# Enhacing the
# Safety
# of Liquid and Vaporised (Cryogenic) Hydrogen

Dr.-Ing. Thomas Jordan, ITES H2, Karlsruhe Institute of Technology KIT

**European Cryogenic Days 2023**

Darmstadt, Germany, 28./29.3.2023

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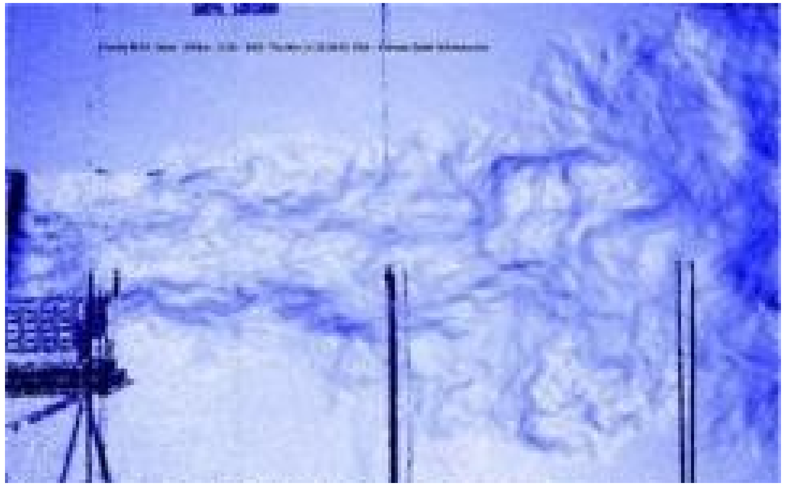
# Presentation Outline

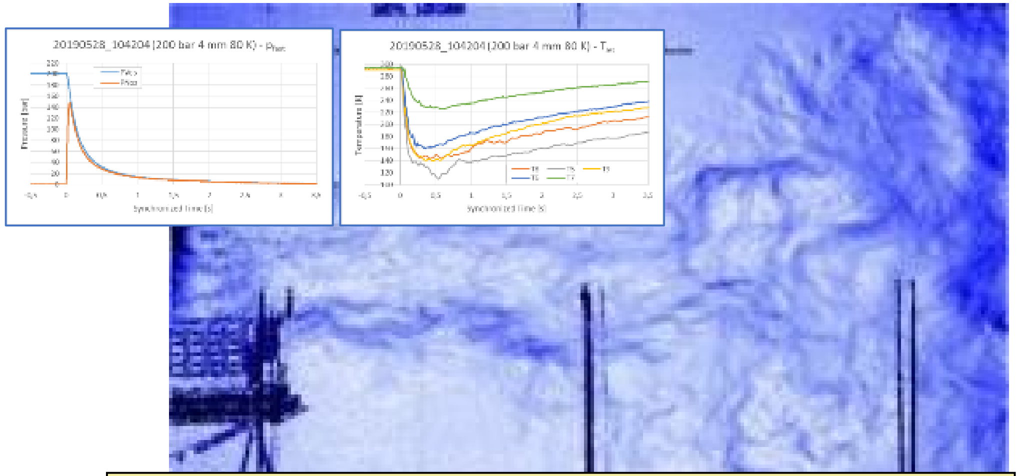
- Recent Work on Cryogenic Hydrogen Safety (pre-ELVHYS) → State-of-the-Art
- Ongoing Activities
- Planned Work
- Open issues



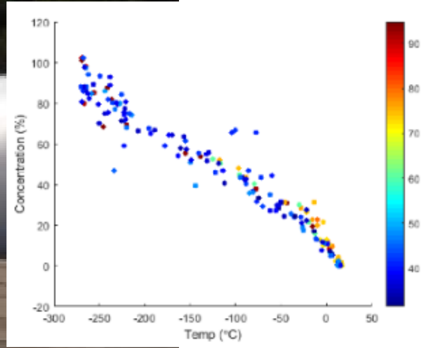
Pre – ELVHYS: PRESLHY

# 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

# Extent of LH2 pools – HyPond (INERIS)

Aim: estimate the maximum extent of a LH2 pool spreading on the ground, following a low pressure spillage. The model addresses continuous spillages, which can be caused by a hose rupturing or disconnection, etc.

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

with
$Q_m$: $LH_2$ 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 $A_{pond} = \pi \cdot r_{pond}^2$.


KIT/PS E3.4 unignited pool tests

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# Closed Knowledge Gaps - Ignition

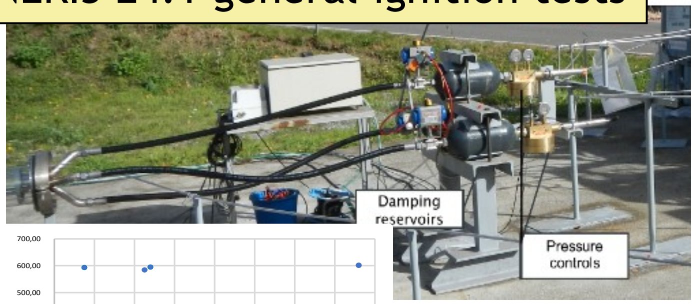
- Ignition temperature by **hot surface** independent on mixture temperature
  Small influence of stoichiometry and flow velocity.

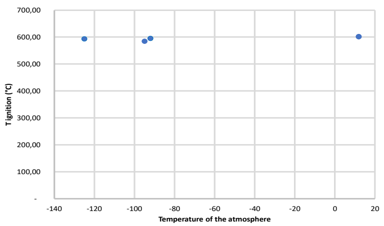
- **Minimum Ignition Energy MIE** by spark ignition showed slight increase for hydrogen-air mixtures at 173 K.
  Analytical and numerical models/simulations to predict MIE by spark ignition for hydrogen-air mixtures.

