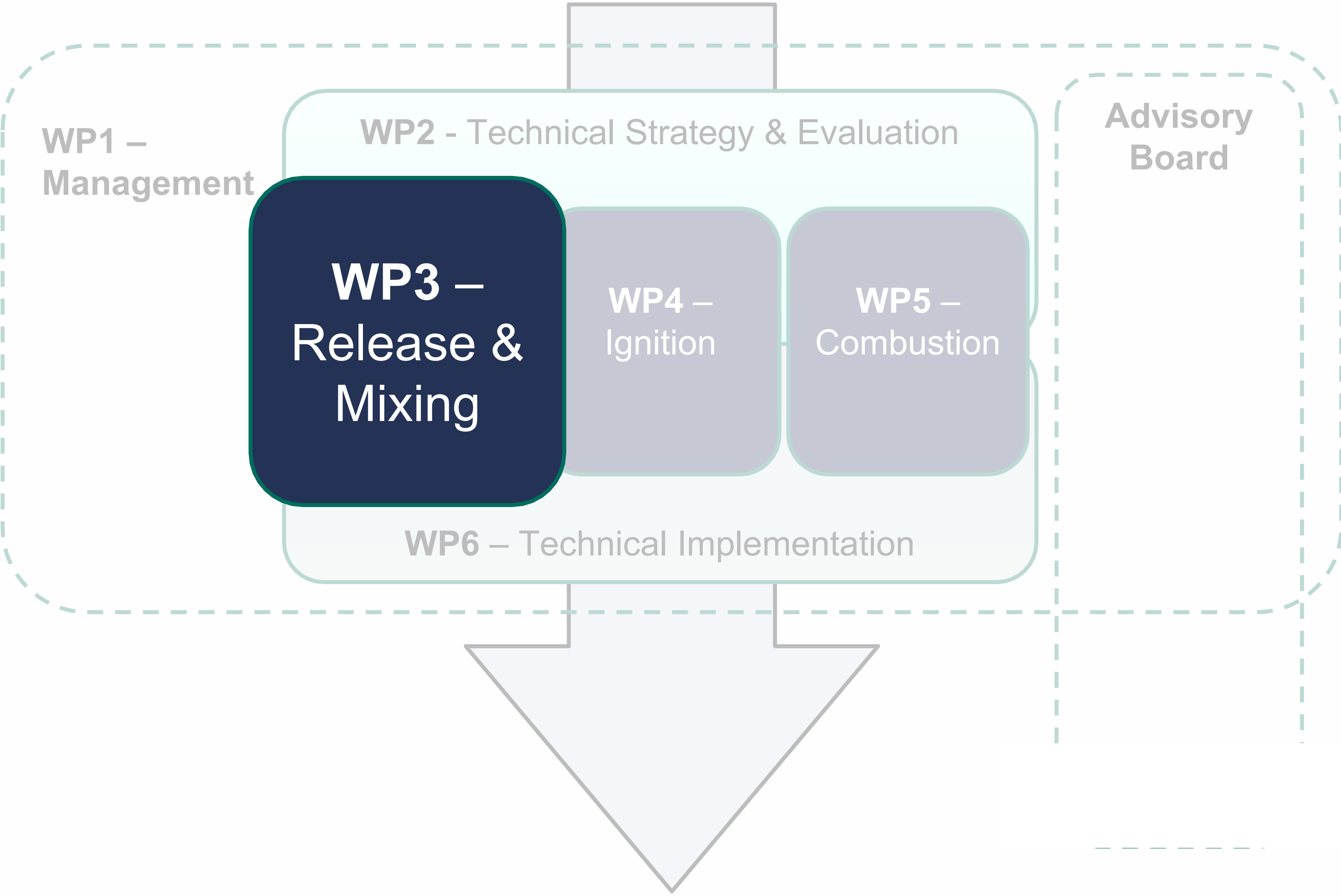
Where we are?

...with cryogenic hydrogen we entered a new galaxy...

...but

...we are preparing some guidance

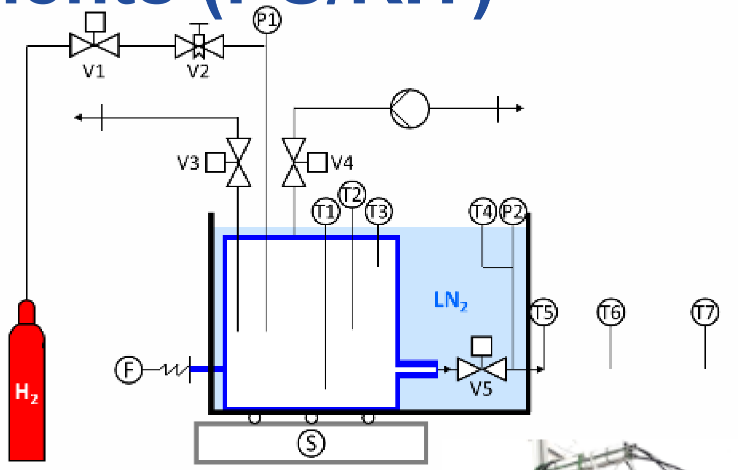
Additional slides

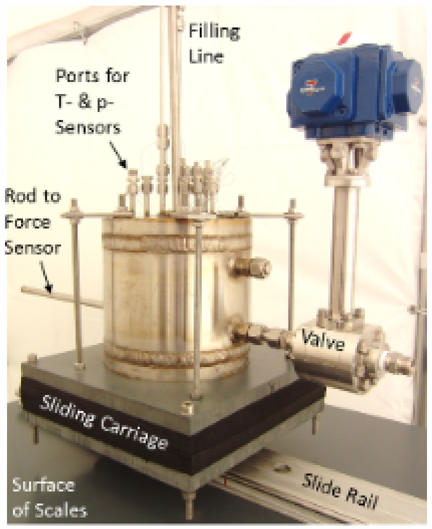

WP1 – Management
WP2 - Technical Strategy & Evaluation
WP3 – Release & Mixing
WP4 – Ignition
WP5 – Combustion
WP6 – Technical Implementation
Advisory Board

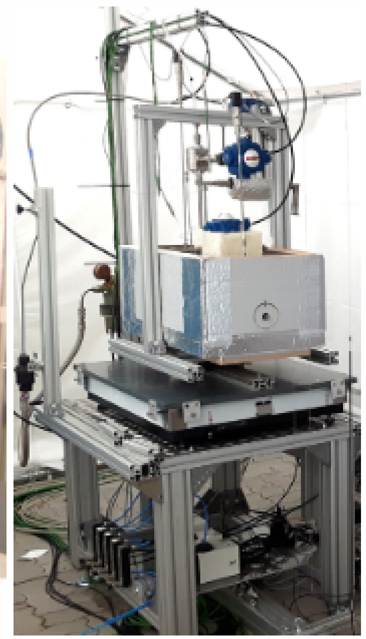
Experimental series E3.1a

Small Scale Multiphase Release experiments (PS/KIT)

- > 200 tests performed at DISCHA facility at HYKA / KIT
- Warm tests (ambient temp) and cold tests (77 K $T_{sat,LN2}$) where 2.81 L stainless steel vessel and release line cooled by bath of LN_2
- 4 nozzle diameters (0.5, 1, 2, 4 mm)
- 7 initial vessel pressures (5, 10, 20, 50, 100, 150, 200 bar)
- Every experiment was repeated at least 2 times (> 100 warm and ≈ 100 cold tests in total)
- **Only single (gaseous) phase conditions at nozzle were achieved**

