Safety of liquified hydrogen systems and infrastructure

Prof. Dr.-Ing. Thomas JORDAN, Karlsruhe Institute of Technology
International School Progress in Hydrogen Safety,
11th-15th March 2019 / Ulster University, Belfast UK

PRESLHY

Pre-normative REsearch for Safe use of Liquid HYdrogen

Karlsruher Institut für Technologie
Air Liquide
HEALTH & SAFETY LABORATORY
hySafe
INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY
INERIS
Pro-Science
Ulster University
WARWICK
THE UNIVERSITY OF WARWICK

Outline

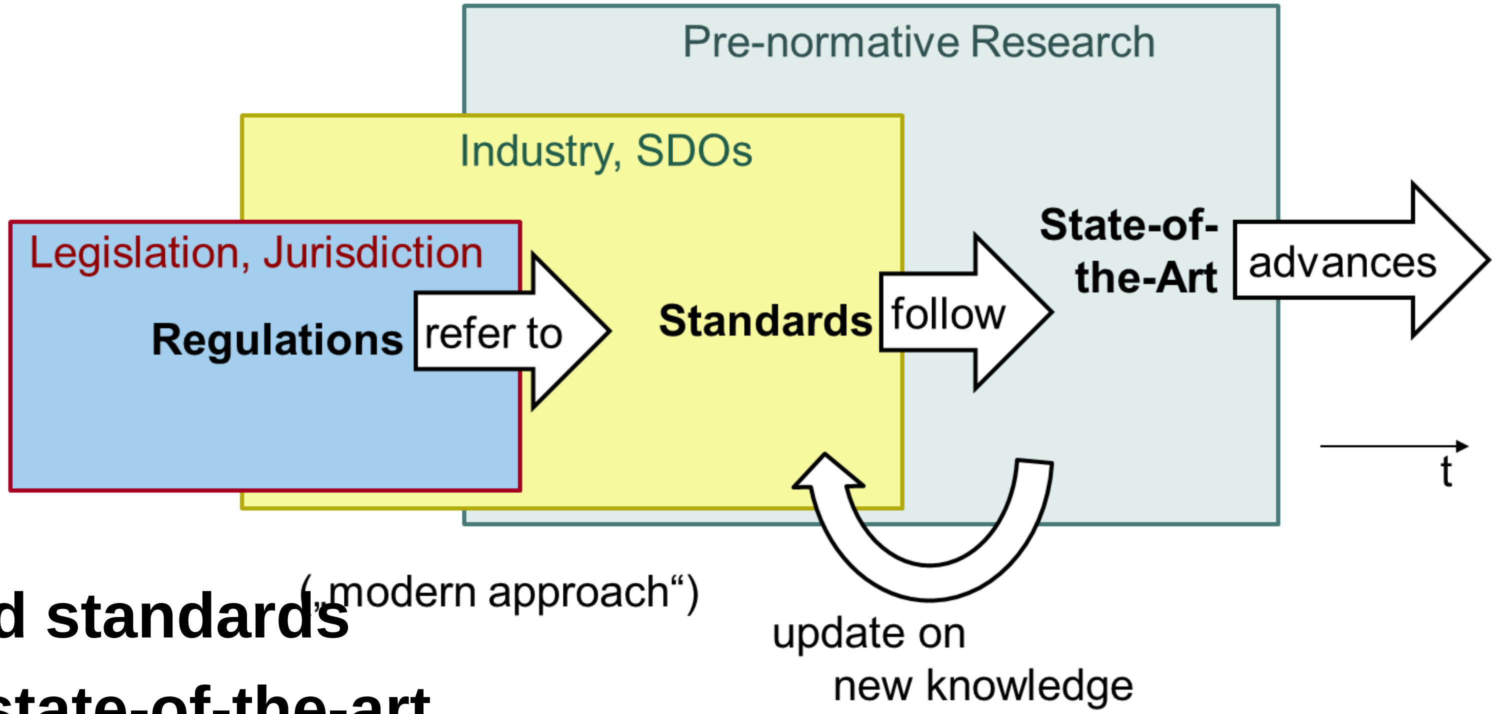
- Motivation
- PRESLHY Overview
- WP3 Release
- WP4 Ignition
- WP5 Combustion
- Exploitation
- Closure

Motivation

- Scale-up of existing and new applications increase demand.
- Liquid hydrogen (LH2) provides larger densities and gains in efficiency over gaseous transport and storage.
- The hazards and risks associated with LH2 are different from the relatively well-known compressed gaseous hydrogen (CGH2).
  (There are indications for reduced risk potential compared to CGH2)
- PRESLHY project addresses the pre-normative research for a safer use of cryogenic and liquid hydrogen as energy carrier.

