PRESLHY

Pre-normative research for the safe use of liquid hydrogen

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Pre-normative REsearch for Safe use of Liquid HYdrogen

PRESLHY Project Overview

Call year:
2017

Call topic:
FCH-04-4-2017: PNR for a safe use of liquid hydrogen

Project dates:
01/2018- 05/2021

Total project budget:
1 905 862,50 €

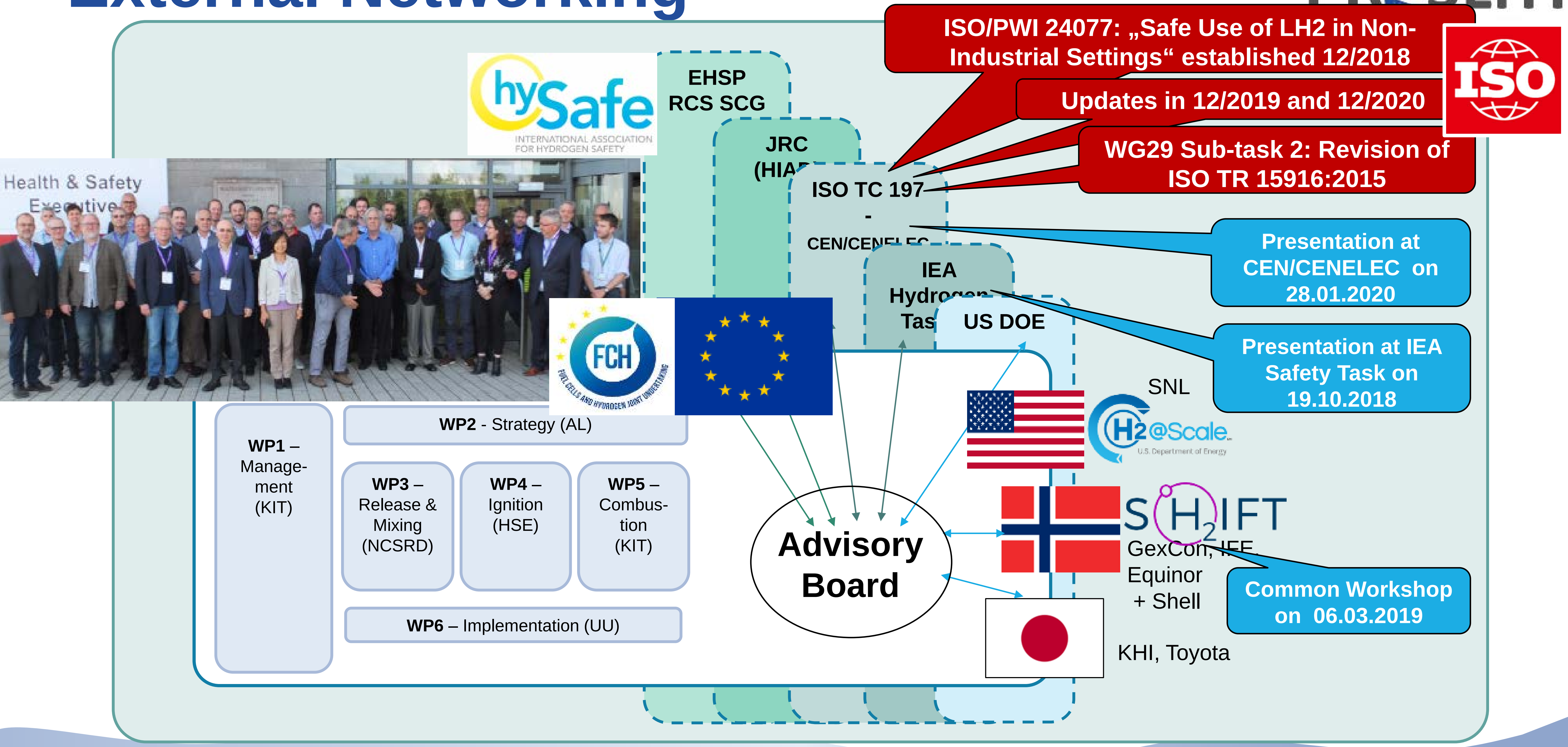
% stage of implementation 16/12/2021: 100%