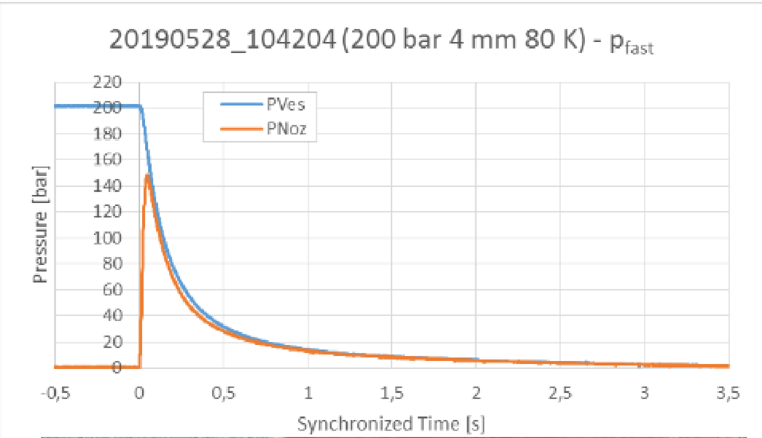


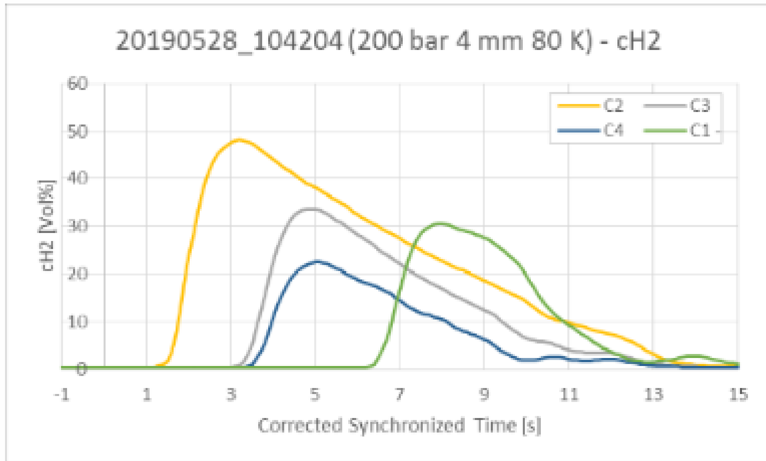


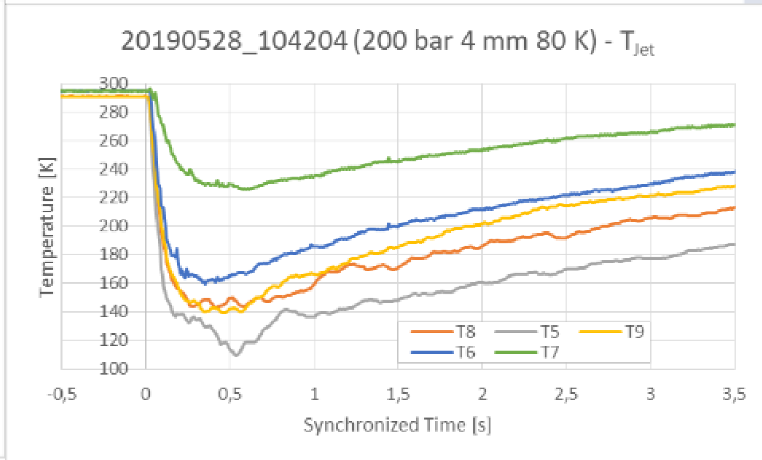


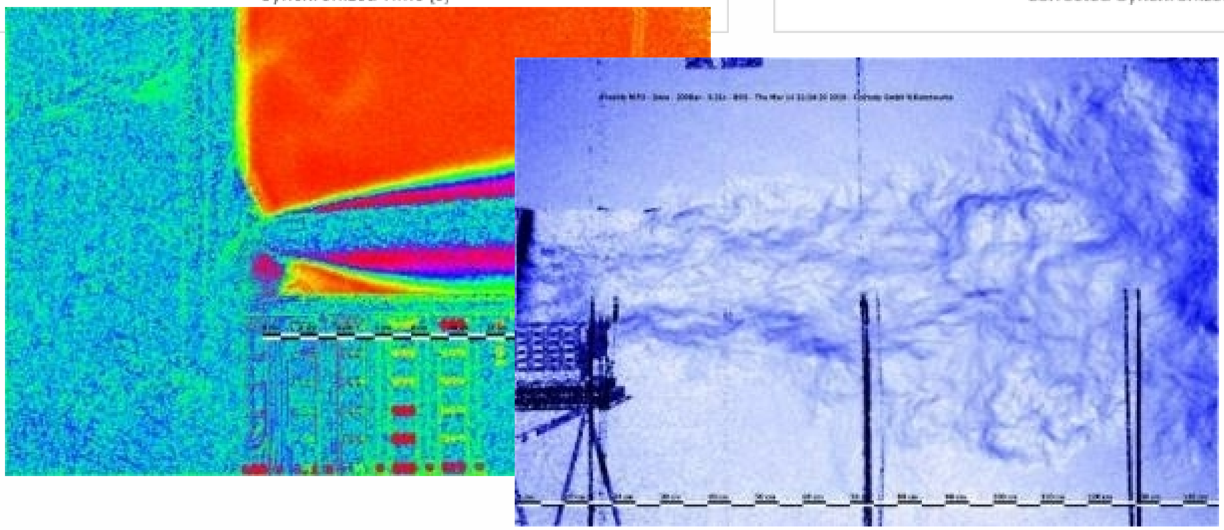
E3.1a: Validation Data

from ~200 tests in- and ex-vessel (jet) p, T, cH2, photography





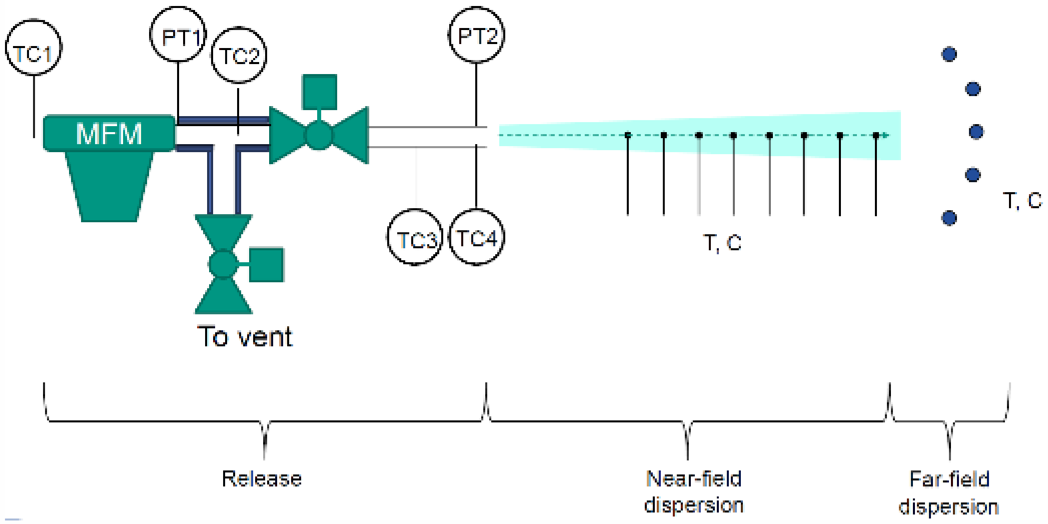


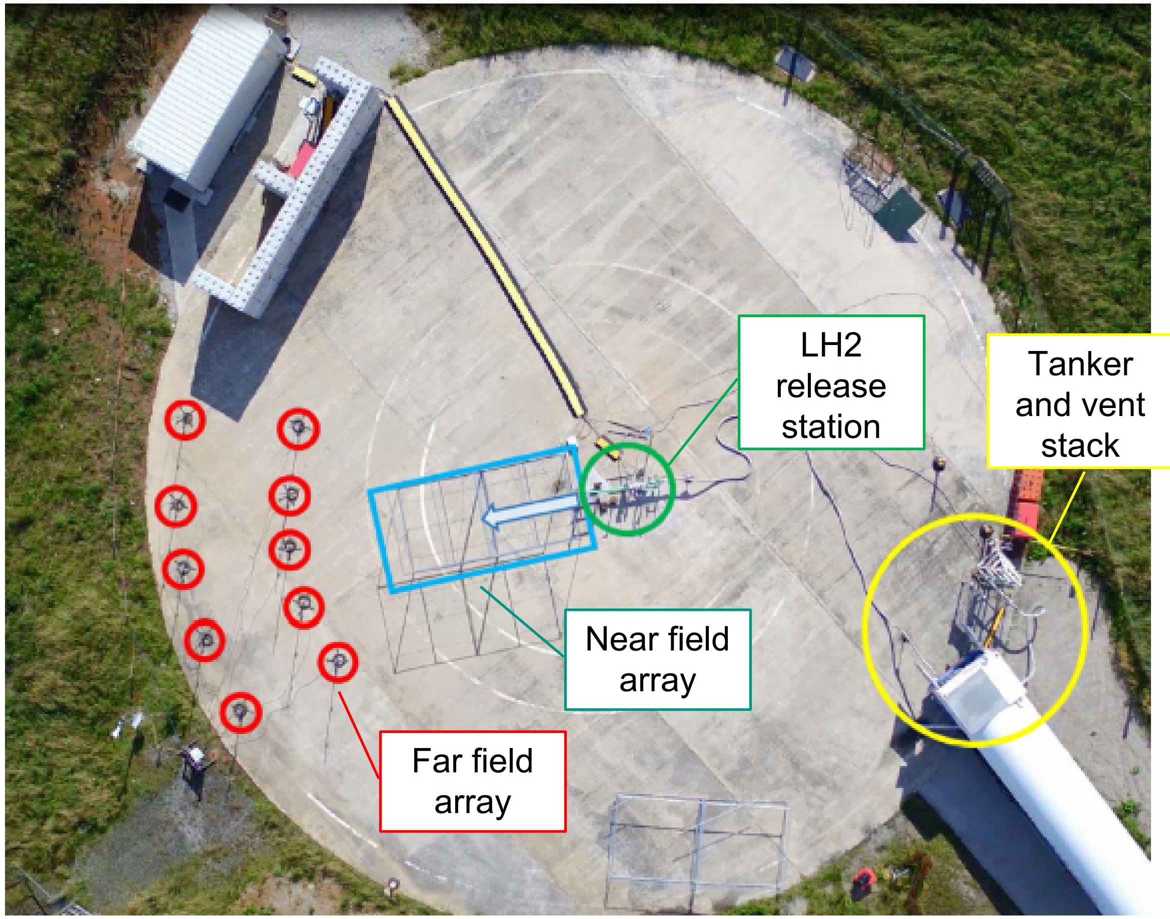


see https://doi.org/10.5445/IR/1000096833.

Experimental series E3.5

"Rain Out Tests" (HSE)