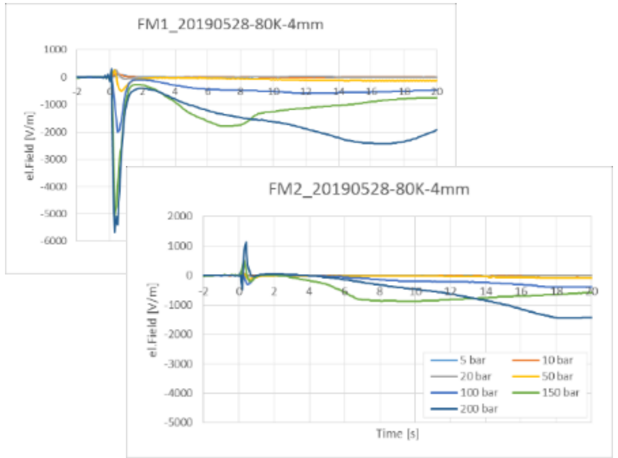
- **Electrostatic** field measurements with field mills in DISCHA experiments (>100) showed strong electrostatic fields (~6000 V/m) for 80 K releases (~100 larger than at ambient T).
  Electrostatic fields increase with increasing release pressure.
  Simple model derived.

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

INERIS E4.1 general ignition tests



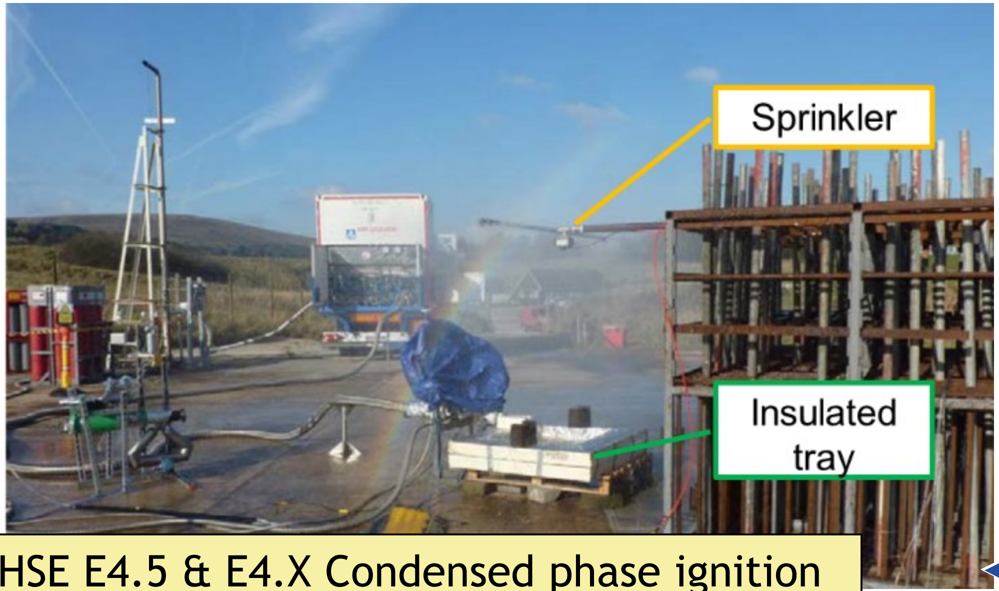




KIT/PS E4.3 electrostatics of cold jet

# 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.

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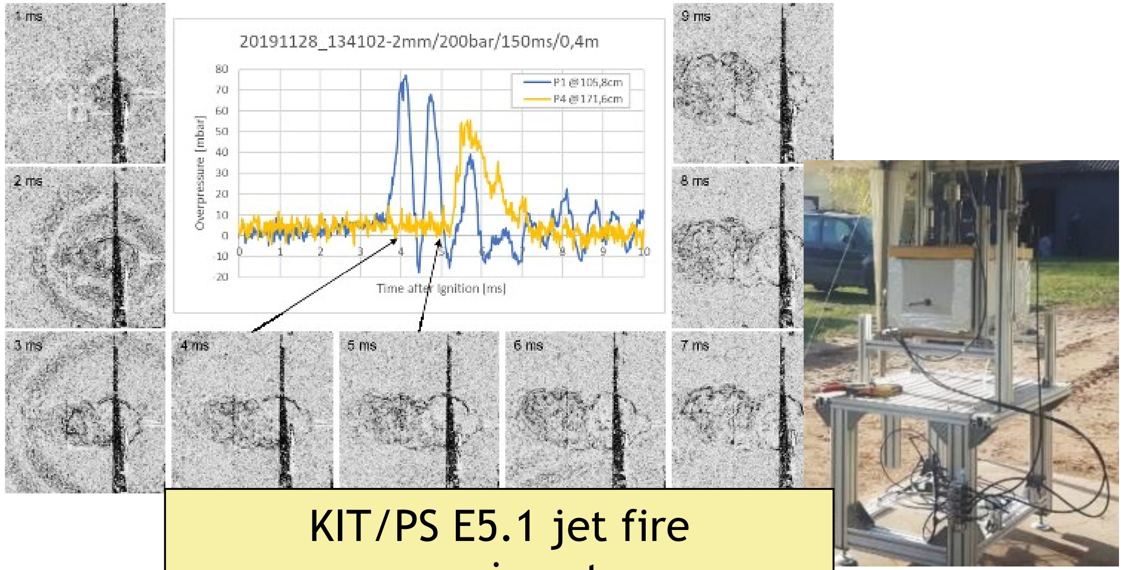
# Transient Combustion Phenomena