FCH JU max. contribution: 1 724 277 €
Other financial contribution: - €

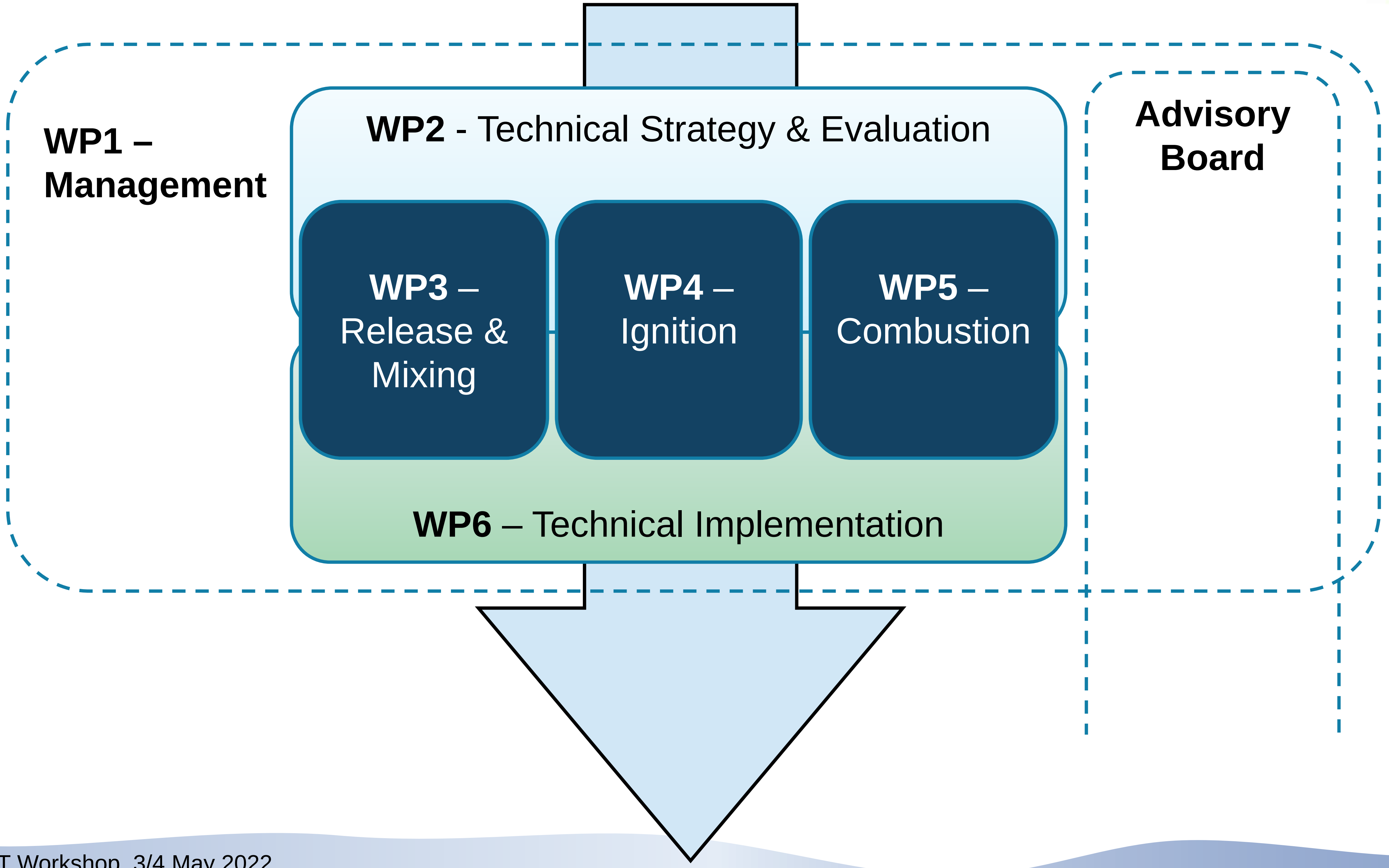
Consortium

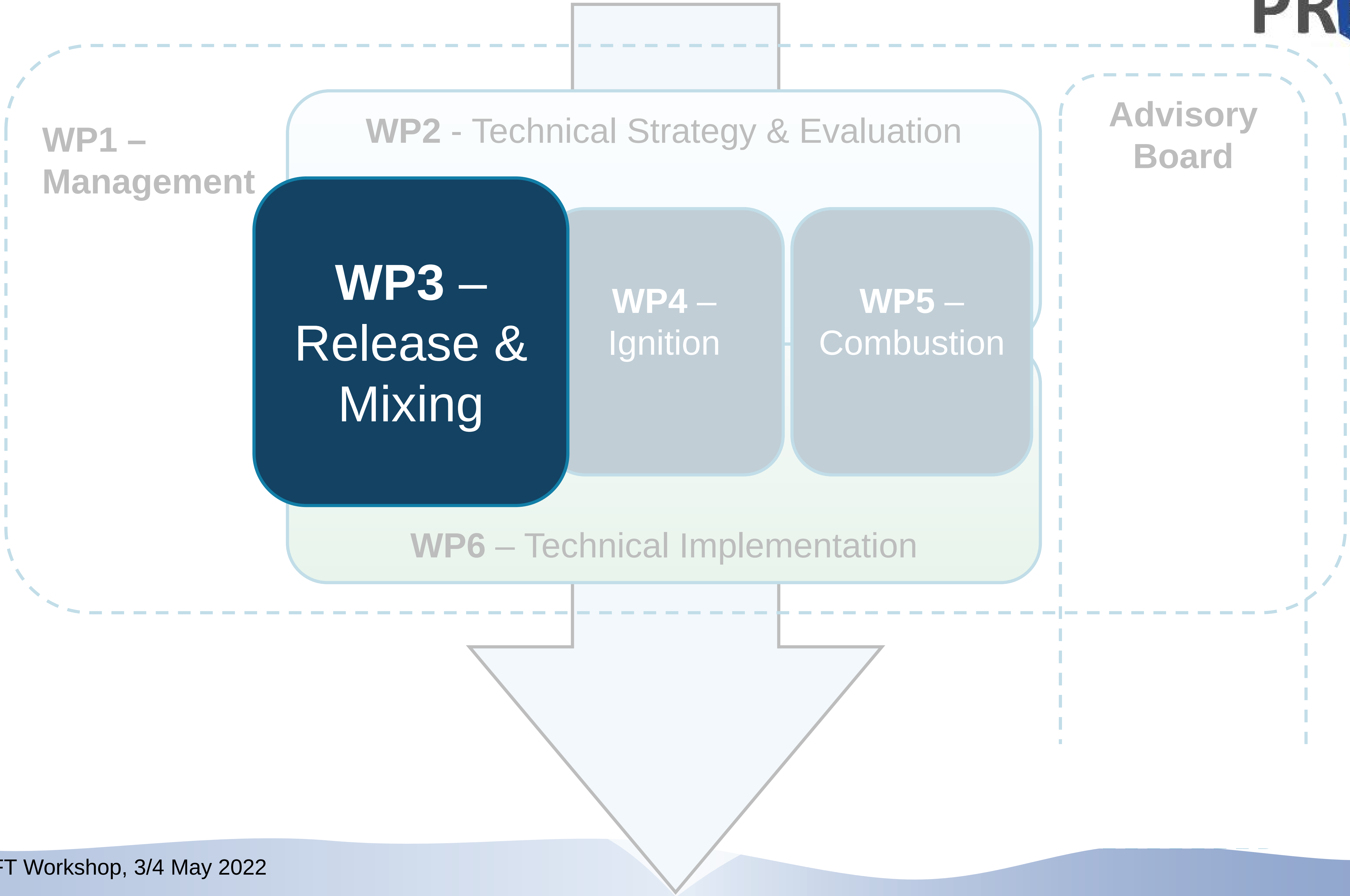

Ulster University
WARWICK
THE UNIVERSITY OF WARWICK
HSE
Health & Safety Executive
hySafe
INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY
KIT
Karlsruher Institut für Technolog
Pro-Science
INERIS
controlling risks for sustainable development
Air Liquide
ΔΗΜΟΚΡΙΤΟΣ

External Networking



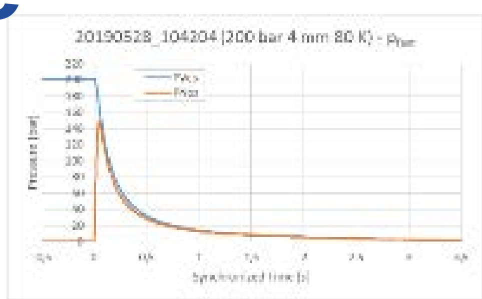
General Approach

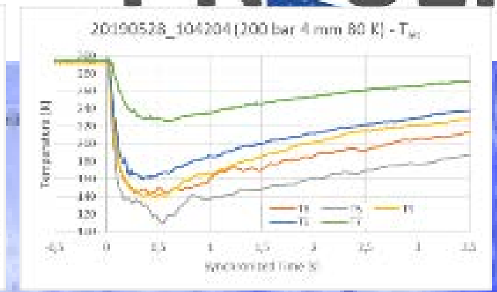


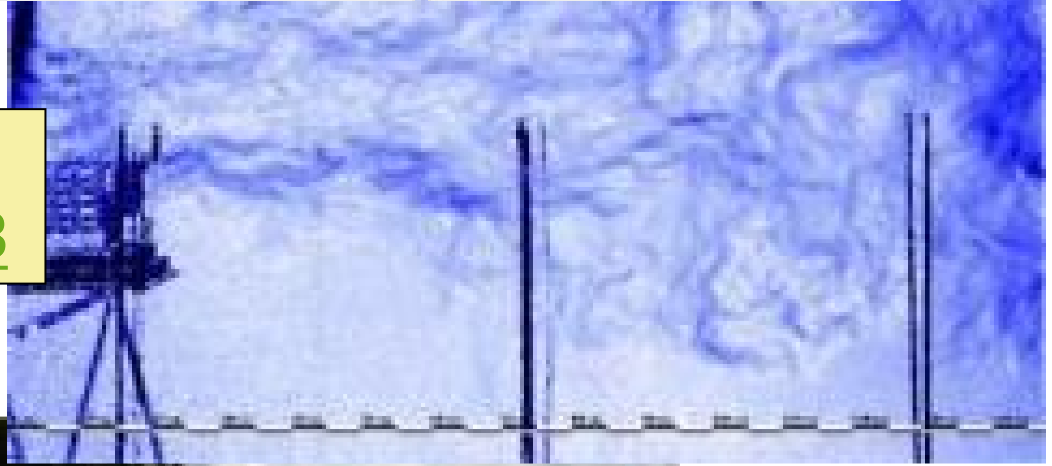

WP1 –
Management
WP2 - Technical Strategy & Evaluation
Advisory
Board
WP3 –
Release &
Mixing
WP4 –
Ignition
WP5 –
Combustion
WP6 – Technical Implementation

Closed Knowledge Gaps - Release

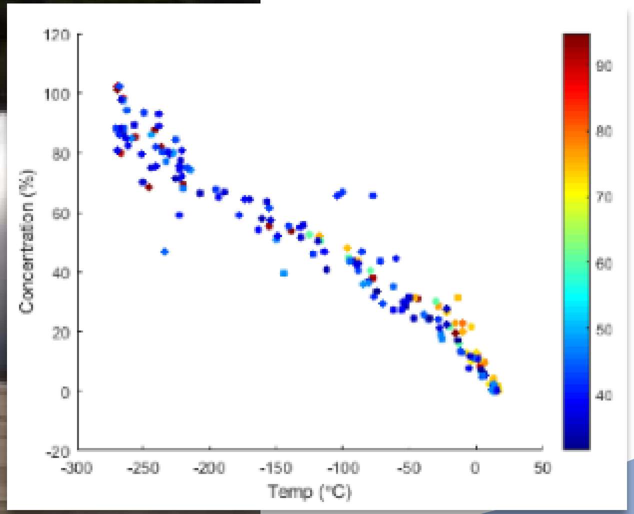
- Discharge coefficients for circular nozzles D=0.5-4 mm
  5 - 200 bar; 20 – 300K
- Mixing behavior and multi-phase effects with ambient air
- No rainout for large scale above ground horizontal releases
- Correlation of T and concentration of cryogenic H2 and air mixtures
- Assessment of effect of heat transfer through a pipe wall during cryogenic hydrogen release







KIT/PS E3.1a,b DISCHA & CRYOSTAT tests, see https://doi.org/10.5445/IR/1000096833



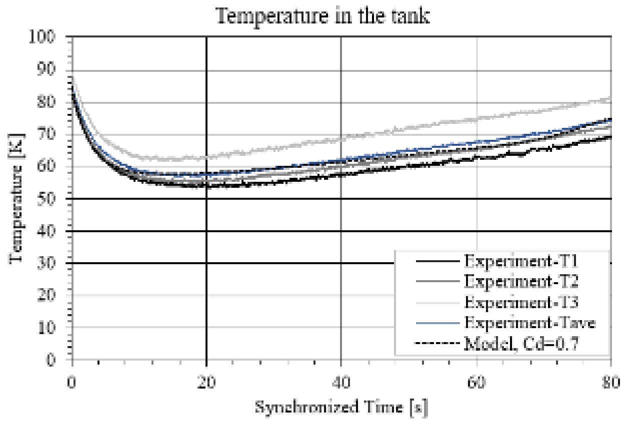
HSE E3.5: rainout tests

Correlations/Tools for Releases

The non-adiabatic blowdown model for a cryogenic hydrogen storage tank (UU)

Aim: accurately predict the temperature and pressure dynamics in cryogenic hydrogen storages during blowdown, the parameters at the nozzle and release rate by taking into account:

- Non-ideal behaviour of hydrogen gas;
- Heat transfer through a tank wall;
- Heat transfer through the discharge pipe wall.



P_{in}=200 bar, T_{in}=80Km d=1 mm

Steady state single / two-phase choked / expanded flow through a discharge line with variable cross section with account of friction and extra resistances (NCSRD)

Aim: predict the choked mass flow rate and distribution of all relevant physical quantities along the discharge line by taking into account:

- Discharge line friction and extra resistances;
- Transition to two-phase state.