PRESLHY Objectives

- Report **initial state-of-the-art and knowledge gaps** with priorities wrt intended use of LH2
- Execute adjusted **experimental program** addressing release, ignition and combustion phenomena with highest priorities
- Document and publish detailed, aggregated and interpreted data in a FAIR way
- Develop **suitable models and engineering correlations** and integrate them in a suitable open risk assessment toolkit
- Provide **enhanced recommendations for safe design and operations** of LH2 technologies
- **Support international SDOs** in
  - **updating of existing standards** or
  - developing of **new international performance based and risk informed standards**
- Document and disseminate the **enhanced state-of-the-art**



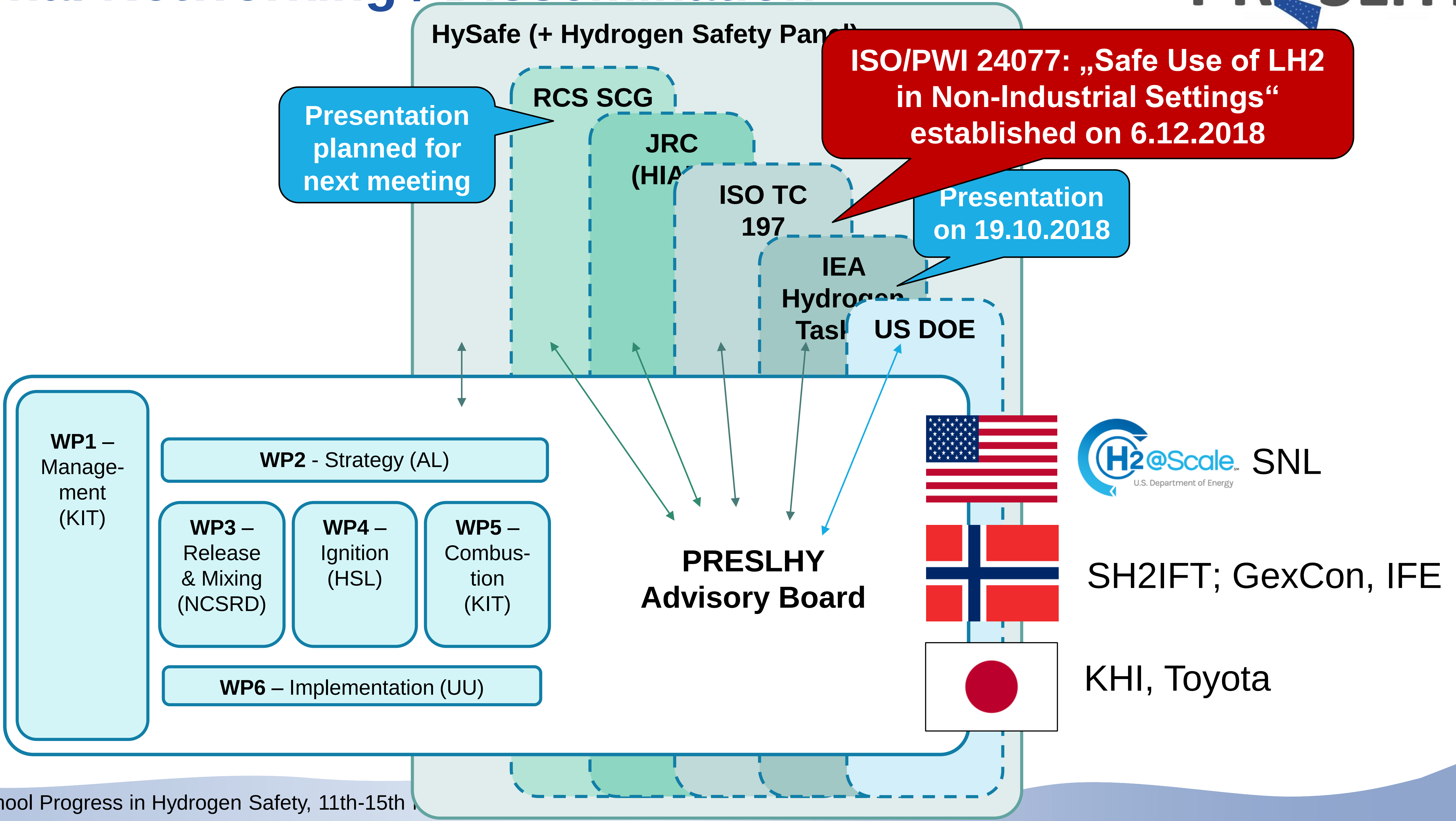
Partners & Advisors

Participant organisation name	Short name	Country