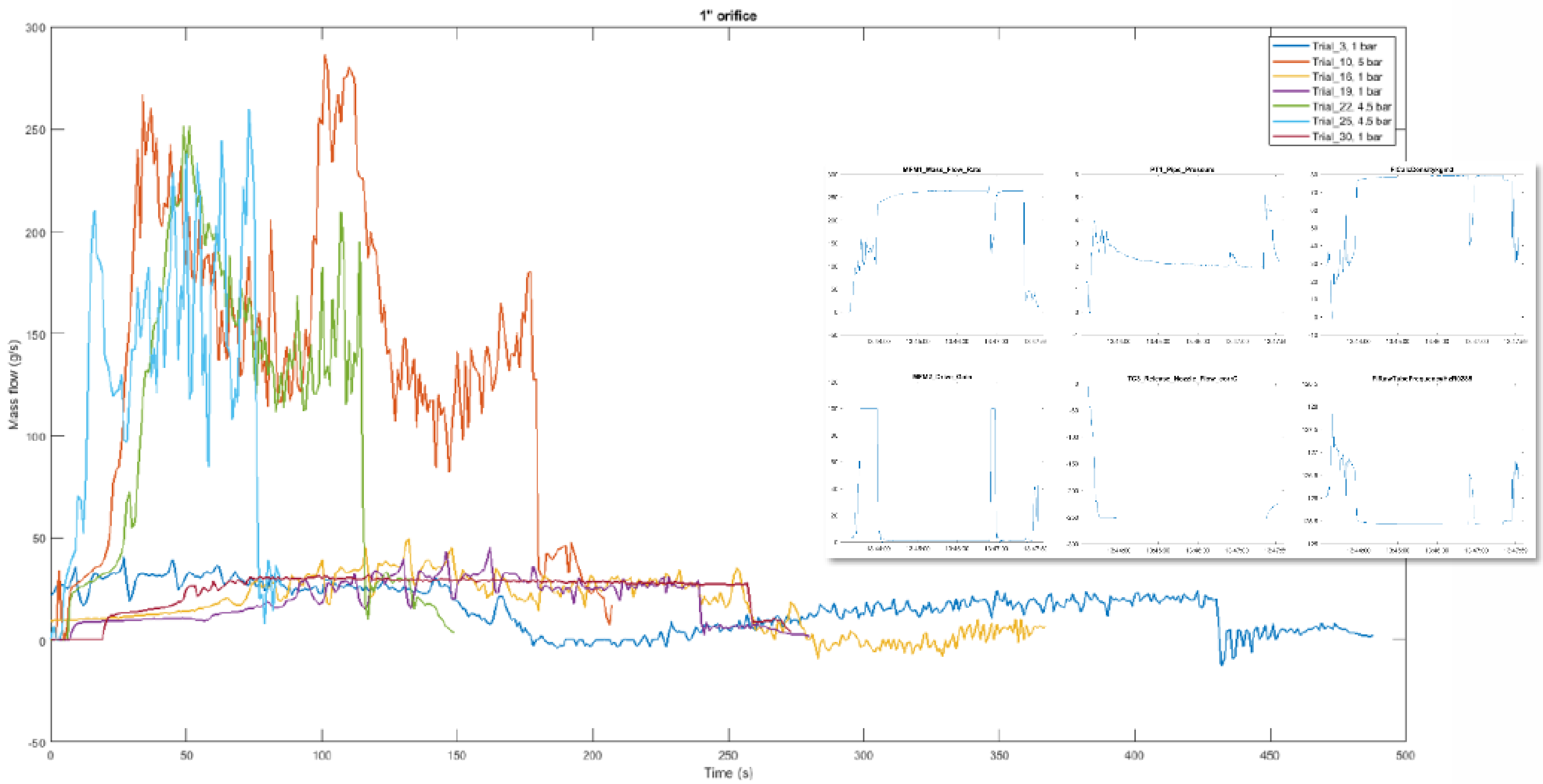




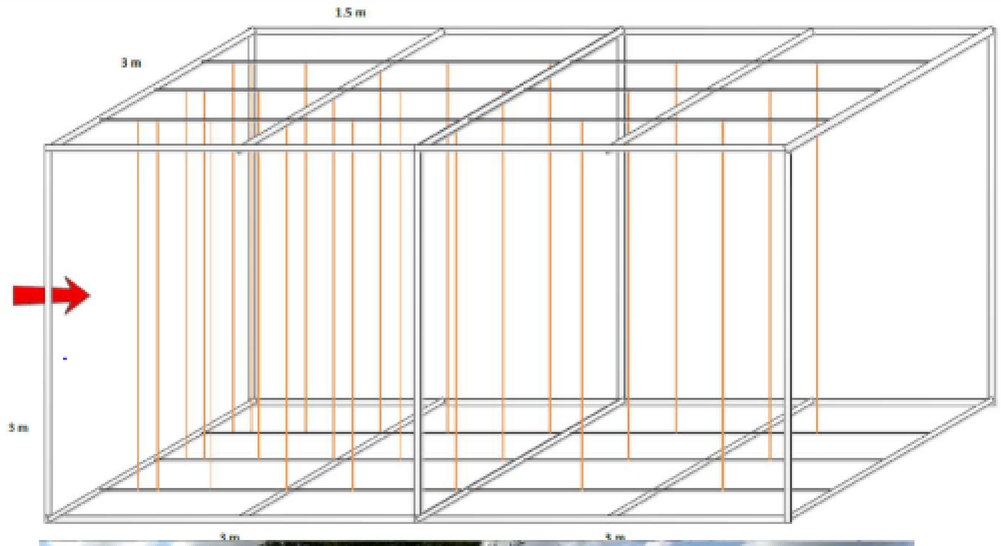
E3.5: Test Matrix

Trial No	Test No	Date	Time of start	Array location	Far Field sensor location	Additional Notes	Resistance
1	3.5.3	11/09/2019	15:16:54	Standard	Option 2a	Commissioning test.	$1.42 \times 10^{6}\ \Omega^{2}$
2	3.5.1	11/09/2019	15:58:09	Standard	Option 2a	Commissioning test.	$1.06 \times 10^{7}\ \Omega^{2}$
3	3.5.1	12/09/2019	11:45:31	Standard	Option 2a	Good conditions.	$1.02 \times 10^{6}\ \Omega^{2}$
4	3.5.2	12/09/2019	12:08:57	Standard	Option 2a	Fist footage of solid air around nozzle.	$1.06 \times 10^{7}\ \Omega^{2}$
5	3.5.3	12/09/2019	14:34:20	Standard	Option 2a		$2.48 \times 10^{6}\ \Omega^{2}$
6	3.5.7	12/09/2019	15:35:30	250mm offset	Option 2a		
7	3.5.8	12/09/2019	16:10:18	250mm offset	Option 2a	0.7m radius pool formed with solid deposit.	
8	3.5.8	13/09/2019	10:32:55	250mm offset	Option 2a		$2.07 \times 10^{7}\ \Omega^{2}$
9	3.5.9	13/09/2019	11:11:19	350mm offset	Option 2a	Baffle 160mm from release.	$2.72 \times 10^{4}\ \Omega^{2}$
10	3.5.10	13/09/2019	13:25:06	50mm offset	Option 2a		$2.67 \times 10^{4}\ \Omega^{2}$
11	3.5.11	13/09/2019	13:43:17	50mm offset	Option 2a		
12	3.5.12	13/09/2019	14:08:44	50mm offset	Option 2a		$2.67 \times 10^{4}\ \Omega^{2}$
13	3.5.17	13/09/2019	14:33:43	250mm offset	Option 2a	1.2m radius pool formed.	
14	3.5.16	13/09/2019	14:57:14	250mm offset	Option 2a		
15	3.5.18	13/09/2019	15:23:26	250mm offset	Option 2a	Baffle 180mm from release.	
16	3.5.4	17/09/2019	11:02:07	Standard	Option 2b		$3.14 \times 10^{4}\ \Omega^{2}$
17	3.5.5	17/09/2019	11:24:11	Standard	Option 2b		
18	3.5.6	17/09/2019	11:41:45	Standard	Option 2b		
19	3.5.4	18/09/2019	10:57:26	Standard	Option 2a		$1.03 \times 10^{7}\ \Omega^{2}$
20	3.5.5	18/09/2019	11:18:55	Standard	Option 2a		
21	3.5.6	18/09/2019	11:40:06	Standard	Option 2a		
22	3.5.13	18/09/2019	14:57:25	Standard	Option 2a	Releases carried out at 4.5 bar.	
23	3.5.14	18/09/2019	15:14:47	Standard	Option 2a	Releases carried out at 4.5 bar.	
24	3.5.15	18/09/2019	15:29:36	Standard	Option 2a	Releases carried out at 4.5 bar.	
25	3.5.13	18/09/2019	15:47:58	Standard	Option 2a	Releases carried out at 4.5 bar.	$1.03 \times 10^{7}\ \Omega^{2}$

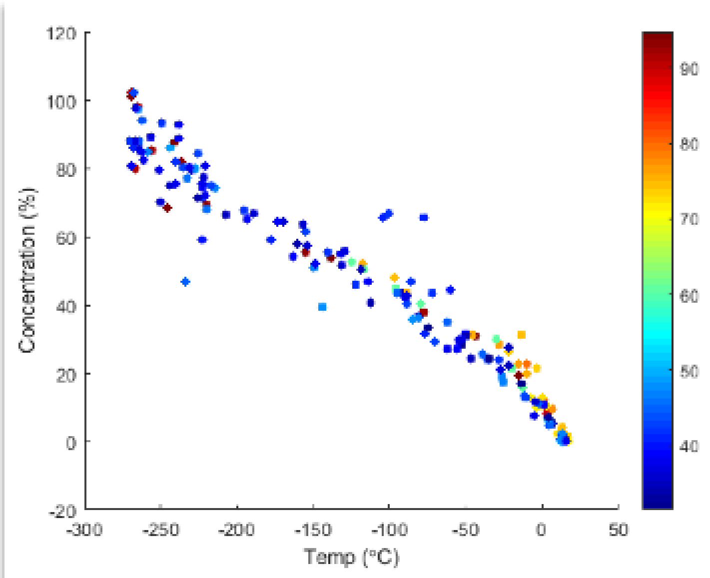
E3.5: Mass Flow Measured



E3.5: Near Field Dispersion



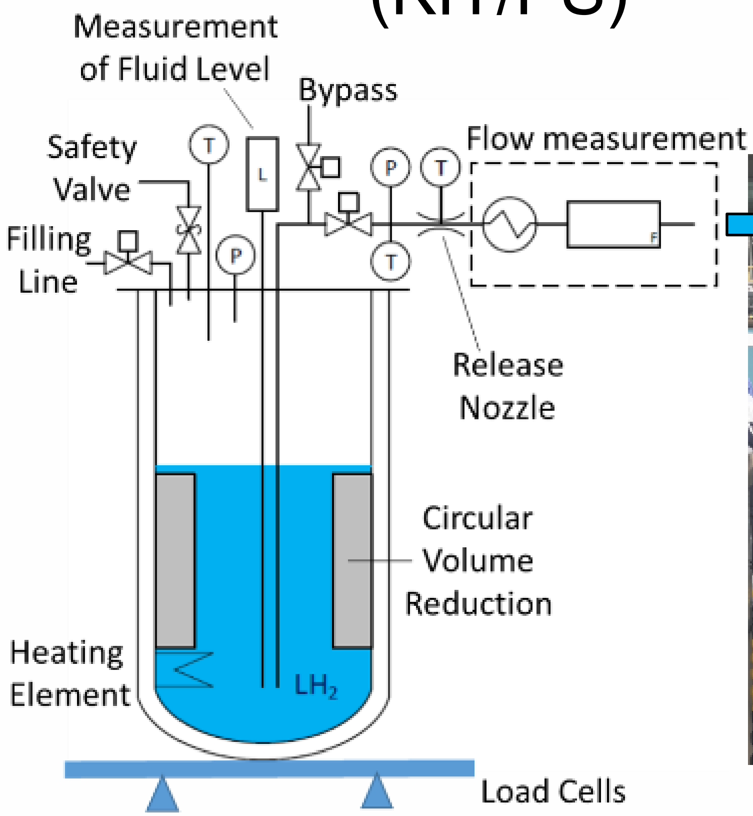
Some „solid material“ partially blocked sampling positions