Correlations/Tools for LH2 pools

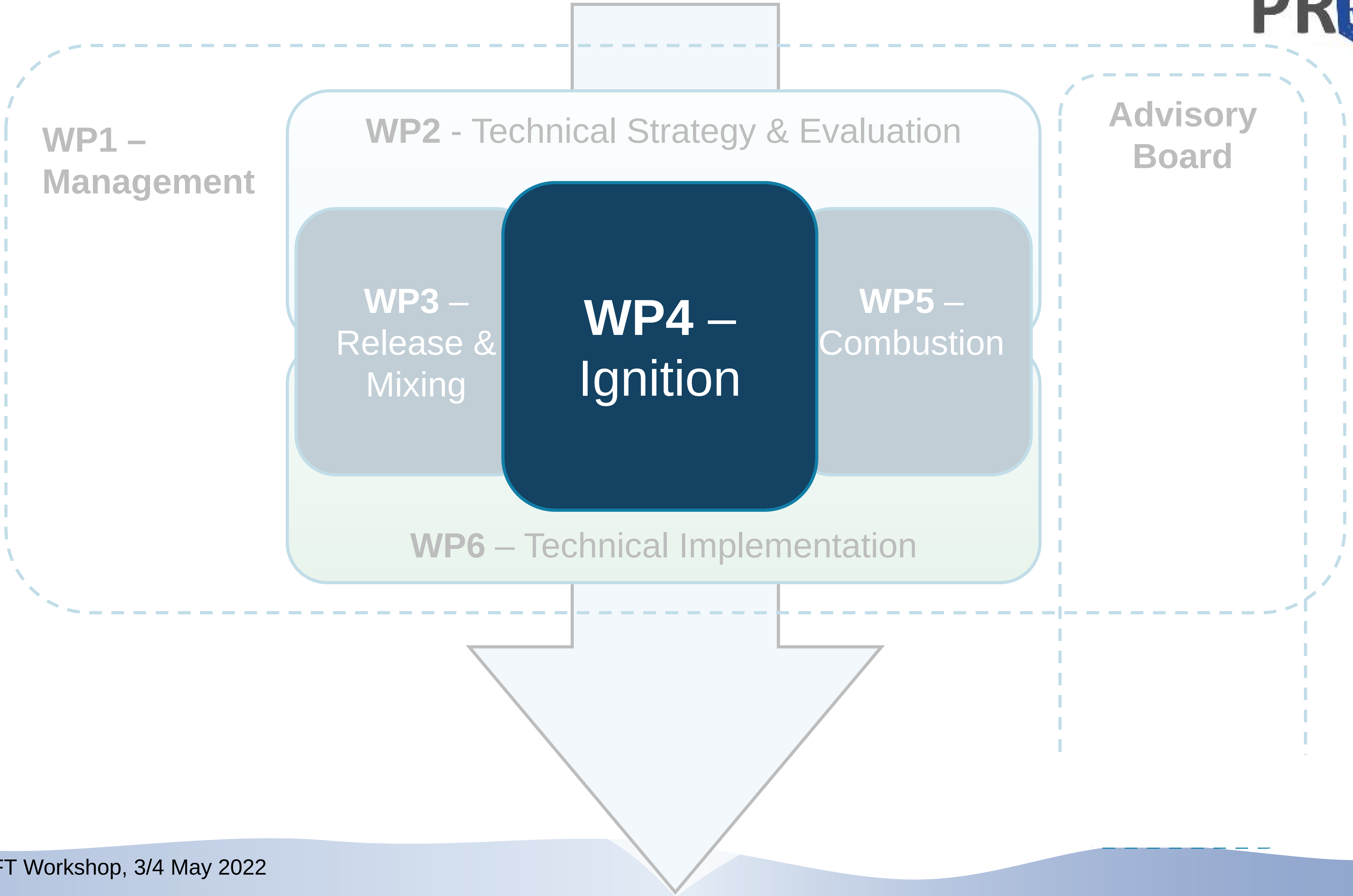
Extent of cryogenic pools – HyPond (INERIS)

Aim: estimate the maximum extent of a liquid pool likely to spread on the ground following a low pressure spillage of liquid hydrogen. The model addresses continuous spillages, which can be caused by a hose rupturing or disconnection, etc.

$$r_{pond} = \sqrt{\frac{Q_m \cdot L_{vap} \cdot \sqrt{\pi \cdot a_{diff}}}{k \cdot \pi \cdot (T_{ground} - T_{eb})}} \cdot t^{1/4}$$

KIT/PS E3.4 unignited pool tests

- Q_m: LH_2 mass flowrate;
- Q_{cond}: thermal exchange between the pool and the ground;
- L_{vap}: heat of vaporization of LH_2;
- k: thermal conductivity of the ground;
- a_{diff}: thermal diffusivity of the ground;
- t: time elapsed since the start of the release;
- A_{pond} is linked to the characteristic radius r_{pond} of the pond as $A_{pond} = \pi \cdot r_{pond}^2$.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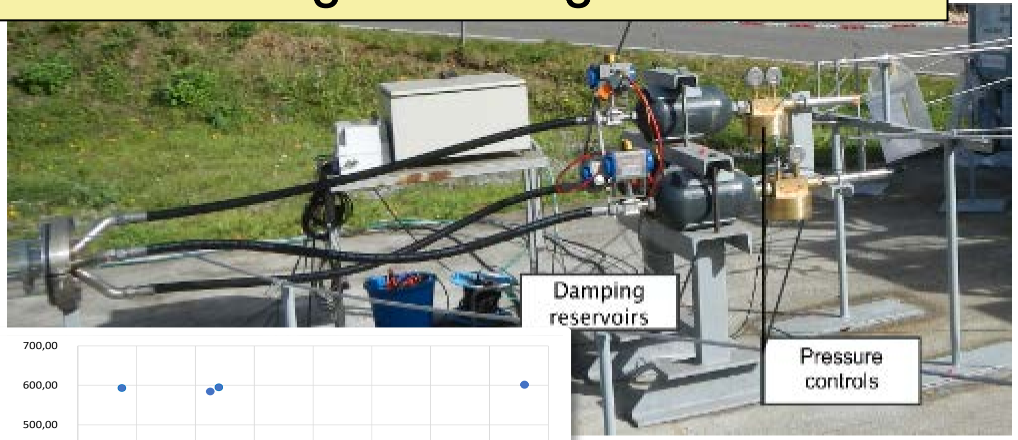
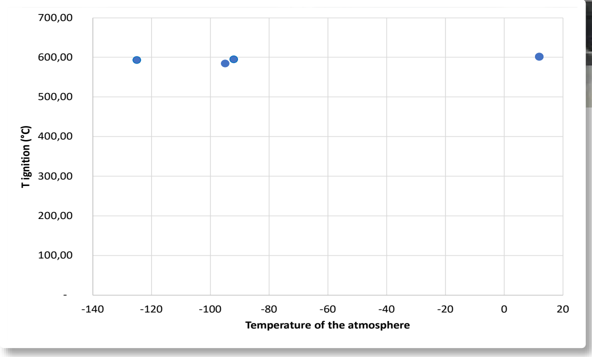
Closed Knowledge Gaps - Ignition

INERIS E4.1 general ignition tests



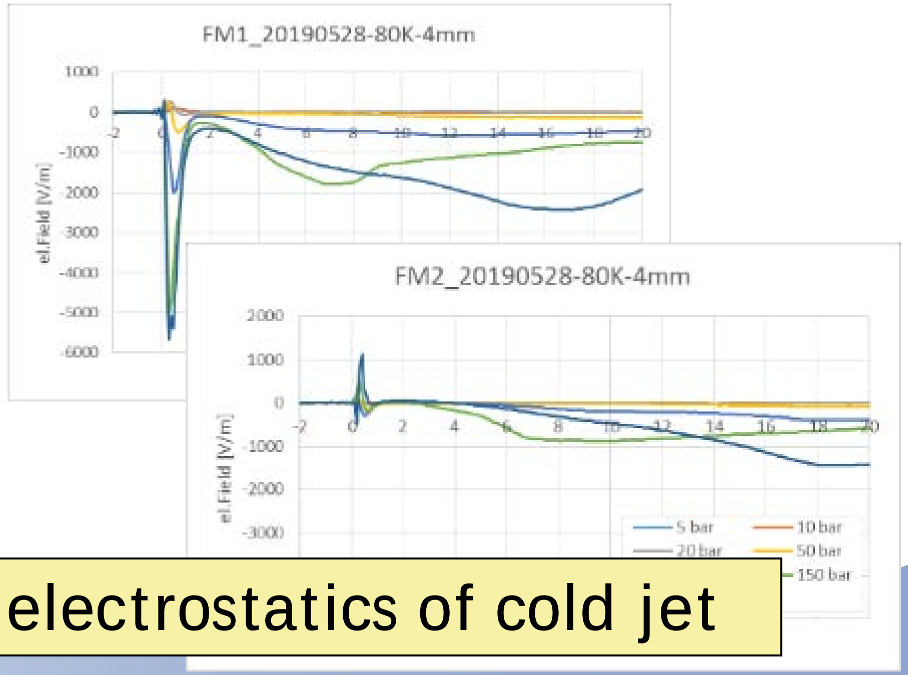


- Ignition temperature by **hot surface** independent on mixture temperature
  Small influence of stoichiometry and flow velocity.

- **Minimum Ignition Energy MIE** by spark ignition showed slight increase for hydrogen-air mixtures at 173 K.
  Analytical and numerical models/simulations to predict MIE by spark ignition for hydrogen-air mixtures.

- **Electrostatic** field measurements with field mills in DISCHA experiments (>100) showed strong electrostatic fields (~6000 V/m) for 80 K releases (~100 larger than at ambient T).
  Electrostatic fields increase with increasing release pressure.
  Simple model derived.

- **No spontaneous ignition** was observed in any experiment.