KIT/PS E5.1 jet fire experiments

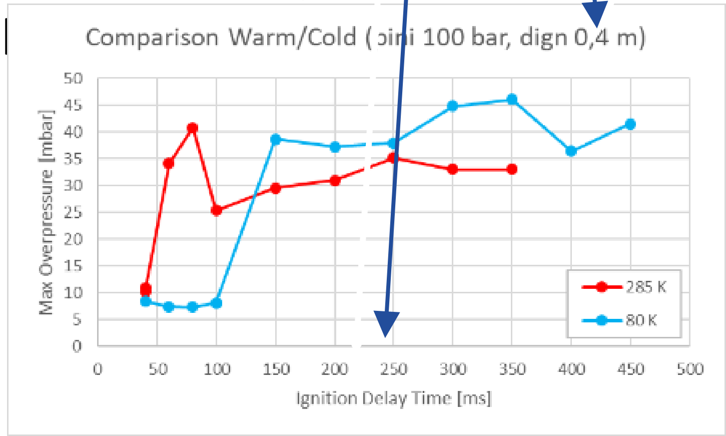
> 100 Ignited jet tests combined with discharge experiments E5.1

T = 80K, 280K

P = 5-200bar

$D_{nozzle}$ = 1, 2, 4mm

Iterative procedure for identifying most critical ignition time and




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

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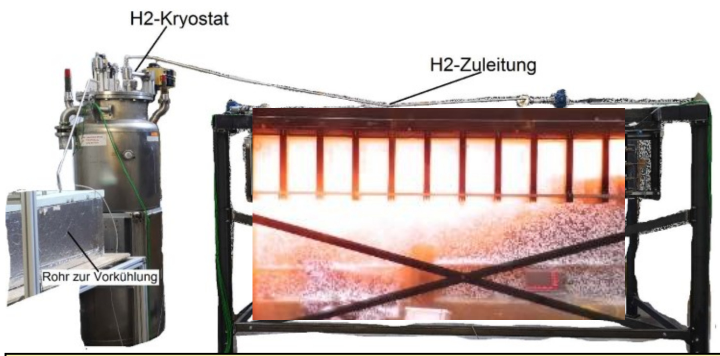
# Combustion in confined/congested domains

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




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

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# Summary Progress / Closed gaps

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
- ✓ …

PRESLHY

# Scientific Data Published

**DOI:** https://doi.org/105445/IR/ + ”KITOpen ID Nr”

| Participant: KIT | KIT Open ID Nr. |
|---|---|
| WP3.1.b | 1000145859 |
| WP3.4 | 1000145885 |
| WP5.1 | 1000147745 |
| WP5.5 | 1000136188 |

| Participant: KIT WP 4.4 | KIT Open ID Nr. |
|---|---|
| Material: sand | 1000145886 |
| Material: concrete | 1000145887 |
| Material: water | 1000145888 |
| Material: gravel | 1000145889 |

| Participant: HSE | KIT Open ID Nr. |
|---|---|
| WP3 | 1000136281 |
| WP4 | 1000136330 |
| WP5 | 1000136285 |

| Participant: KIT WP 5.3 warm | KIT Open ID Nr. | Participant: KIT WP 5.3 cold | KIT Open ID Nr. |
|---|---|---|---|
| BR ratio: 0% | 1000145890 | BR ratio: 0% | 1000145893 |
| BR ratio: 30% | 1000145891 | BR ratio: 30% | 1000145895 |
| BR ratio: 60% | 1000145892 | BR ratio: 60% | 1000145896 |

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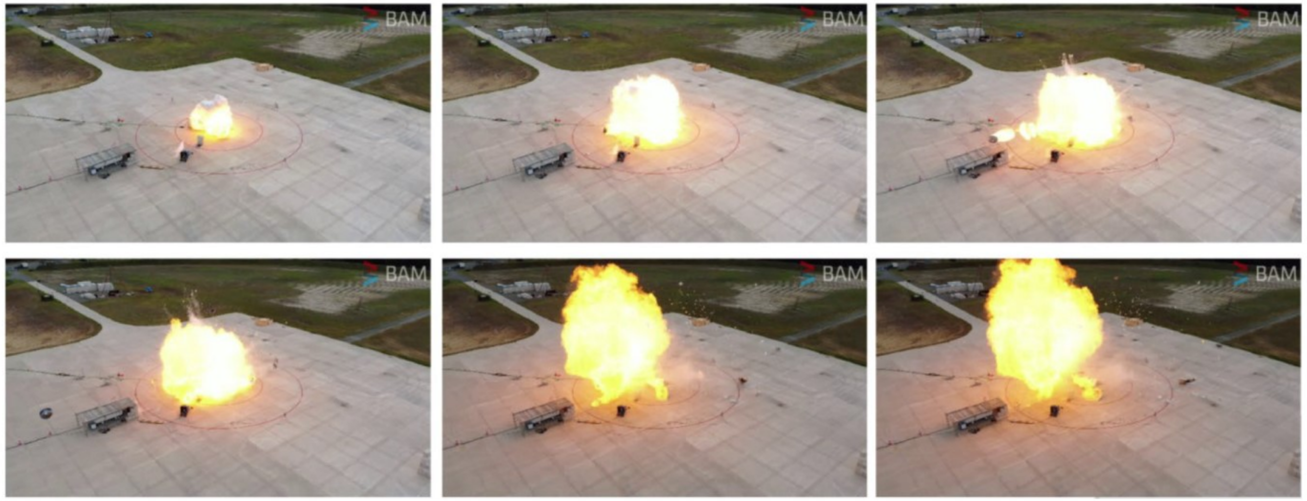
# SH2IFT Project Findings