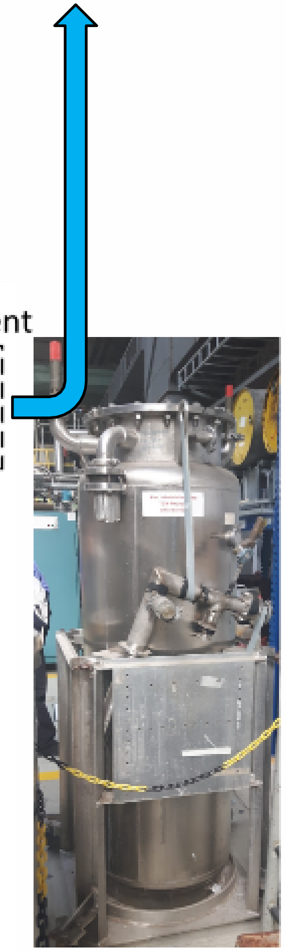


Correlation of T and H_2 concentration with little influence of humidity in far field

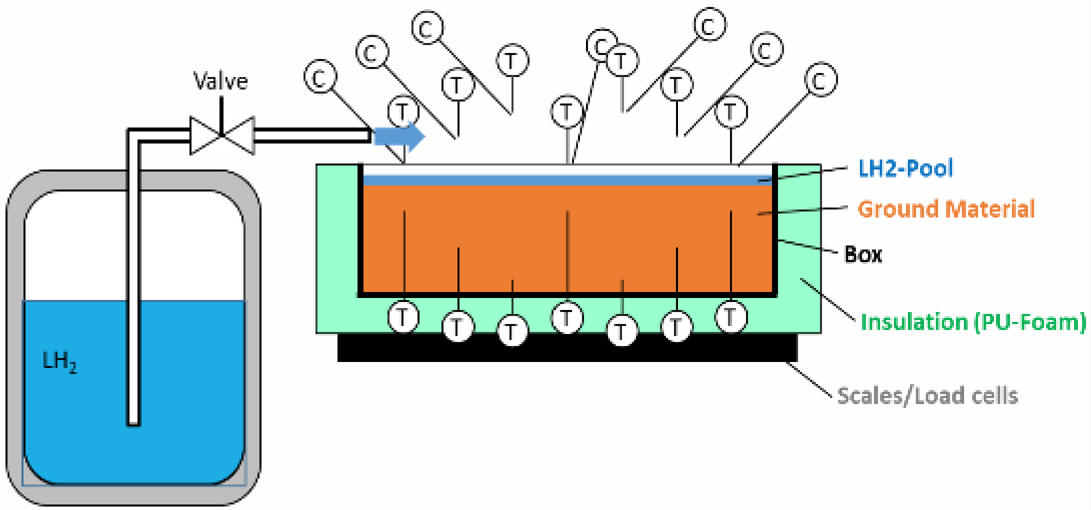
Next Release & Mixing Experiments

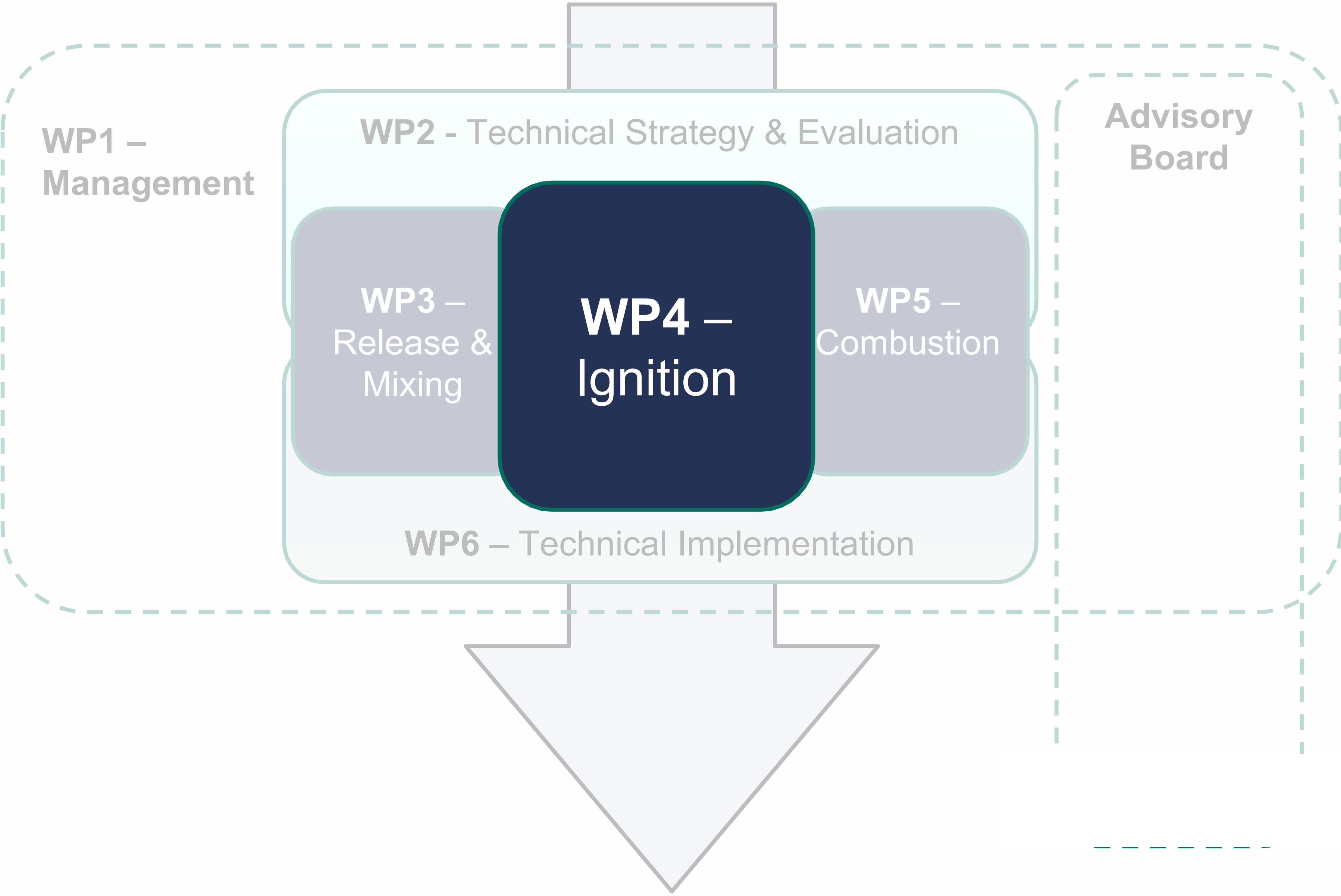
- E3.1b CRYOSTAT
  2-Phase release
  (KIT/PS)





- E3.4 Pool
  Release and evaporation
  (KIT/PS)