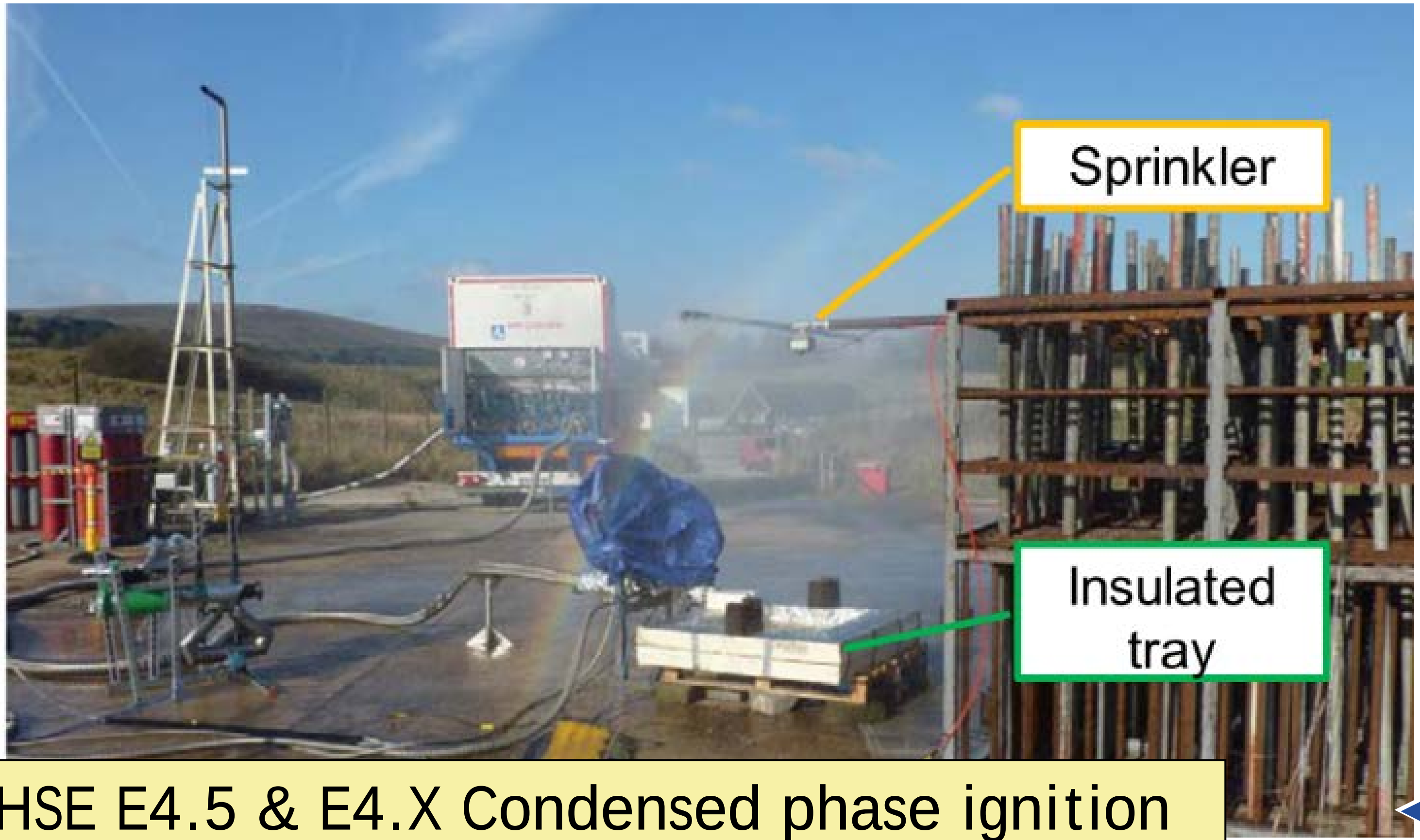


KIT/PS E4.3 electrostatics of cold jet

Multi-phase accumulations with explosion potential

Repeated spills on gravel bed might generate highly reactive condensed phase mixtures.
Not on other substrates!

KIT/PS E4.4 ignition above pool



HSE E4.5 & E4.X Condensed phase ignition

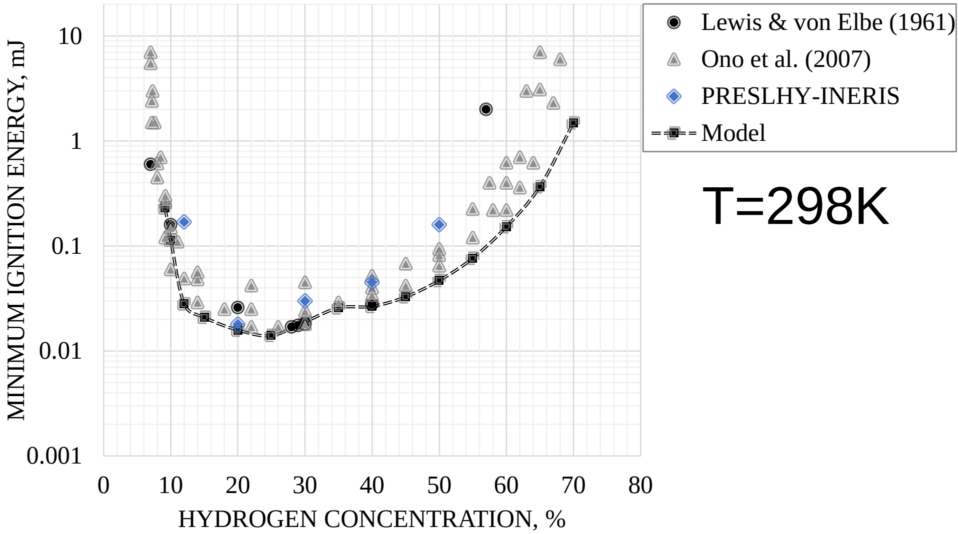
No critical effects observed for water sprays on LH2 and LH2 spills on small water pools.

Correlations/Tools for Ignition

Ignition Energy for hydrogen-air mixtures (UU)

Aim: determine the Minimum Ignition Energy (MIE) by spark ignition in hydrogen-air mixtures with arbitrary concentration and initial temperature. Novelties:

- Use of the laminar flame thickness to determine the critical flame kernel instead of experimental data not available for low T
- Account of flame stretch and preferential diffusion



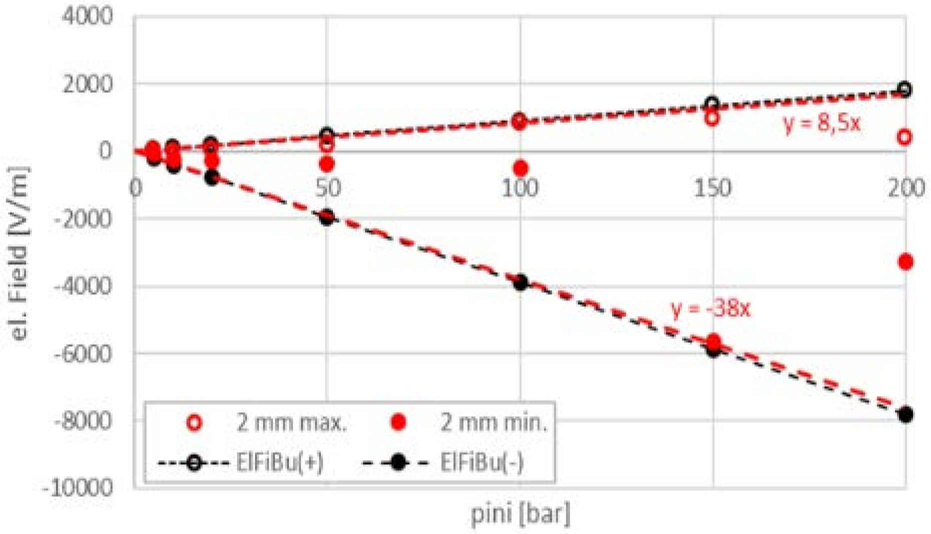
T=298K

Electrostatic field built-up generated during H2 releases (PS)

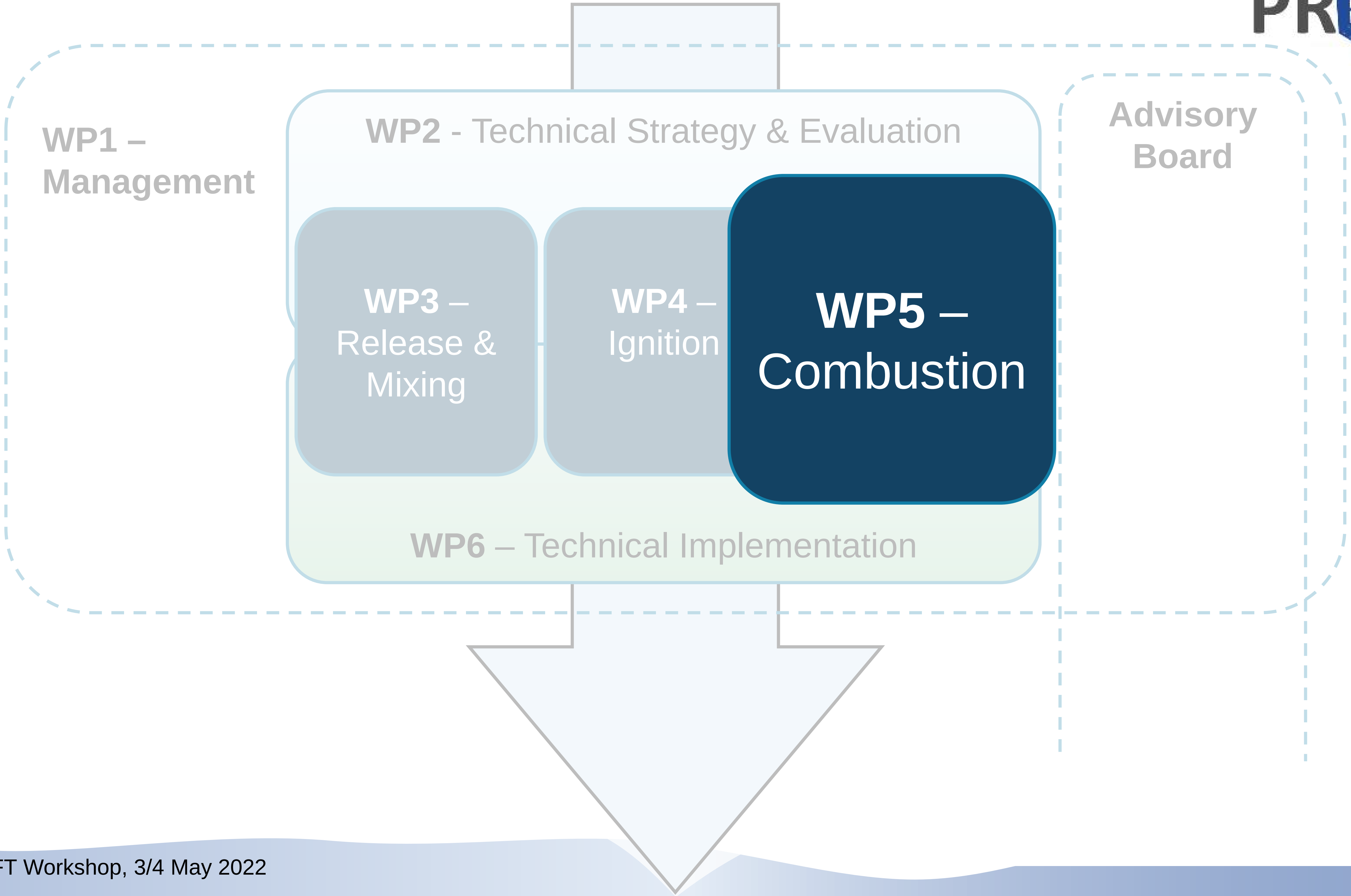
Aim: assess the electrostatic field built-up during hydrogen releases through a nozzle with circular aperture. The ElFiBU-correlation consists of two formulas:

Positive Field Built-up: $E(+) \leq (4 \cdot dNz + 1) \cdot p_{ini}$

Negative Field Built-up: $E(-) \leq (-14 \cdot dNz - 11) \cdot p_{ini}$



dNz=2mm, T=80K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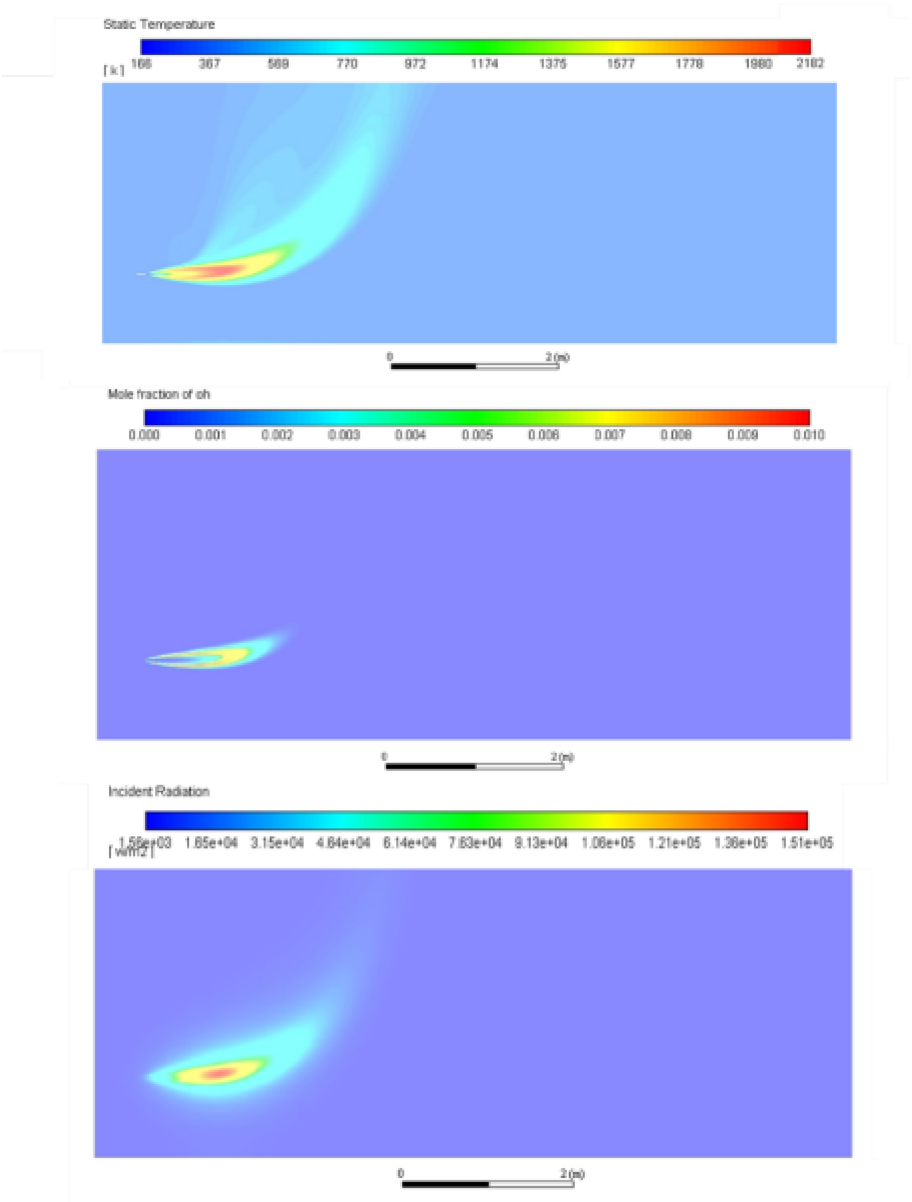
Cryogenic hydrogen jet fires: thermal hazards

- Validation of a CFD model to assess radiative heat flux from cryogenic hydrogen jet fires with vertical and horizontal orientation.
- The buoyancy of combustion products has a positive effect on the reduction of the “no harm” distance by temperature from x=3.5L_f for vertical jet fires to x=2.2L_f for horizontal jet fires.
- Thermal radiation leads to longer “no-harm” distances in the direction of the jet (x=3.0-3.2L_f) compared to hazard distance defined by temperature.
- Thermal dose provides to be a useful parameter to define hazard distances for emergency personnel.
- Use of flame length dimensionless correlation can be expanded to cryogenic releases.



Correlations/Tools for Jet Fires

Flame length correlation and hazard distances for jet fires (UU)

Aim: dimensionless correlation for hydrogen jet flames calculates the flame length knowing the storage conditions. Hazard distances for people can be defined as:

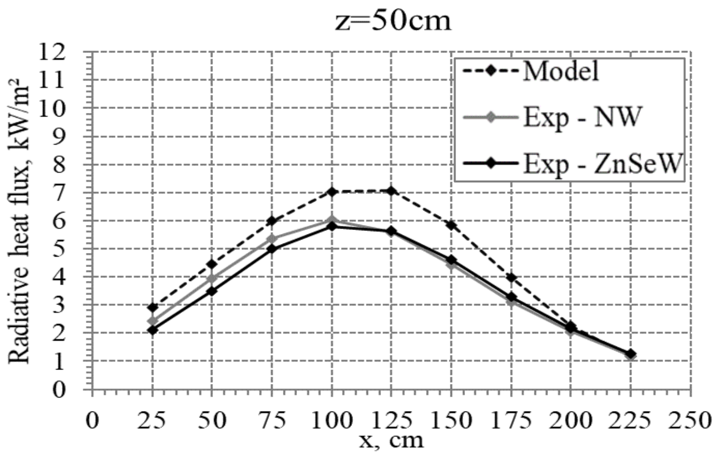
- No harm (70°C) hazard distance, $X_{70} = 3.5L_f$;
- Pain limit (5 mins, 115°C) hazard distance, $X_{115} = 3L_f$;
- Third degree burns (20 sec, 309°C) hazard distance, $X_{309} = 2L_f$.

The tool is available on e-lab platform developed within NET-Tools (https://elab-prod.iket.kit.edu/).

Assessment of thermal load from hydrogen jet fires (UU)

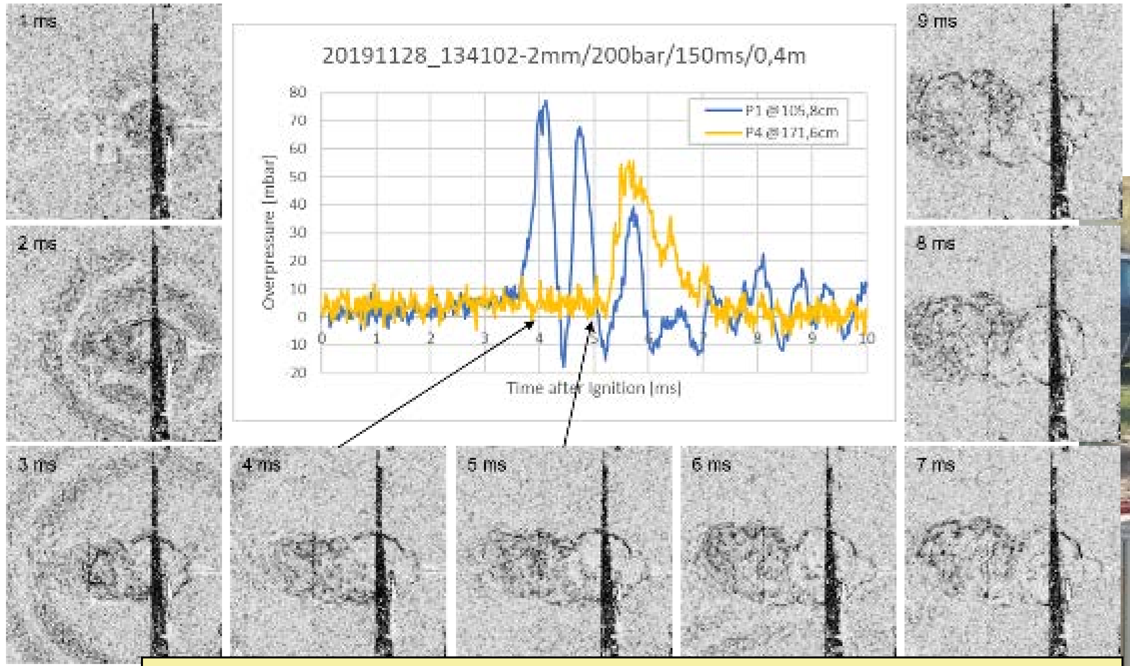
Aim: assess the radiative heat flux from vertical and horizontal hydrogen jet fires.

- The reduced tool is based on the weighted multi source flame radiation model developed by Hankinson and Lowesmith (2012) and further expanded by Ekoto et al. (2014).
- The model was adapted to use the dimensionless correlation to estimate flame length and expand the validation range to cryogenic hydrogen jet fires.



Test: T=80 K, P=3 bar, d=4 mm

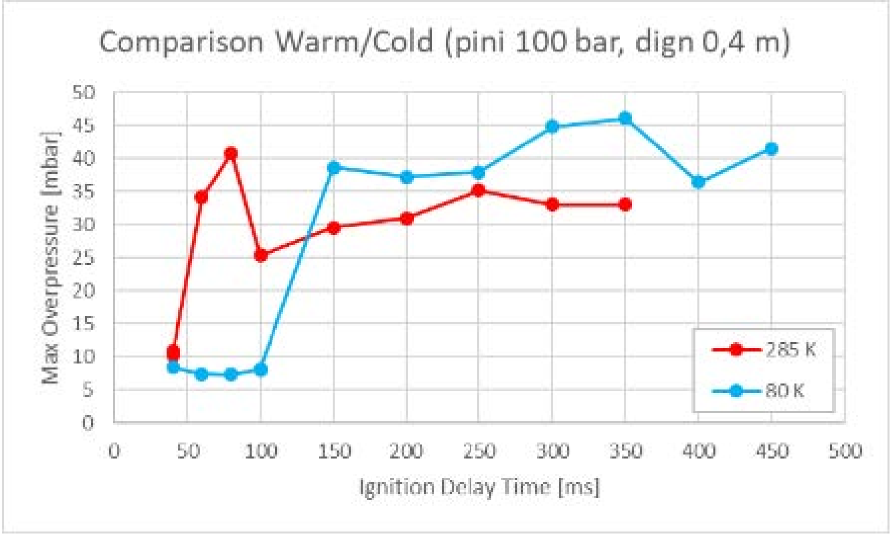
Transient combustion effects



KIT/PS E5.1 jet fire experiments

> 100 Ignited jet tests combined with discharge experiments E5.1
T = 80K, 280K
P = 5-200bar
D_{nozzle}= 1, 2, 4mm