## Fundamental/Modelling “BLEVE”:

✓ Experiments performed and BLEVE observed at BAM

(see van Wingerden, Kees, et al. *Chemical Engineering Transactions*, 2022, 90. Jg., S. 547-552)



## Fundamental/Modelling “RPT”:

✓ RPT observed in BAM tests spilling LH2 on water

(see van Wingerden, Kees, et al. "Experimental Investigation into the Consequences of Release of Liquified Hydrogen onto and under Water." (2022))

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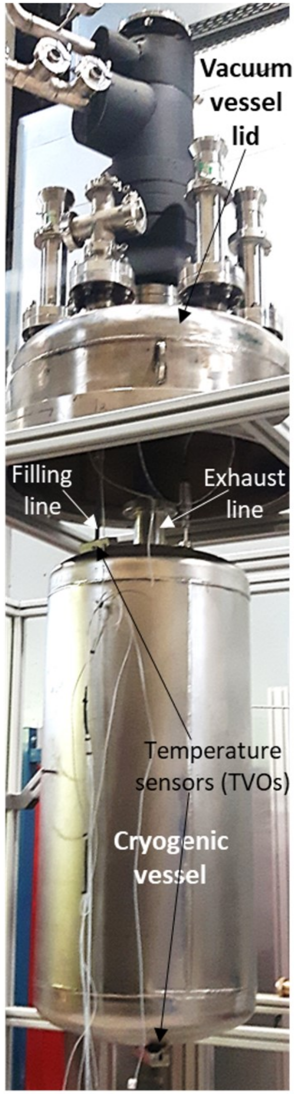
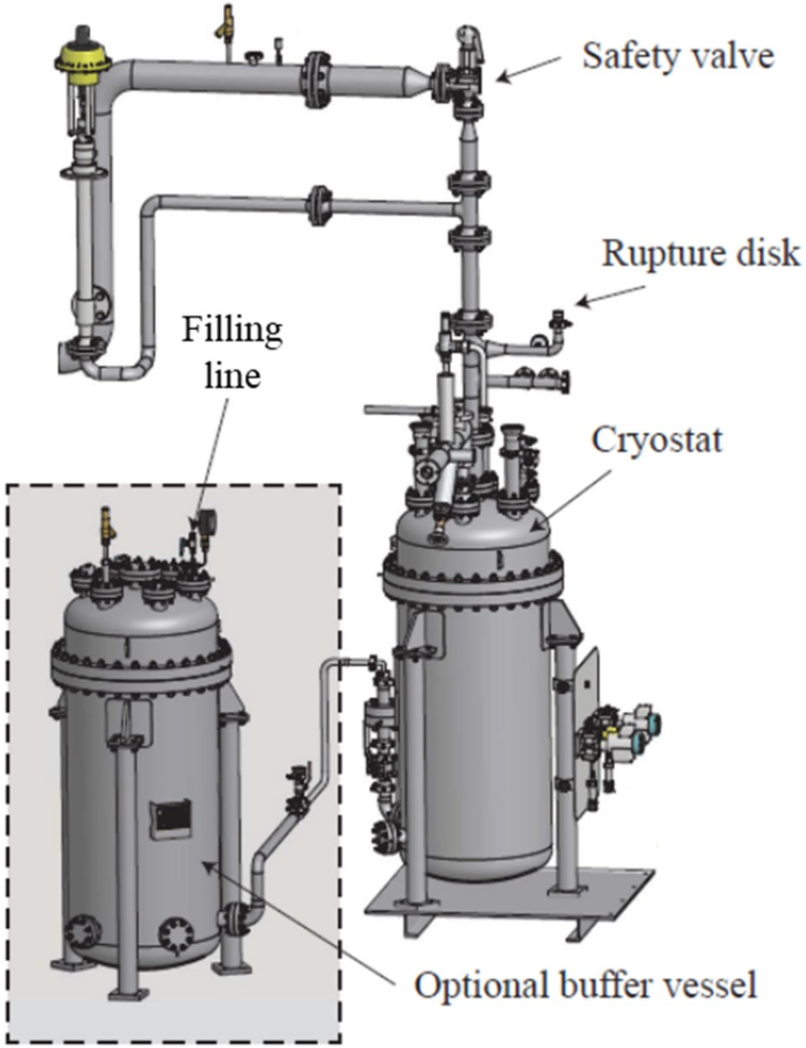
# Work in Progress at KIT




- ISO TR 15916 revised wrt LH2 / cryogenic hydrogen (TR → TS?)

## PICARD Facility

- Loss Of VAcuum (LOVA) experiments and heat transfer modelling
  →
  proper design and standards for safety valves,…

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# Objectives of French Project ESKHYMO

1. Quantifying the physical phenomena involved in a cryogenic tank consecutive to air ingress,
2. Understanding the kinetic of LH2 evaporation during spillage,
3. Predicting the size of flammable clouds in case of LH2 spillage,
4. Predicting the severity of ignition flammable clouds following a LH2 spillage.

# ELVHYS

Follow-up of PRESLHY

## About

**Funding programme**: Horizon Europe

**Budget**: 2.0 M€

**Duration**: 2023-2026 (36 months)

**Type**: Research & Innovation Action

**Objective**: provide indications on inherently safer and efficient cryogenic hydrogen transfer technologies and protocols in mobile applications by proposing innovative safety strategies including selection of effective safety barriers and hazard zoning strategies, which are the results of a detailed risk analysis.