WP1 – Management
WP2 - Technical Strategy & Evaluation
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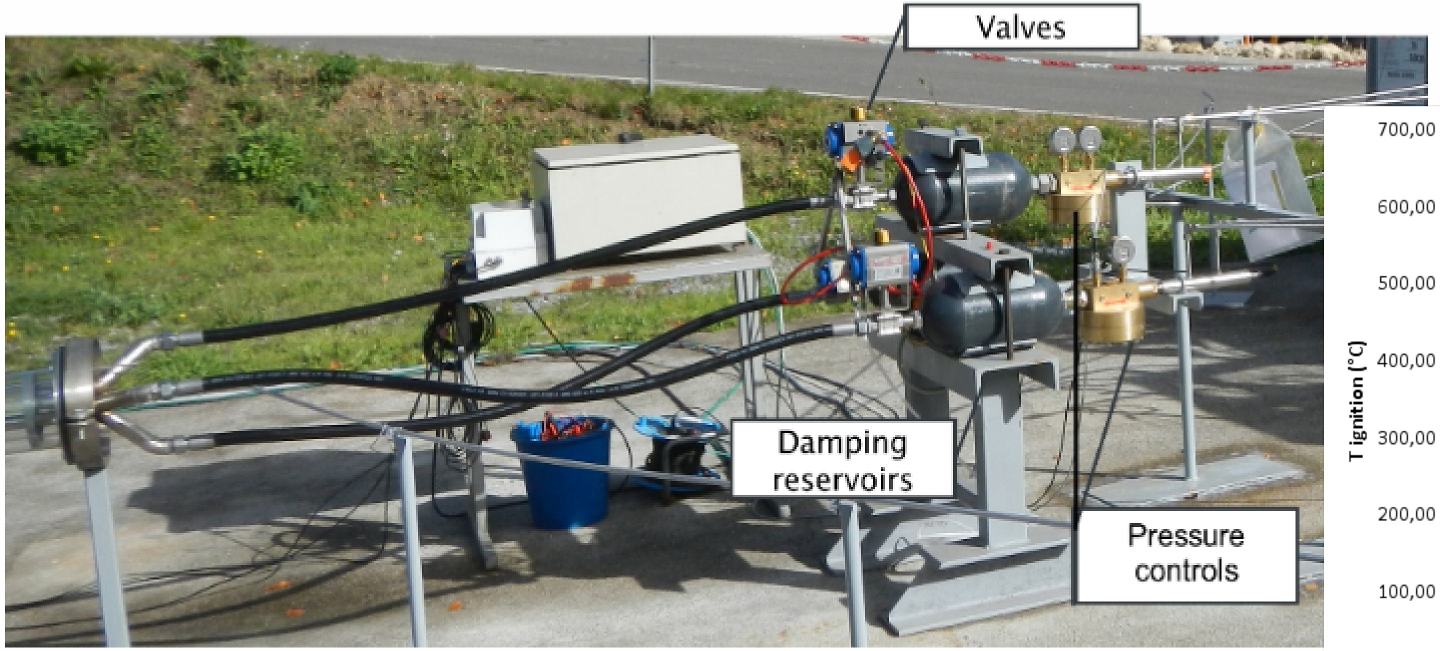
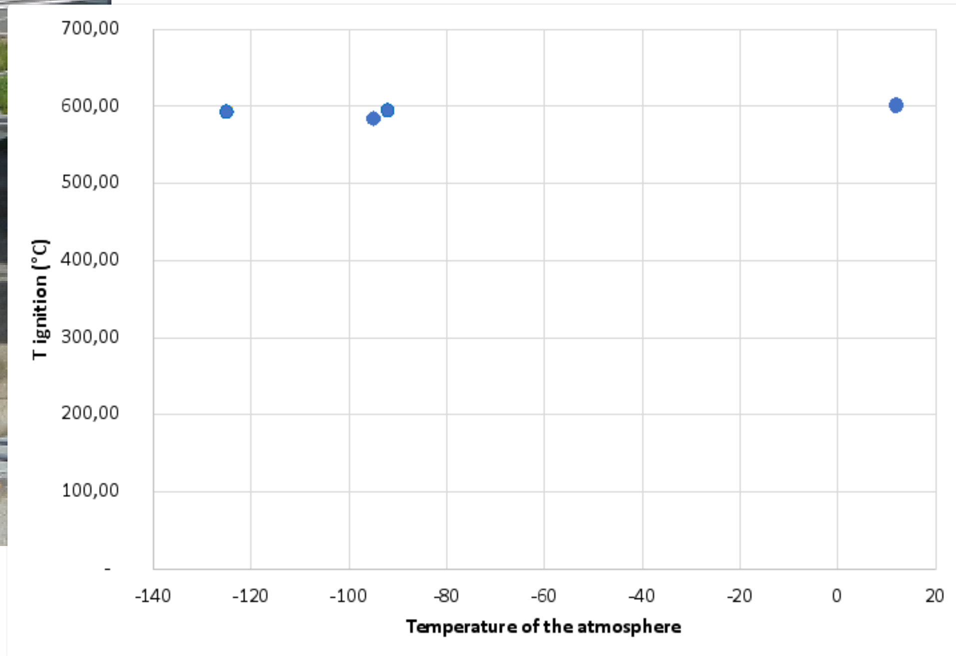
Advisory Board

E4.1: Ignition by hot surfaces/power (INERIS)





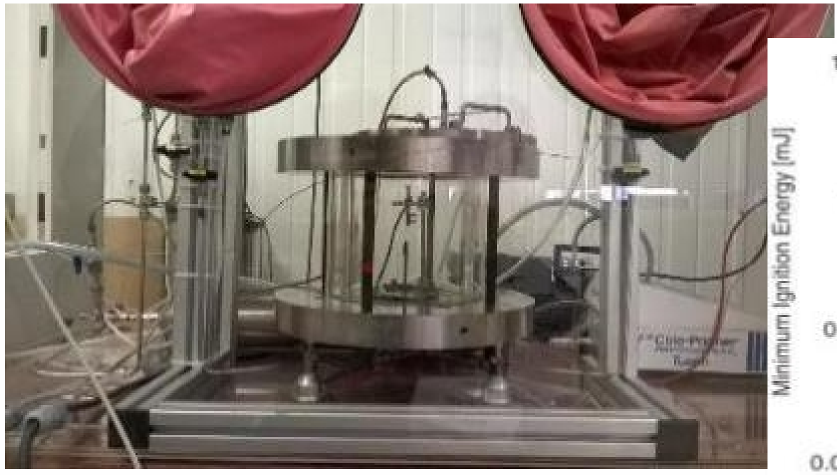
First conclusions:

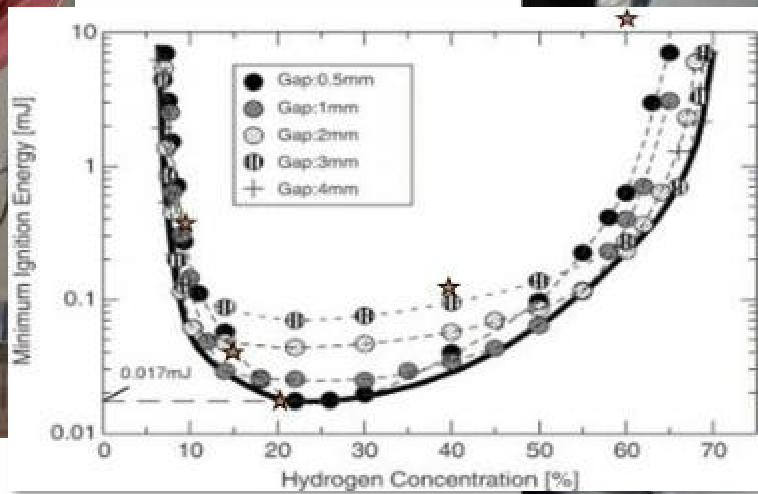
- Ignition on hot surface independent on T of surface
- Stoichiometry and flow velocity marginal influence

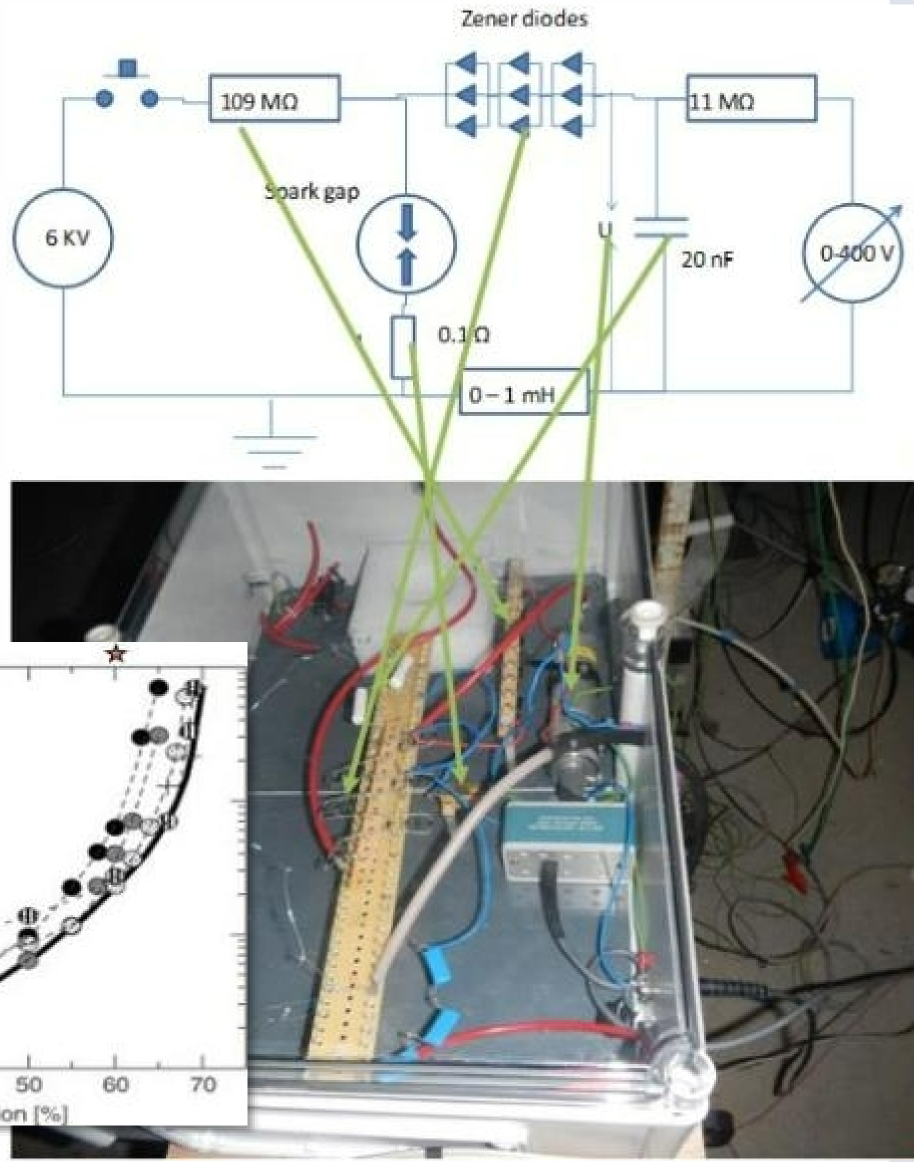
E4.1: Minimum Ignition Energy MIE (INERIS)

New device constructed:

- Triggered spark
- Current and voltage measured in the spark gap
- Inductance = 1 mH or zero
- Capacitance : variable
- From a few microjoules to 1 joule
- Ambient reference tests successful
- 80K tests under preparation