Iterative procedure for identifying most critical ignition time and location



- Better understanding of transient jets and combustion processes
- **Inventory based map of worst effects** (pressure & thermal) **to be extrapolated to large inventories for RCS**

Correlations/Tools for Pressure hazards

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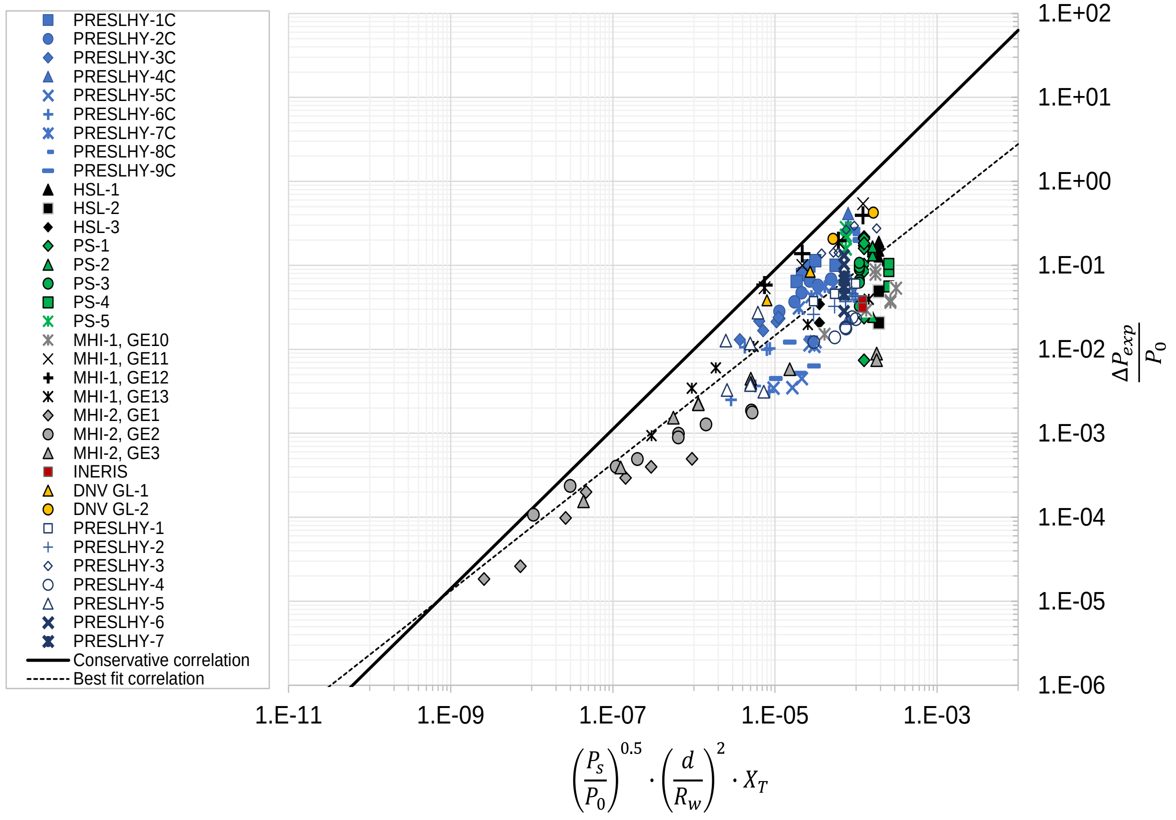
Maximum pressure load from delayed ignition of turbulent jets (UU)

Aim: predict the maximum overpressure generated by delayed ignition of a hydrogen jet at an arbitrary location for known storage pressure, P_s, and release diameter, *d*. The correlation is applicable only to free jets in open atmosphere.

The semi-empirical correlation was built by using overpressure measurements from about 80 experiments and the similitude analysis:

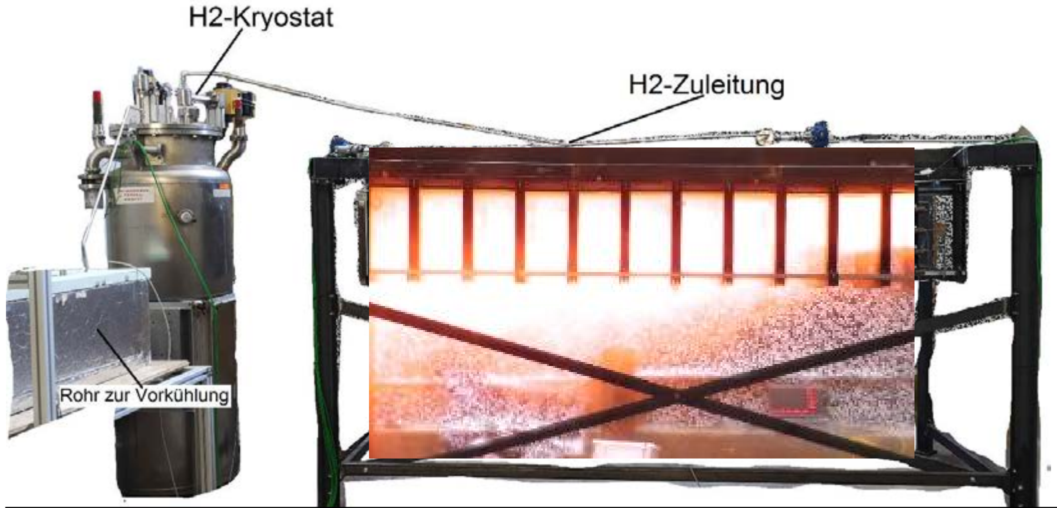
$$\Delta P_t = P_0 \cdot 5000 \cdot \left[\left(\frac{P_s}{P_0} \right)^{0.5} \cdot \left(\frac{d}{R_w} \right)^2 \cdot X_T \right]^{0.95}$$

- R_w: distance between the centre of the fast burning mixture (25-35% by volume) and the target location
- $X_T = 1$ for ambient temperature releases
- $X_T = \frac{T_S}{T_0} \frac{E_{i,T_S}}{E_{i,T_0}}$ for cryogenic releases, where E_{i,T_S} is the expansion coefficient at T_S.



Combustion in confined/congested domains

- Stronger pressure loads for cold tests in comparison with warm tests with the same volume, hydrogen concentration and blockage ratio