Karlsruhe Institute of Technology	KIT	Germany
Air Liquide	AL	France
Health & Safety Laboratory	HSL	United Kingdom
International Association for Hydrogen Safety	HYSAFE	Belgium
INERIS	INERIS	France
National Center for Scientific Research “Demokritos”	NCSRD	Greece
Pro-Science GmbH	PS	Germany
University of Ulster	UU	United Kingdom
The University of Warwick	UWAR	United Kingdom

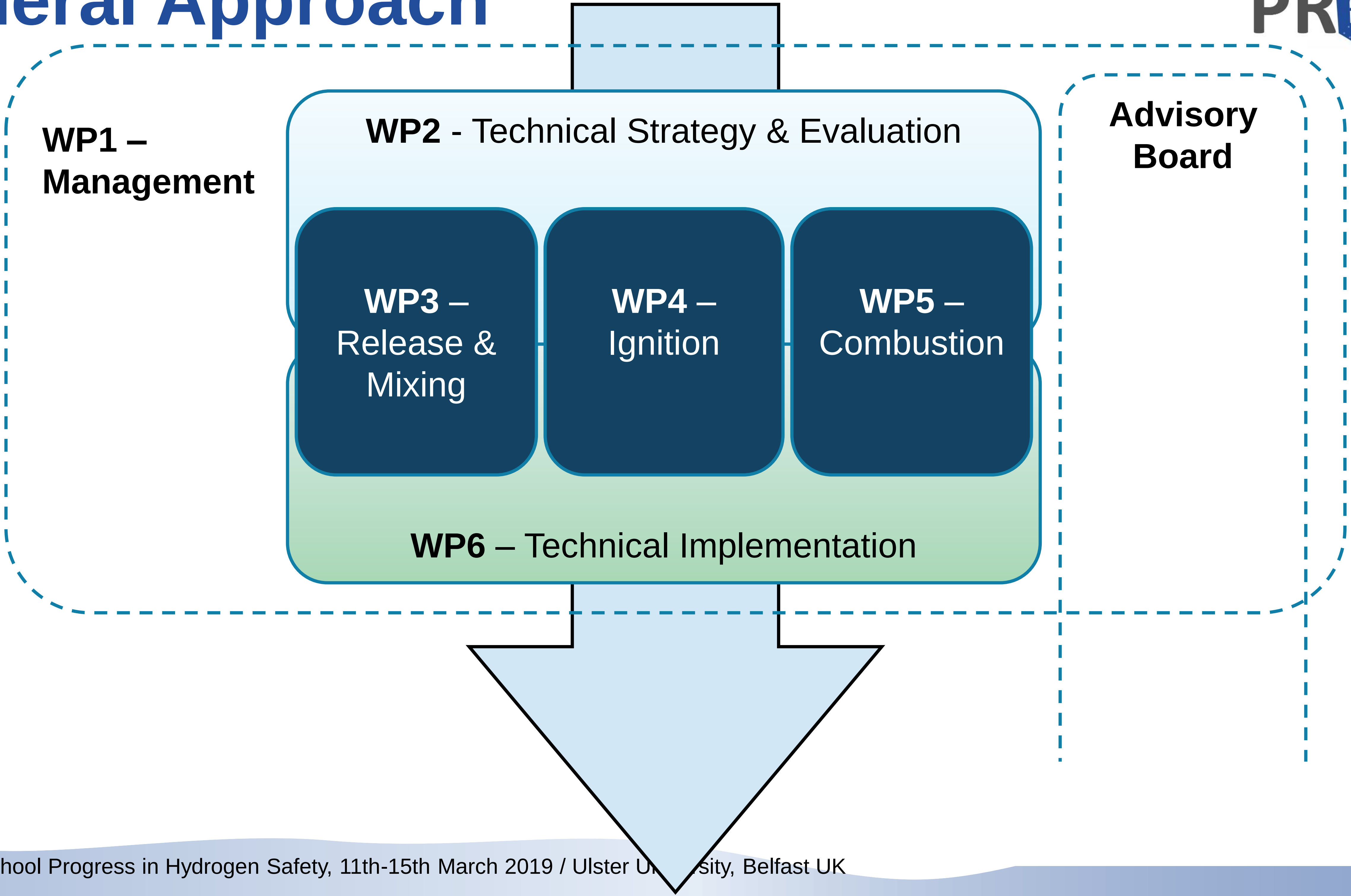
Advisor name	Company Institution	Nation
Derek Miller	Air Products	US
Andrei Tchouvelev	AVT	CAN
Klaus Schäfer	DLR	D
Franz Grafwallner	ET	D
Trygve Skjold	GexCon	N
Karl Verfondern	Jülich	D
Shoji Kamiya	KHI	JP
Salvador Aceves	LLNL	US
Lee Philips	Shell	UK
Ethan Hecht	SNL	US
Christoph Haberstroh	Uni Dresden	D
Olav Hansen	Loyds	N
Gerd-Michael Würsig	*DNV GL*	*D*
Pietro Moretto	*JRC*	*NL*
Volker Schröder	*BAM*	*D*
Steve Woods	*NASA*	*US*