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# ELVHYS

**Expected outcomes**

1. Detailed risk analysis for LH2 transferring operations for mobile applications (ships, trucks, stationary tanks) fillings
2. Generic hazard distances for LH2 transferring operations in the different applications, also addressing SimOps
3. Guidelines for design of LH2 transferring facilities
4. Consensual loading procedures for LH2 transferring operations
5. Provide inputs for developing Standards, Technical Specifications, or Technical Reports at the international level

# ELVHYS – Consortium

ELVHYS

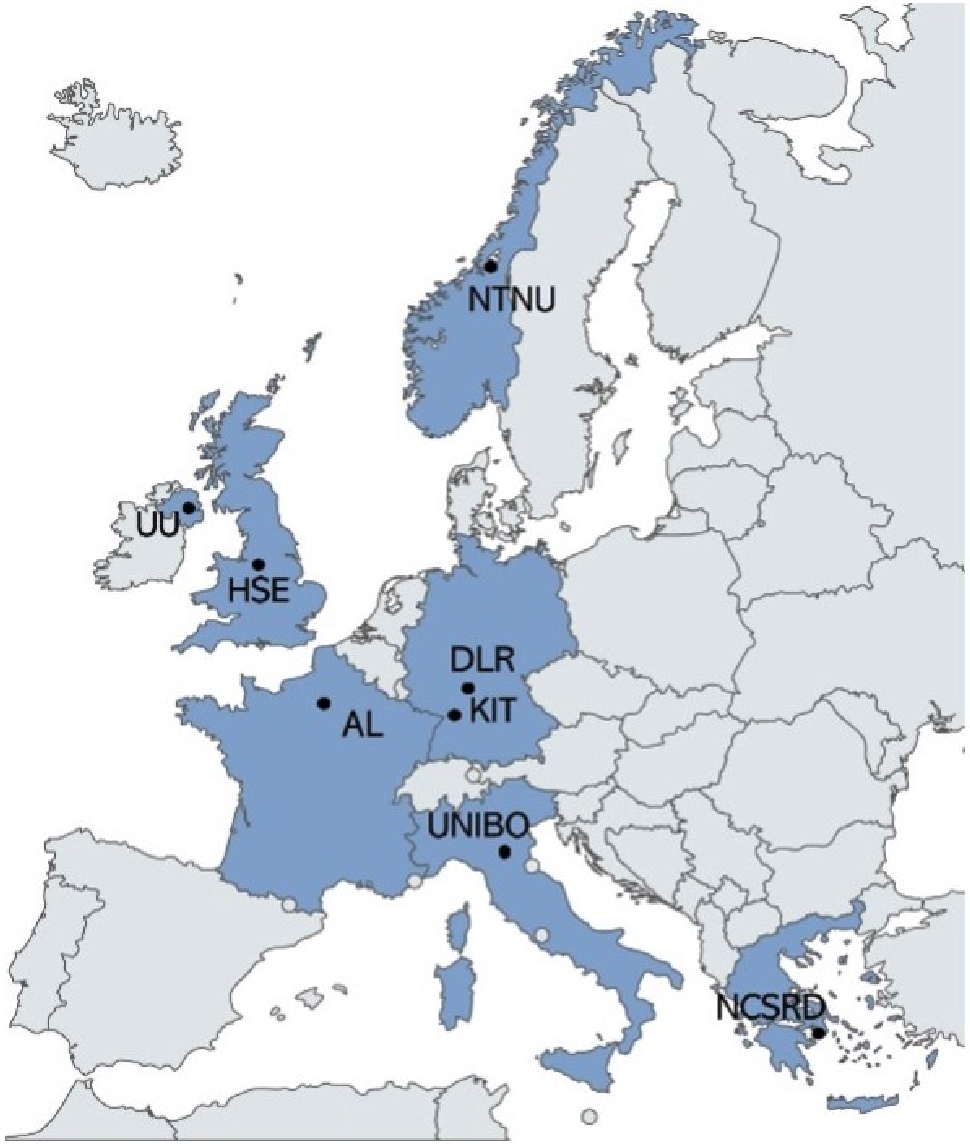
NTNU (Coordinator)

Ulster University

DEMOKRITOS

HSE

Air Liquide



# ELVHYS – Stakeholder Advisory Board

| No | Organization | Type | Country |
|---|---|---|---|
| 1 | International Association for Hydrogen Safety (HySafe) | Association | Belgium |
| 2 | IEA | Intergovernmental org. | --- |
| 3 | Hydrogen Council | Industry organization | --- |
| 4 | Sandia National Laboratory | Research center | USA |
| 5 | Kawasaki Heavy Industries | Industry | Japan |
| 6 | Daimler | Industry | Germany |
| 7 | Airbus | Industry | France |
| 8 | University of Trieste | University | Italy |
| 9 | DNV | Certification body | Norway/UK |
| 10 | HYEX | Company | Norway |
| 11 | Norled | Company | Norway |
| 12 | University of Salerno | University | Italy |
| 13 | ISPRA - Italian National Institute for Environmental Protection and Research | Public body | Italy |
| 14 | PPG | Company | UK |
| 15 | RIVM - the Netherlands National Institute for Public Health and the Environment, Centre for Environmental Safety and Security | Public body | The Netherlands |
| 16 | SNCF - DIRECTION TECHNOLOGIES, INNOVATION ET PROJETS GROUPE (rail operator) | Operator | France |