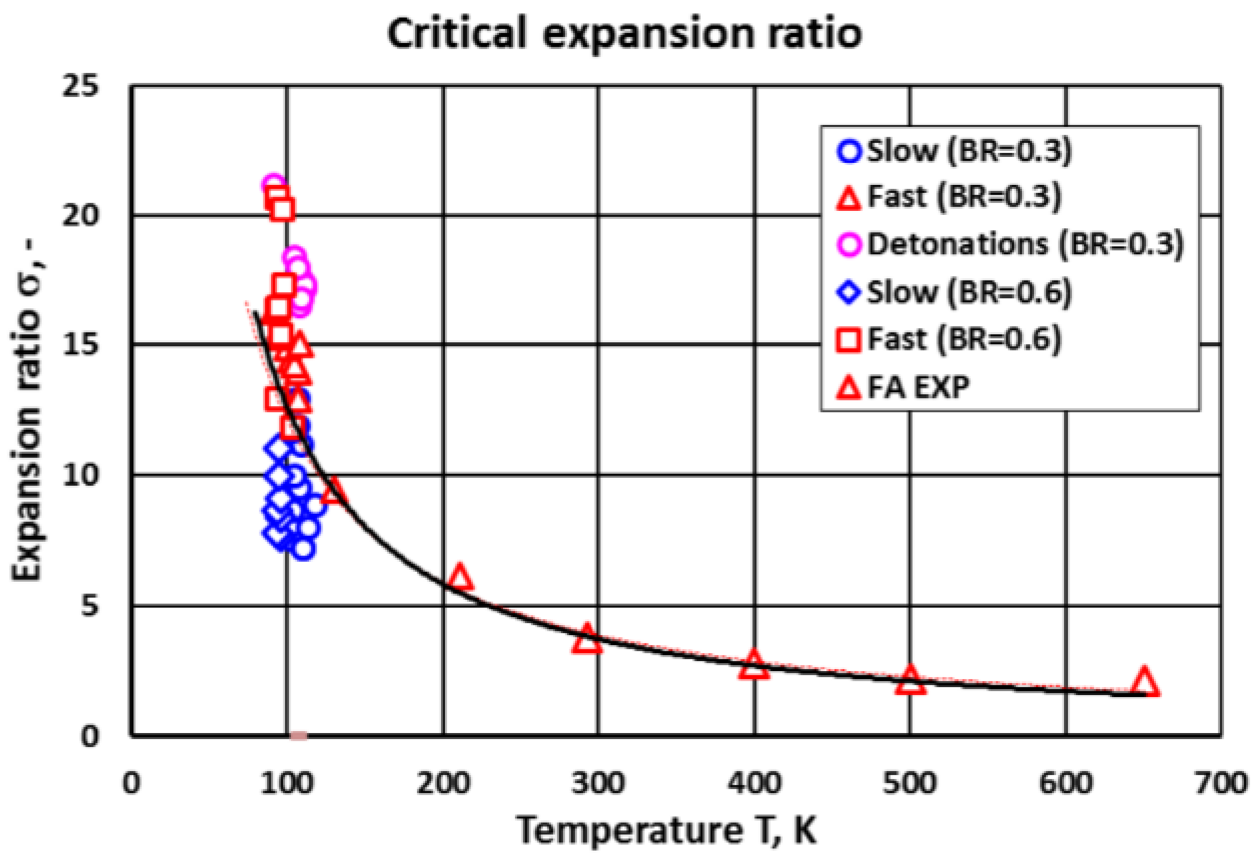
KIT/PS E5.3 semi-confined channel

HSE E5.5 confined/obstructed cloud

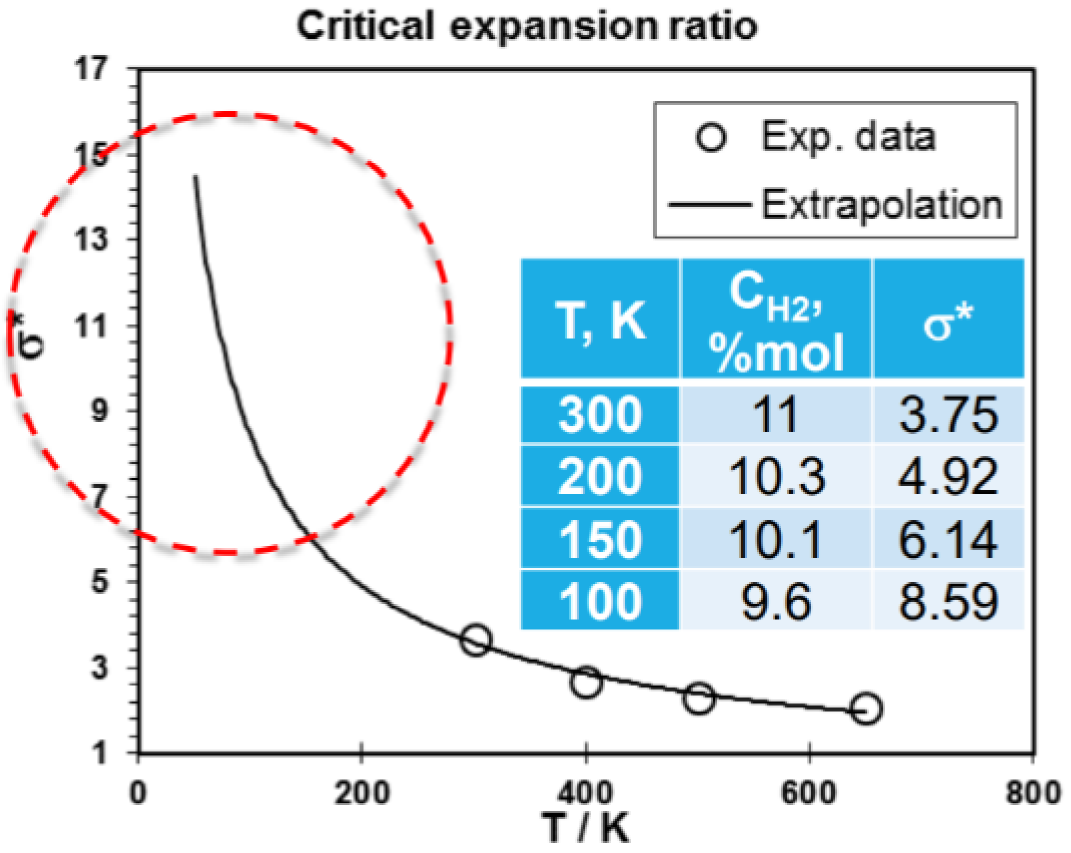
- Increase in critical and effective expansion ratios determine flame acceleration in cryogenic mixtures
- Reduced run-up distance for detonation transition DDT in cryogenic mixtures (← density effects)
- Influence of blockage ratio on DDT less pronounced
- Effects in free unconfined domains to be investigated

Critical Expansion Ratio for FA

Experiments



Predictions



T, K	C_{H2}, %mol	σ*
300	11	3.75
200	10.3	4.92
150	10.1	6.14
100	9.6	8.59

- The critical expansion ratio at T=100K was experimentally found to be σ* =12.5 (16%H2), much higher than that predicted by far extrapolation σ* =8.6 (9.6%H2)
- Approximation line as a function of initial temperature can be used - or more simplified relationship (more conservative: σ*=11 instead of σ*=12.6 according to experimental correlation)

$$\sigma^* = 2200 \cdot T^{-1.12}$$

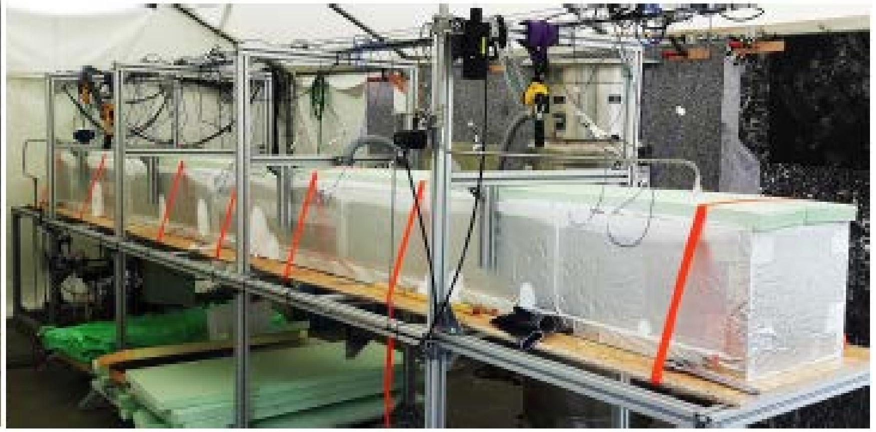
$$\sigma^*(T) = \sigma^*(T_0) \cdot \left(\frac{T_0}{T}\right)$$

DDT and Pressure Effects

- The **detonation cell sizes** at cryogenic temperature T = 100K are evaluated on the basis of existing criteria for detonation onset in smooth and obstructed tubes:

$$\lambda[mm] = 0.0006724[H_2]^4 - 0.1039[H_2]^3 + 6.0786[H_2]^2 - 159.74[H_2] + 1603.3$$

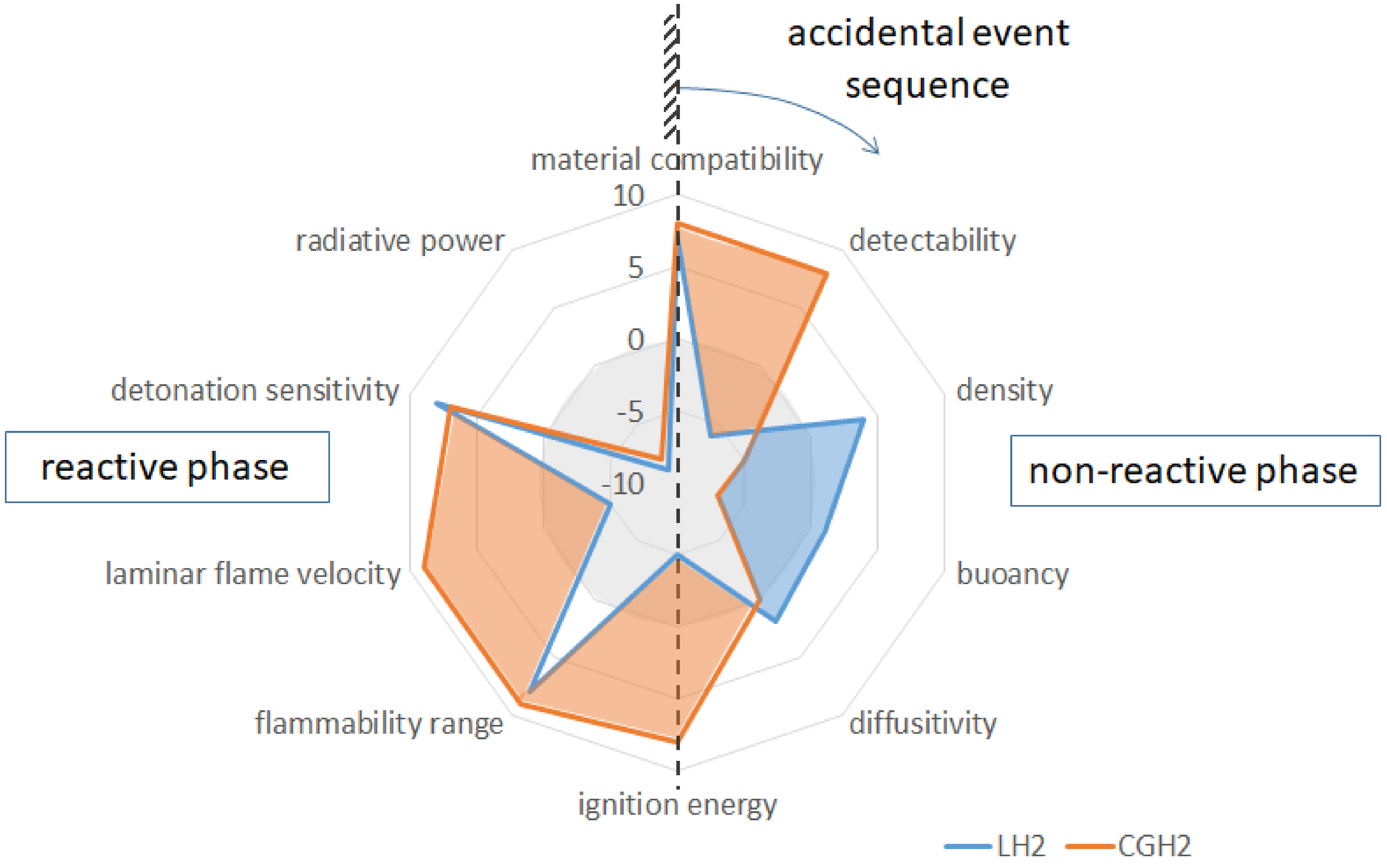
- With this correlation established criteria may be used to assess **detonability of H2-air** mixtures at cryogenic temperatures in different geometries and scales.
- **Run-up distance** to detonation at cryogenic temperatures **0.5 x** at ambient temperature.
- First time in un-obstructed channel **quasi-detonation** observed
- Maximum **combustion pressure** at cryogenic temperatures **2-3 x** at ambient conditions.