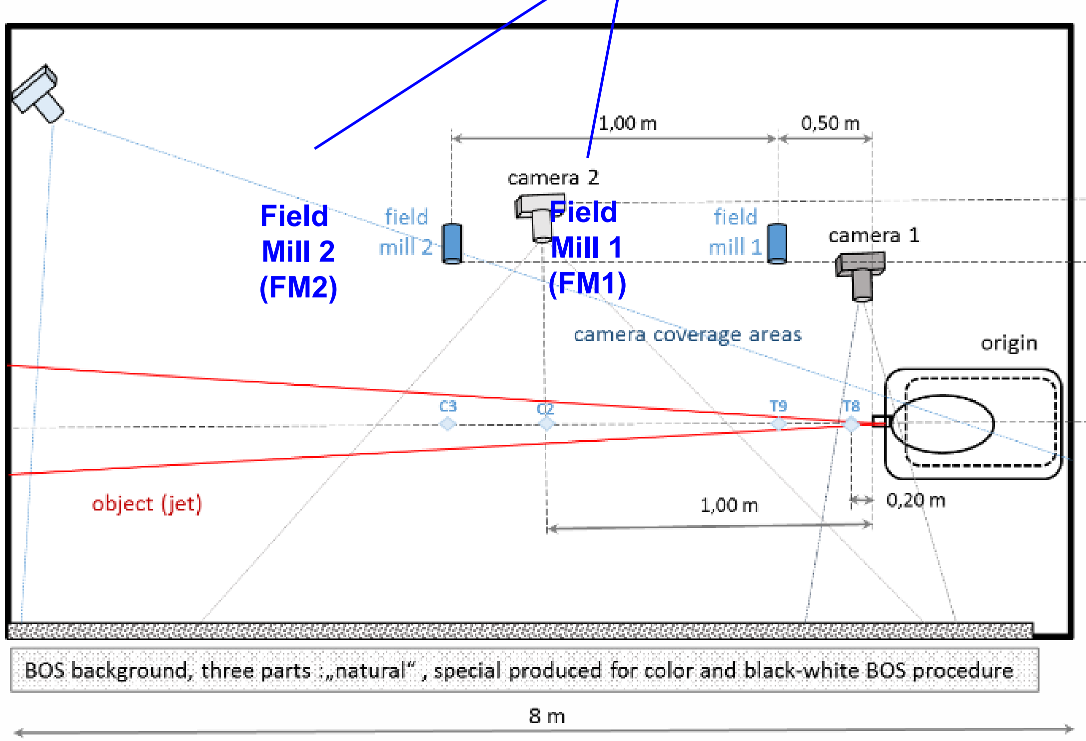






E4.2: Electrostatic Ignition in cold jet (KIT)

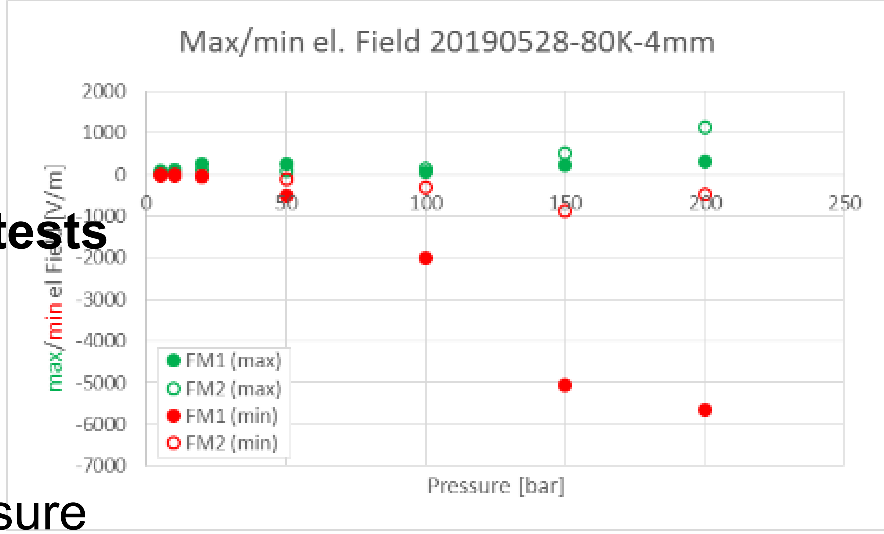
- Electrostatic field measurements with 2 field mills FM (field meters) were performed in more than 100 DisCha-experiments (see E3.1a)

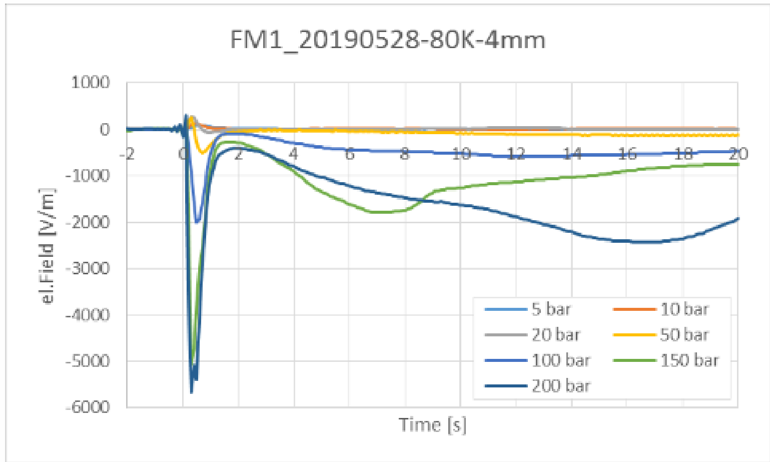


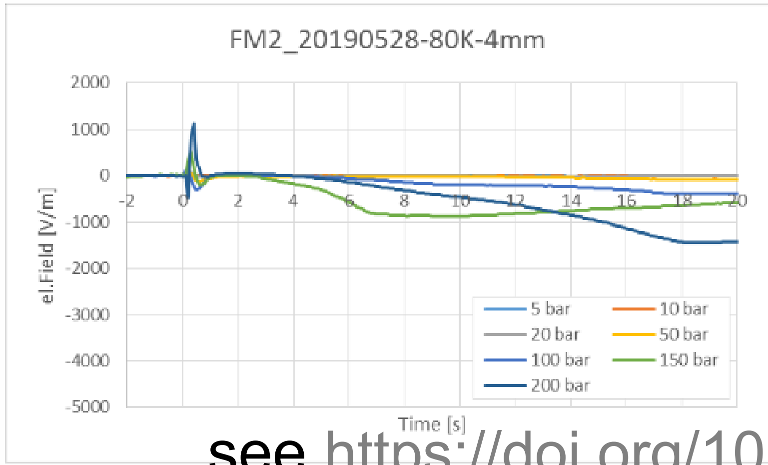
E4.2: Electrostatic Ignition in cold jet (KIT)

Initial conclusions:

- Strong electrostatic fields (~6000 V/m) observed for 80 K releases (~ factor 100 larger than at ambient T)
- **No spontenous ignition in more than 200 discharge tests**
- Positive as well as negative values
- Larger electrostatic fields close to nozzle (field mill FM1) than at farther position (FM2)
- Increasing electrostatic field values with increasing pressure

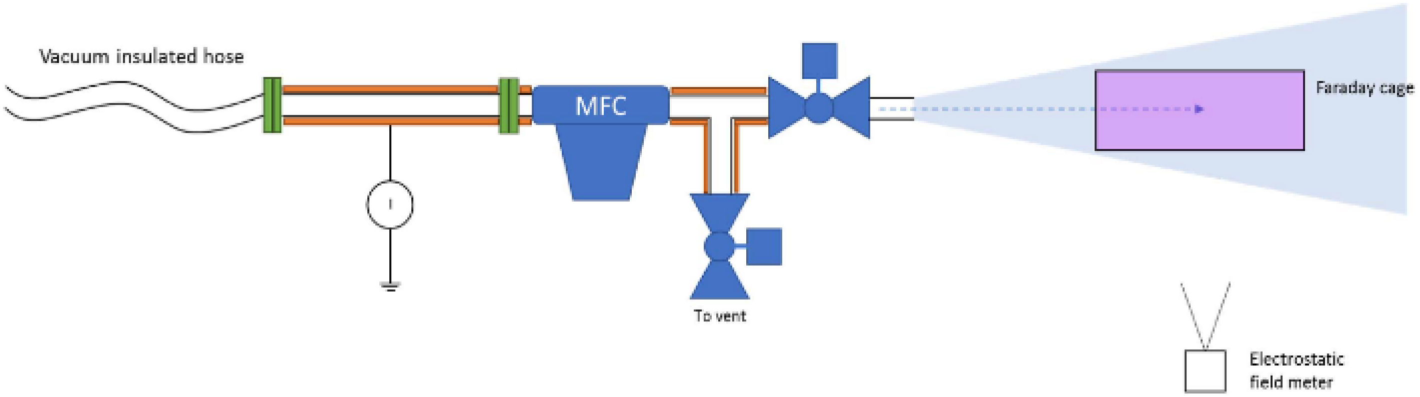






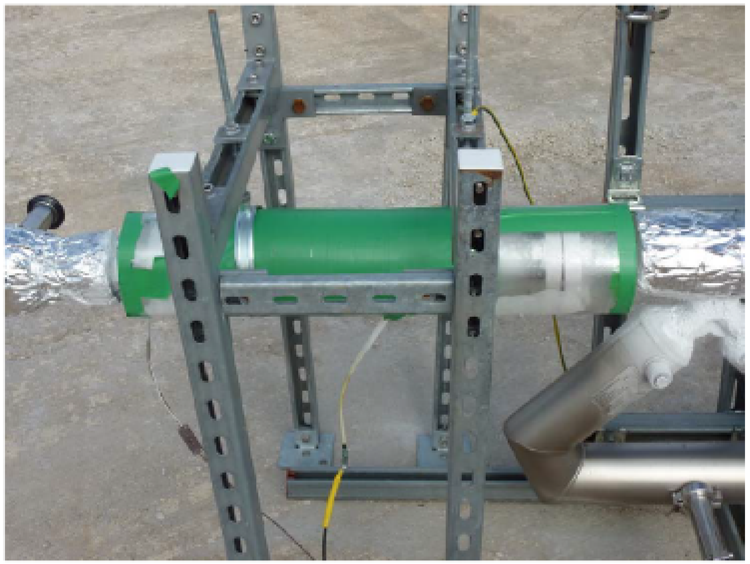
see https://doi.org/10.5445/IR/1000096833.