PRESLHY

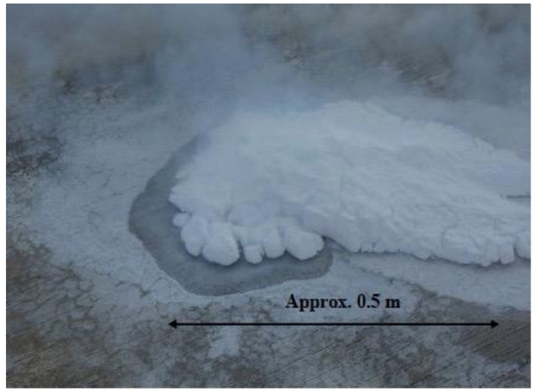
External Networking / Dissemination

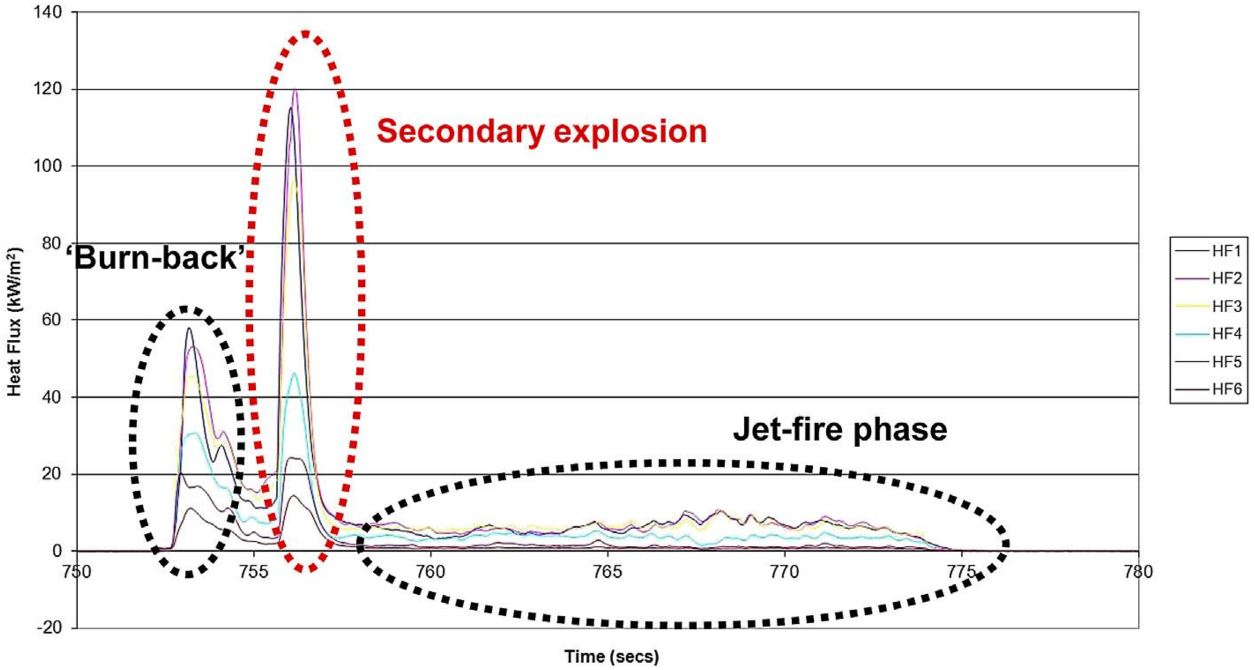


General Approach



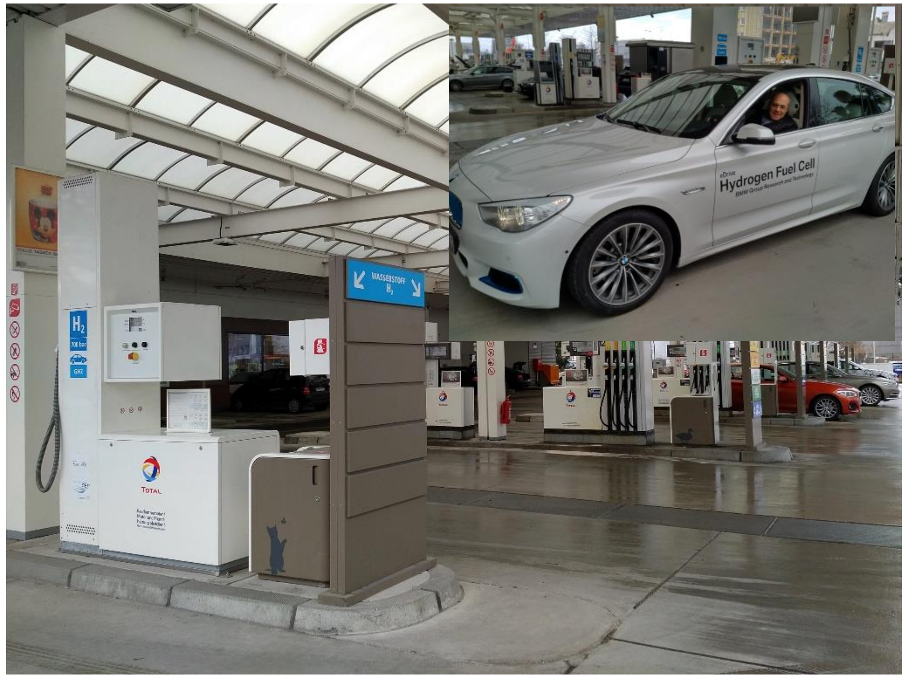
Visuals for RCS Priority Topics

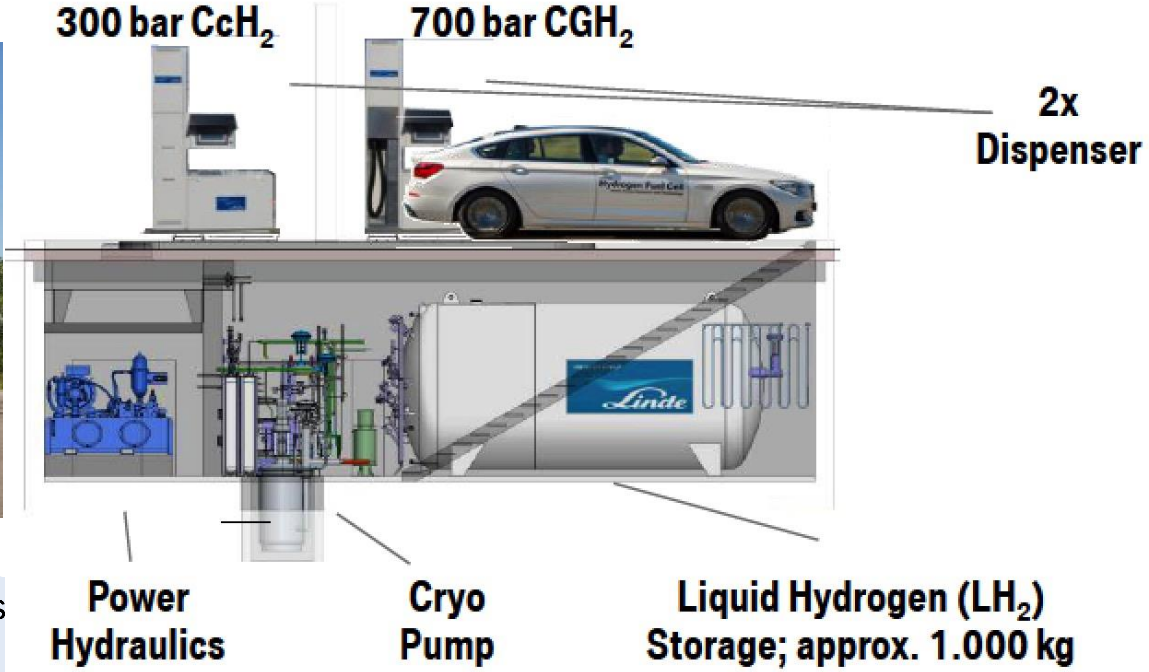




RCS- Visuals for LH2 Separation Distances

Density LH_2 / CGH_2 (@35MPa) → **4 t LH_2** vs. **0,5t CGH_2** per trailer
Temperature -250°C → **Cooling capacity** at filling station
Liquid Phase → **Transfer from vessel to vessel** w/o loss of expended energy (e.g. pressurization)





PRESLHY

RCS Status - NFPA2:2016 LH_2 Separation Distances

Table 8.3.2.3.1.6(A) Minimum Distance from Bulk Liquefied Hydrogen [LH_2] Systems to Exposures

Type of Exposure	Total Bulk Liquefied Hydrogen [LH_2] Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