Drop an email if you would like to join the ELVHYS SAB

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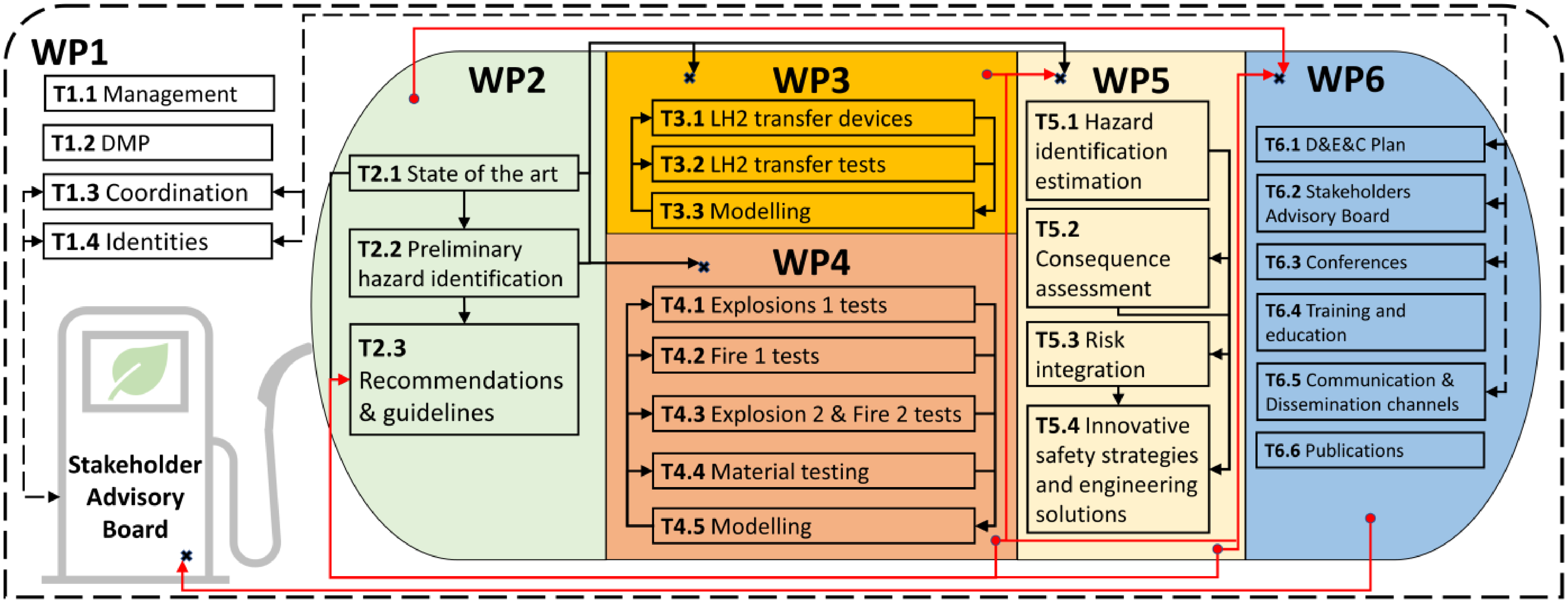
# ELVHYS – Collaboration with other projects

Intention to establish collaborations with other projects related to LH2 and cryogenic hydrogen transfer and storage

- **STACY** - Towards Safe Storage and Transportation of Cryogenic Hydrogen (EIG Concert Japan, 2022-2026, coordinator: Ernst-Arndt Reinecke, Julich, Germany)
- **MF Hydra** (LH2 ferry, Norway, Norled)
- **ESKHYMO** - Enhance Safety Knowledge for Hydrogen Measurements/Modelling in cryOgenic phase (France, 2022-2026, coordinator: Etienne Havret, CEA, France)

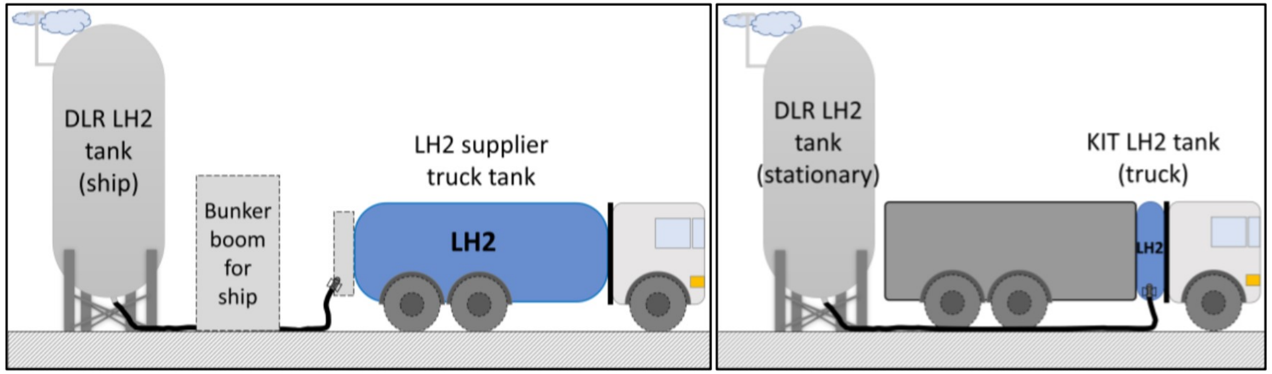
# ELVHYS – Work Plan



# ELVHYS – Tasks

**WP3 - Cryogenic hydrogen transfer facilities performance**

- **Task 3.1** - LH2 transfer devices definition
- **Task 3.2** - LH2 transfer tests: bunkering, fuelling, refuelling, defueling
- **Task 3.3** - Support by theoretical and numerical studies for experimental setup, and numerical experiments to formulate cryogenic hydrogen transfer protocols