E4.3: Electrostatic Ignition in cold plume (HSE)



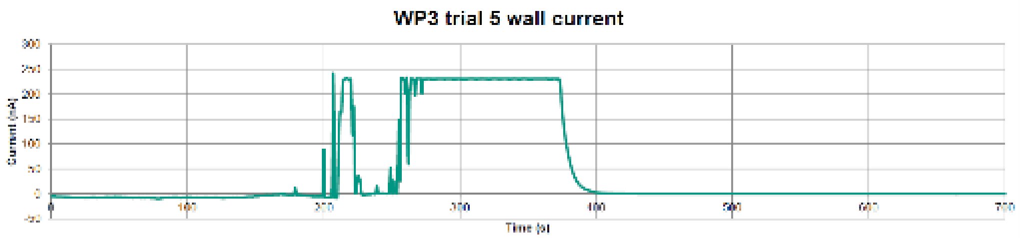
Intrumentation:

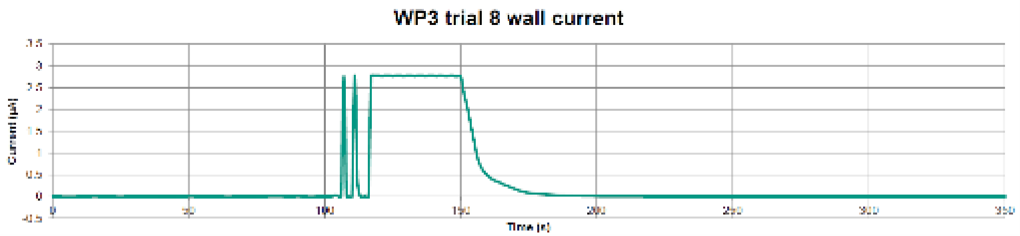
- Wall current:
  Isolated pipe section + electrometer
- Plume electrostatics measurement:
  Field meter + Faraday cage

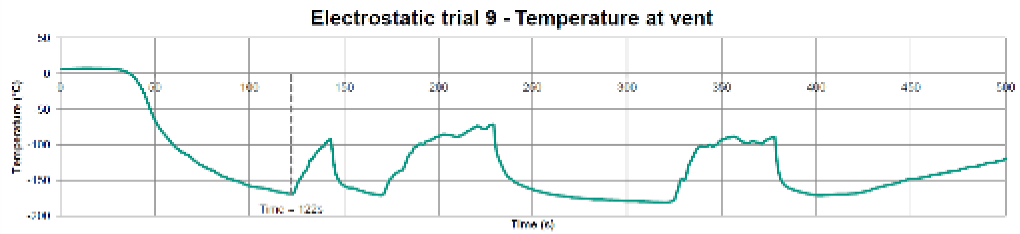

Isolated pipework

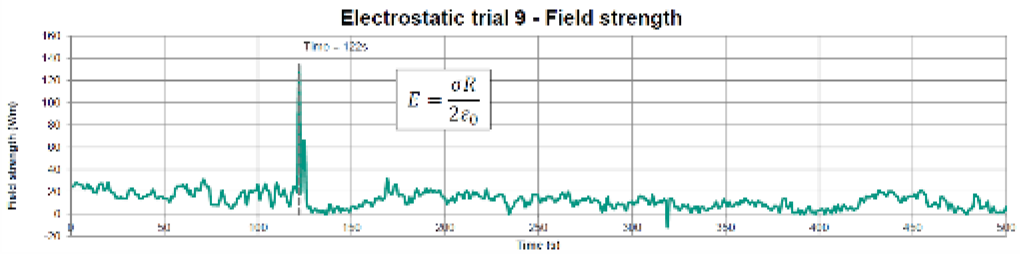

Faraday cage and field meter

E4.3: Electrostatic Ignition in cold plume





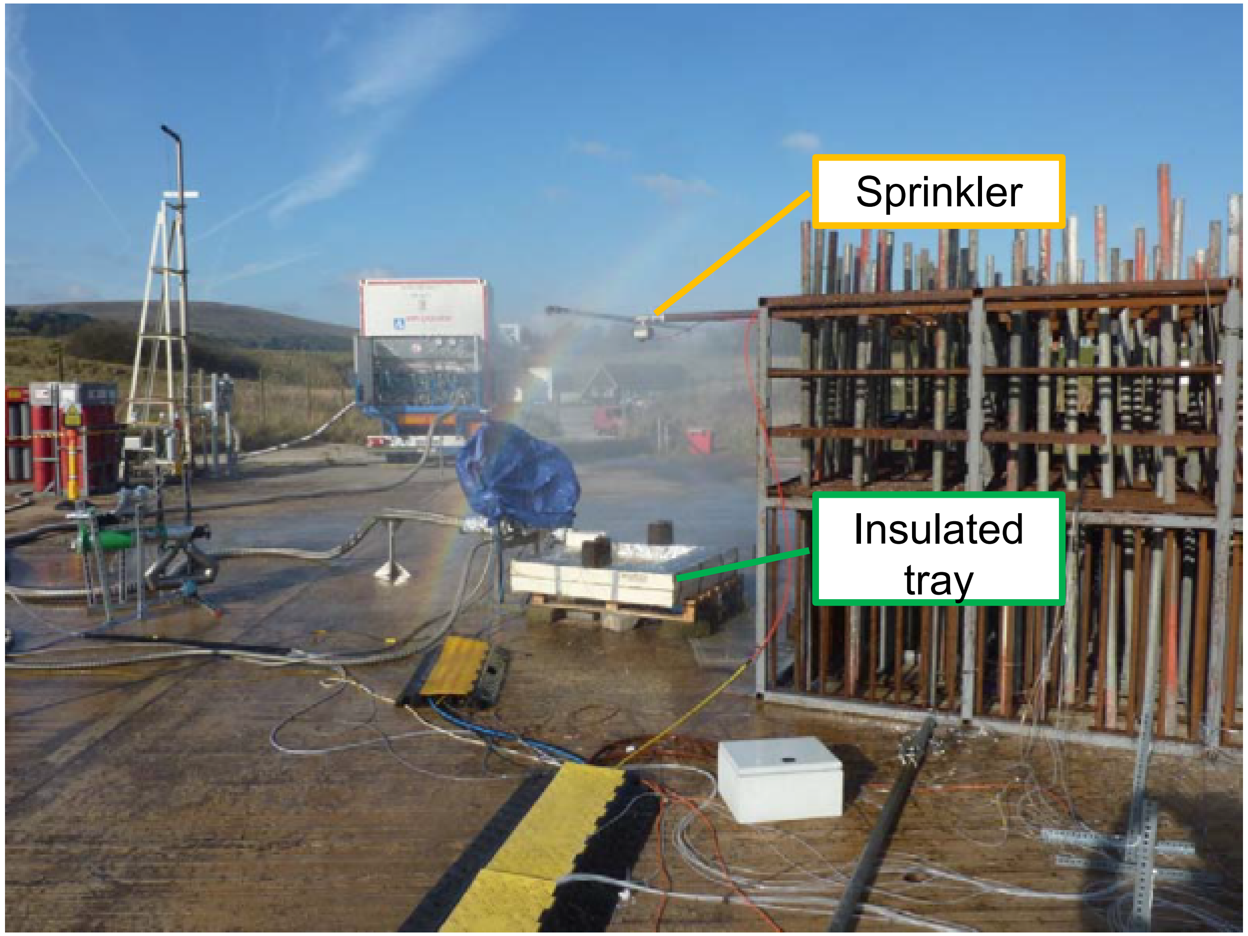




Initial conclusions:

- H2 did not hold a significant charge
- Multiphase H2 flow can generate a current in isolated pipework
- Occasional charge spikes have been identified, possibly cause by ice breaking off the nozzle or air being ejected from un-purged pipework

E4.X: Rapid Phase Transition RPT Tests



Sprinkler system test

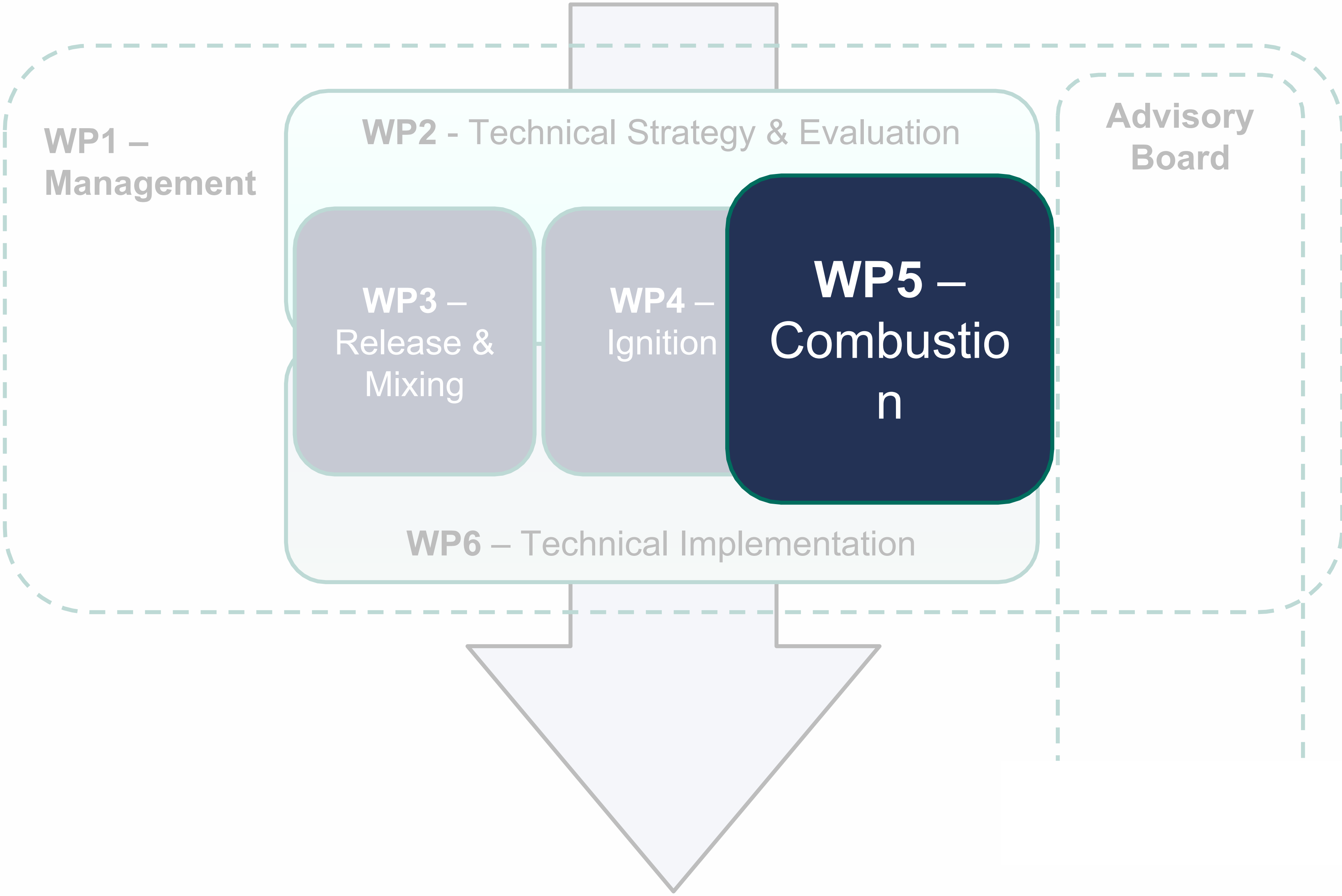
- Insulated tray to collect fluid
- Thermocouples arranged to indicate pool depth
- Water release system with sprinkler and hose attachment