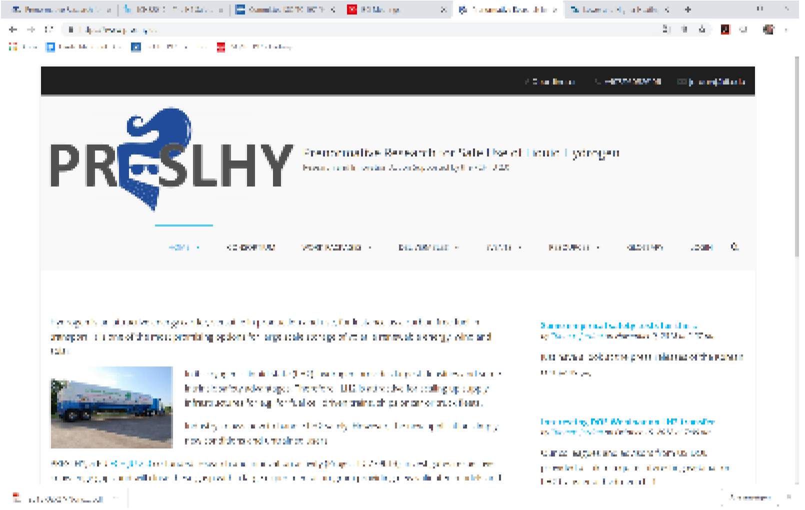
KIT/PS E5.2 cryotube FA and DDT experiments

EXPLOITATION

Risk Profiles LH2 vs CGH2



Outreach

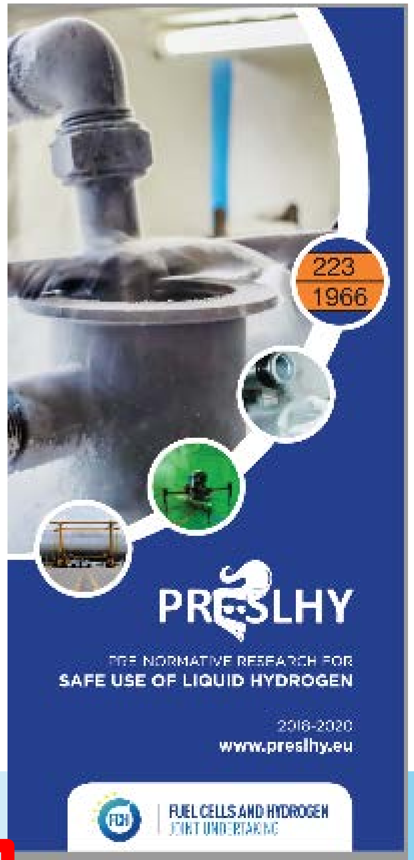


www.preslhy.eu

PRESLHY Exploitation & Dissemination Activities

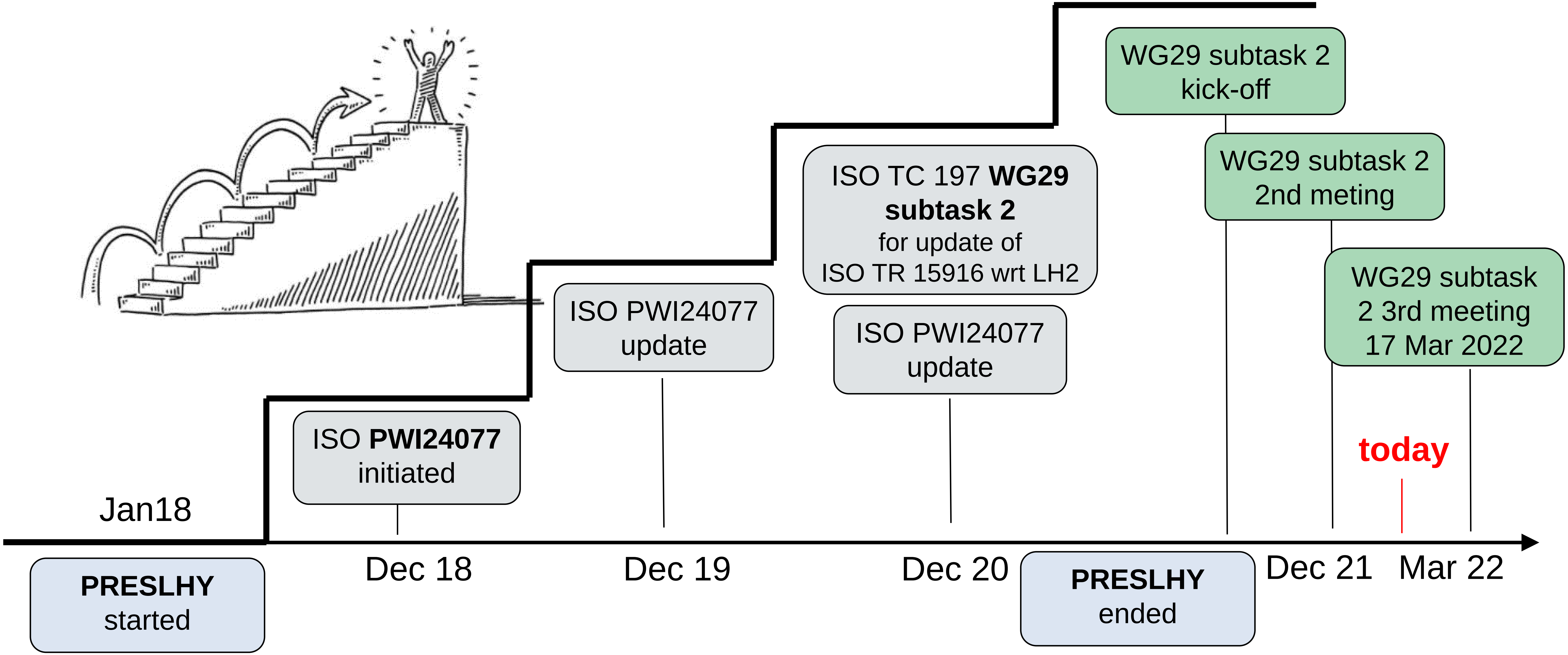
Management (WP1)

Implementation (WP6)



- Task 1.3 Website
- Data Manage ment
- Engineering tools
- Handbook
- Guidelines
- RCS Recom-mendations
- White Paper
- Task 6.6 Dissemina-tion Conference

Stairways to standardisation

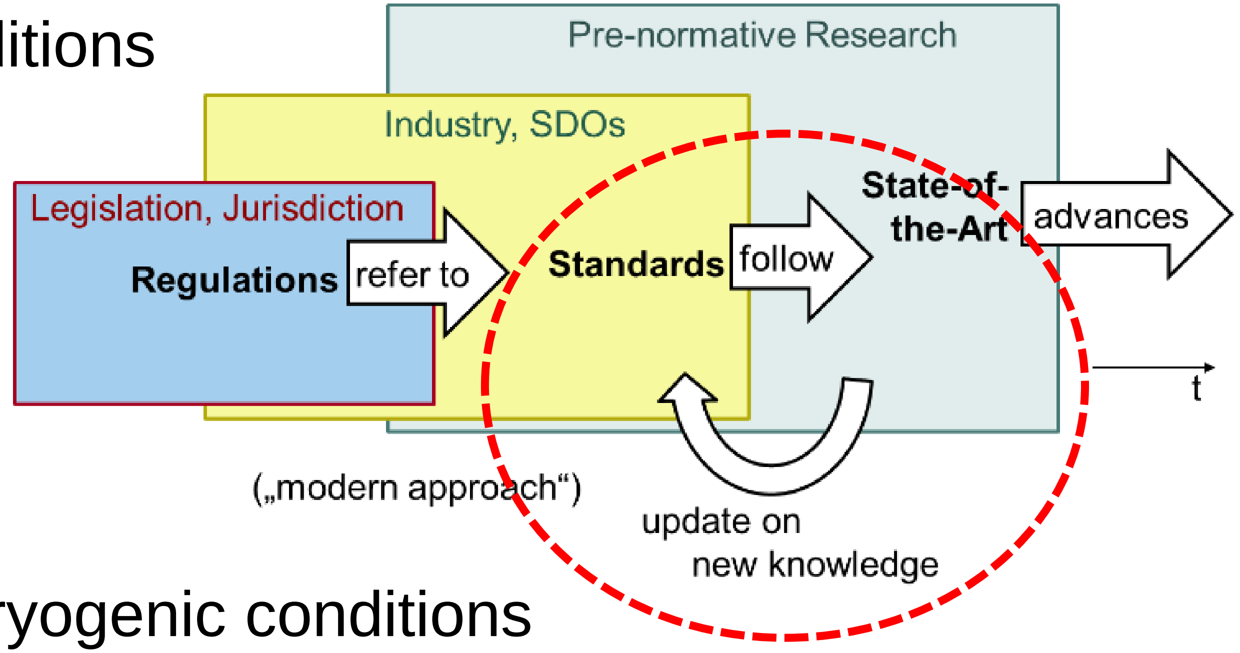


Closure

Recent achievements

Fundamental/Modelling "Release":
- ✓ Discharge coefficients for cryo- and cryocompressed releases
- ✓ Rainout phenomena better understood
- ✓ Fundamental data for mixing of large scale releases

Fundamental/Modelling "Ignition":
- ✓ MIE and hot surface T determined for cryogenic conditions
- ✓ Empirical tests for RPT without fast reaction
- ✓ Electrostatics of cryogenic releases
- ✓ Worst case effects for small cryogenic inventories determined via variation of ignition time and position



Fundamental/Modelling "Combustion":
- ✓ Flame length correlations validated
- ✓ σ, σcrit and run-up distance for DDT determined at cryogenic conditions

All published in more than hundred public available datasets/publications

Future work, open issues, priorities

PRESLHY

Fundamental/Modelling:

- ? Clarify **material issues** with cryogenic hydrogen
- ? improve **thermodynamic modelling** in multiphase, non-equilibrium, reaction kinetics (< 200K)
- ? determine **induction times** and **detonation cell sizes** (< 200K)

Dispersion phenomena:

- ? **Ventilation** of closed rooms and interaction with other mitigation concepts
- ? **Multiphase effects** on large scale dispersion with obstruction and/or (partial) confinement

Combustion phenomena:

- ? Broader assessment of FA and DDT for varying congestion and confinement at larger scale
- ? Evaluation of **detonation potential of solid O_2** in LH_2 pools
- ? Scaling of **BLEVE**s

Risk assessment and mitigation strategies:

- ? Proper **design and approval of safety valves**
- ? Integral (applied) tests (dispersion and combustion in closed rooms) for **mitigation strateg**ies, including sensor placement and performance
- ? **Crash test** for vehicle tank systems

Acknowledgement

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… and many thanks to all contributors (e.g. Equinor, SHELL, …)