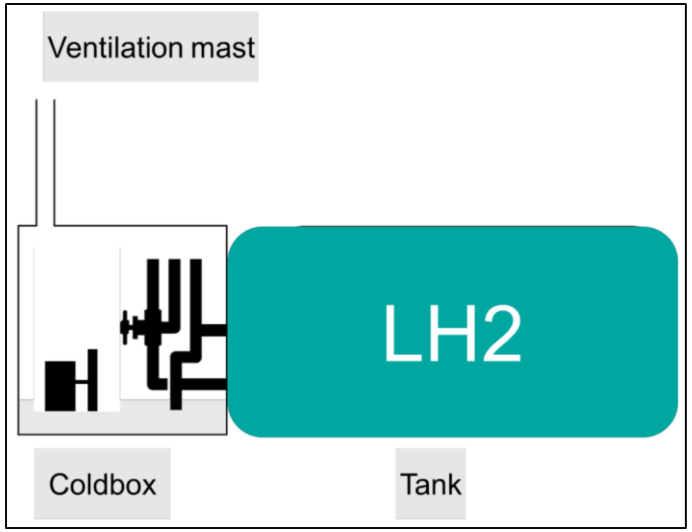

**Tests will be carried out by DLR**

# ELVHYS – Tasks

## WP4 - Fires and explosions from cryogenic hydrogen transfer facilities

- **Task 4.1** – Oxygen enrichment and condensed phase explosions
- **Task 4.2** – Leakage into cold room/tank connection space considering barriers and obstacles

HSE test (Hooker et al., 2012)





DNV test (Aaneby et al., 2021)

**Tests will be carried out by HSE**

# ELVHYS – Tasks

**WP4 - Fires and explosions from cryogenic hydrogen transfer facilities**

- **Task 4.3** – Performance of LH2 components and explosion consequences
- **Task 4.4** – Material testing against unignited and ignited jets (MLI, glass spheres, perlite layers and fire protecting wall) according to ISO 20088
- **Task 4.5** – Modelling in support of and utilising WP4 experimental activities

**Tests will be carried out by KIT**

SH2IFT test (Ødegård et al., 2022)

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# ELVHYS – Tasks

**WP5 - Risk Analysis for selected cryogenic hydrogen transferring operations**

- **Task 5.1** – Hazard identification and damage state estimation
  - Sub-Task: 5.1.1 Hazard identification
  - Sub-Task: 5.1.2 Damage state of the installation resulting in the release of hydrogen
- **Task 5.2** – Consequence assessment
  - Sub-Task: 5.2.1 Modelling of accidental phenomena
  - Sub-Task 5.2.2: Vulnerability assessment
- **Task 5.3** – Frequency assessment and risk integration
  - Sub-Task: 5.3.1 Frequency of incident occurrence
  - Sub-Task: 5.3.2 Risk integration
- **Task 5.4** – Innovative safety strategies and engineering solutions
  - Sub-Task: 5.4.1 Safety barriers
  - Sub-Task: 5.4.2 Safety zoning strategies

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# Future work, open issues, priorities

SRC-01 call of the Clean Hydrogen Partnership AWP2023 (10 M€)

**Fundamental/Modelling:**

- Clarify **material issues** (metallic, non-metallic, additive manufactured) with cryogenic hydrogen
- Improve **thermodynamic modelling** in multiphase, non-equilibrium, close to critical conditions and reaction kinetics (< 200K)
- Determine **induction times** and **detonation cell sizes** (< 200K)

Partially addressed in ESKHYMO (F)

**Mixing phenomena:**

- **Multiphase effects** on large scale mixing with obstruction +(partial) confinement (underground storage)

**Combustion phenomena:**

- Broader assessment of **transients** FA and DDT for varying congestion &confinement at larger scale
- Evaluation of **detonation potential of solid $O_2$** in $LH_2$ pools
- Scaling of **BLEVE**s and transients like pseudo-boiling

Addressed in ELVHYS

**Risk assessment and mitigation strategies:**

- Safe **transfer** protocols (fast filling, large inventories, flash gas management,...)
- Proper **design and approval of safety valves and heat insulation** (e.g. for LOVA)
- Integral (applied) tests (dispersion and combustion in closed rooms) for **mitigation strategies** (**ventilation**, water sprays, etc.) including **sensor** placement and performance
- **Crash test** for vehicle tank systems (sloshing, pulsed loads on close to critical inventory)
- Safety of LH2 cooled superconductors

# Thank you for your attention

thomas.jordan@kit.edu

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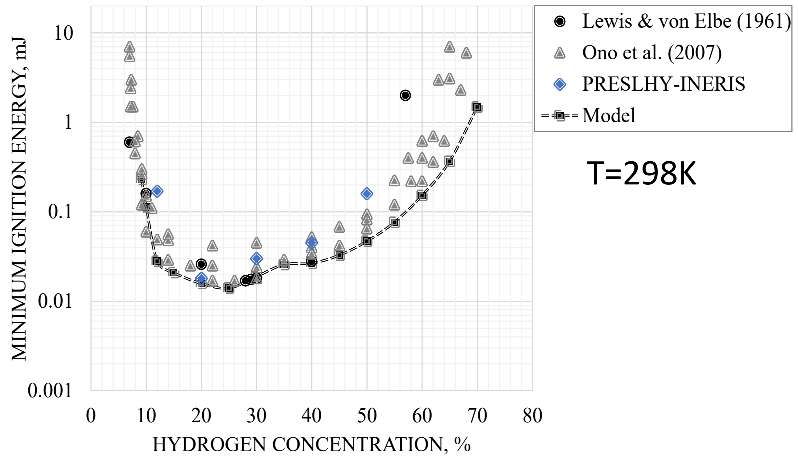
# Correlations for Ignition of Cryogenic Hydrogen