Initial conclusions:

- Sprinkler system did not cause RPTs, when interacting with LH2 pool
- Fire hose deluge increased the evaporation rate of the LH2 pool

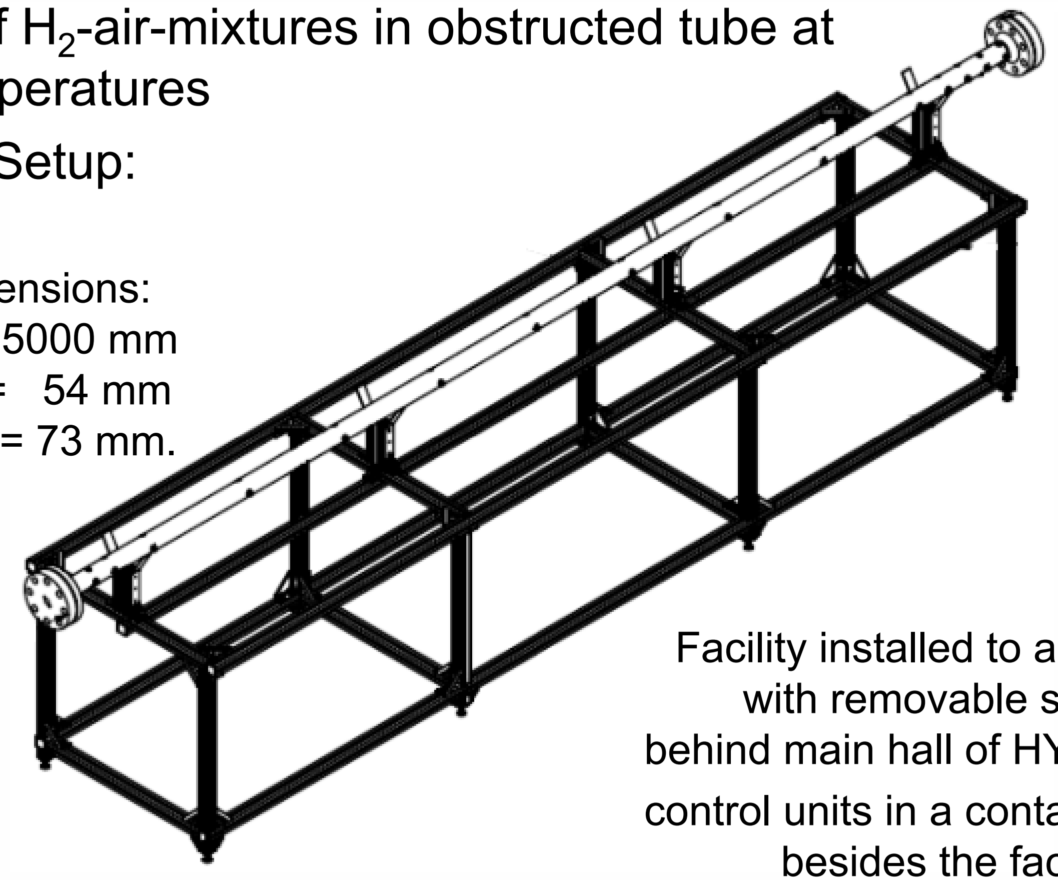
Next Ignition Experiments

- E4.1b Cold MIE (INERIS)
- E4.4 Ignition above pool (KIT)
- E4.5 Condensed phase ignition (HSL)


WP1 –
Management
WP2 - Technical Strategy & Evaluation
WP3 –
Release &
Mixing
WP4 –
Ignition
WP5 –
Combustio
n
WP6 – Technical Implementation
Advisory
Board

E5.2: FA and DDT at cryogenic T
("Tube experiments")

- Combustion of H_2-air-mixtures in obstructed tube at cryogenic temperatures
- Experimental Setup:



Dimensions:
L = 5000 mm
D_{in} = 54 mm
D_{out} = 73 mm.

Facility installed to a tent with removable sides behind main hall of HYKA,

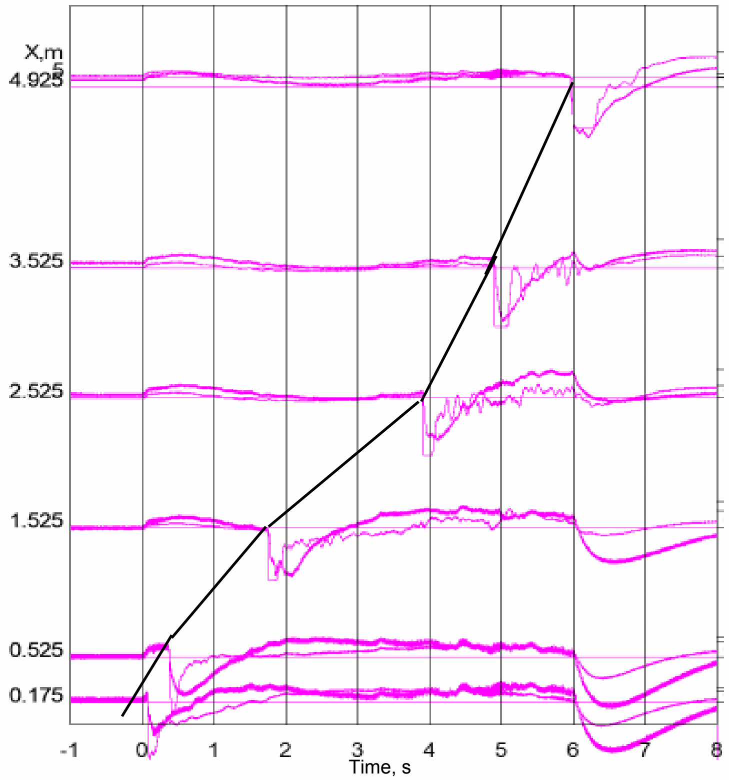
control units in a container besides the facility.

E5.2: Reference tests

Several tests at ambient T have been conducted to check the facility

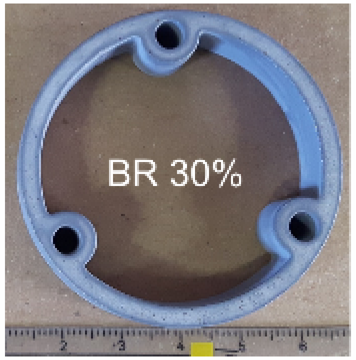
- Tests without obstacles
- Hydrogen-concentrations investigated in the warm tests are: cH_2 = 10, 11, 12, 15, 20, 30, 45, 60 vol%

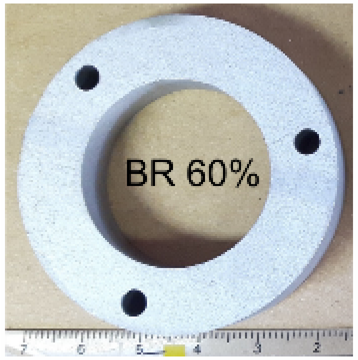
x-t Diagram: Pressure signals along tube
10,6 Vol% H2, no obstacles



E5.2: Test Parameters for 80K Tests

- 2 blockage ratios (30% and 60%)

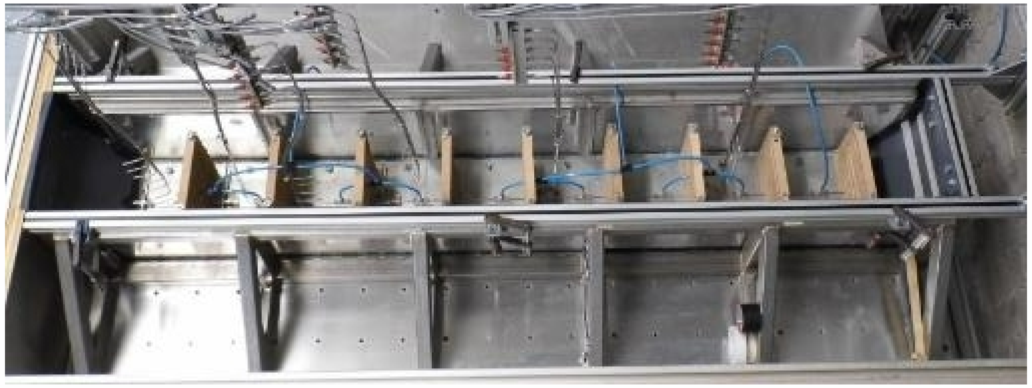




- 10 H2-concentrations from within the ranges
  - 6 to 12 Vol.% H2
  - 15 to 20 Vol.% H2
  - 30 Vol.% H2
  - 60 to 75 Vol.% H2

Next Combustion Experiments

– E5.3 Flame propagation above LH2 pool (KIT/PS)



– E5.5 Flame propagation in confined /obstructed cold cloud (HSE)
(done – first report expected within 12/2019)