**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
- Account of flame stretch and preferential diffusion



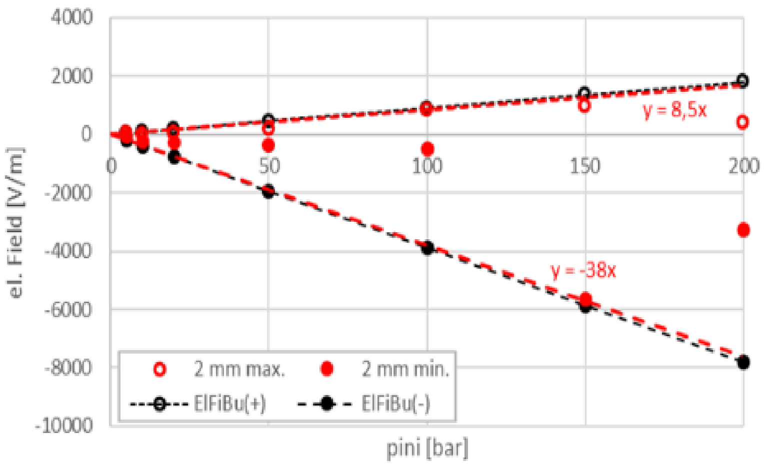

T=298K

**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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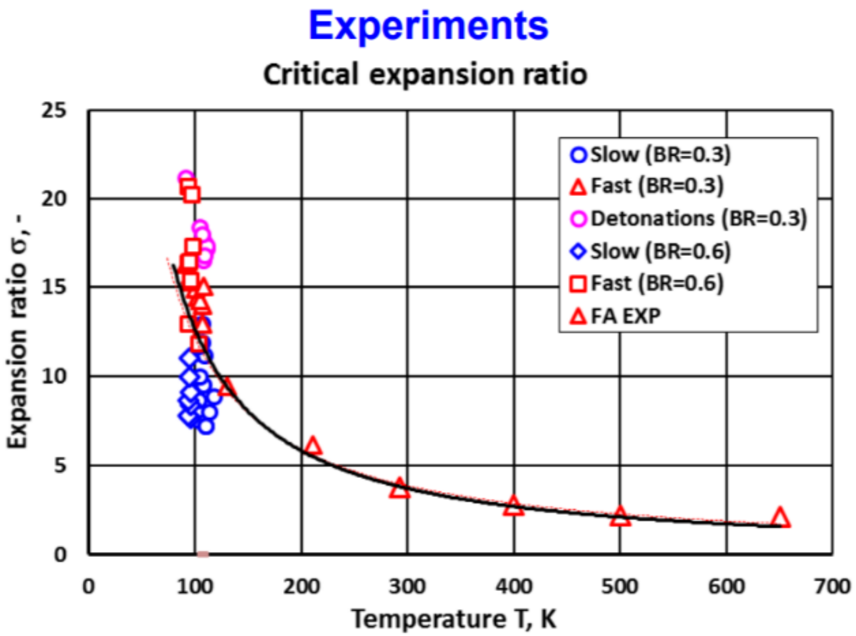
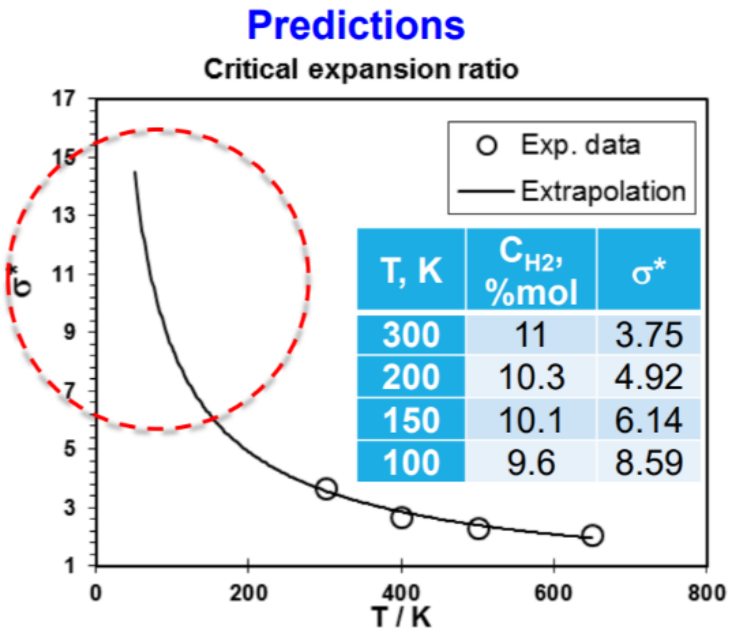
# Critical Expansion Ratio for FA




| 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*(100K) = 12.5
- Approximation line as a function of initial temperature can be used $\sigma^*(T) = \sigma^*(T_0) \cdot \left(\frac{T_0}{T}\right)$ or more simplified relation $\sigma^* = 2200 \cdot T^{-1.12}$ (more conservative with σ*(100K) = 11 instead of experimentally determined value)

# ELVHYS – Work Plan

**Work Packages**

- WP1 - Project Management and Coordination
- WP2 - From industrial background and strategy to findings application
- WP3 - Cryogenic hydrogen transfer facilities performance
- WP4 - Fires and explosions from cryogenic hydrogen transfer facilities
- WP5 - Risk Analysis for selected cryogenic hydrogen transferring operations
- WP6 - Dissemination, exploitation and communication

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