	ft	m	ft	m	ft	m
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air conditioning equipment (HVAC, compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6
Group 3						
7. Building or structure						
(a) Buildings constructed of noncombustible or limited-combustible materials						
(1) Sprinklered building or structure or unsprinklered building or structure having noncombustible contents	5[a]	1.5	5[a]	1.5	5[a]	1.5
(2) Unsprinklered building or structure with combustible contents						
(i) Adjacent wall(s) with fire resistance rating less than 3 hours	25	7.6	50	15	75	23
(ii) Adjacent wall(s) with fire resistance rating of 3 hours or greater[b]	5	1.5	5	1.5	5	1.5
(b) Buildings of combustible construction						
(1) Sprinklered building or structure	50	15	50	15	50	15
(2) Unsprinklered building or structure	50	15	75	23	100	30.5
8. Flammable gas storage or systems (other than hydrogen) above or below ground	50	15	75	23	75	23
9. Between stationary liquefied hydrogen containers	5	1.5	5	1.5	5	1.5
10. All classes of flammable and combustible liquids (above ground and vent or fill openings if below ground)[c]	50	15	75	23	100	30.5
11. Hazardous materials storage or systems including liquid oxygen storage and other oxidizers, above or below ground	75	23	75	23	75	23
12. Heavy timber, coal, or other slow-burning combustible solids	50	15	75	23	100	30.5

Do these numbers make sense?

What are correct criteria / methodology?

RCS Status - EIGA Code of Practice for LH_2

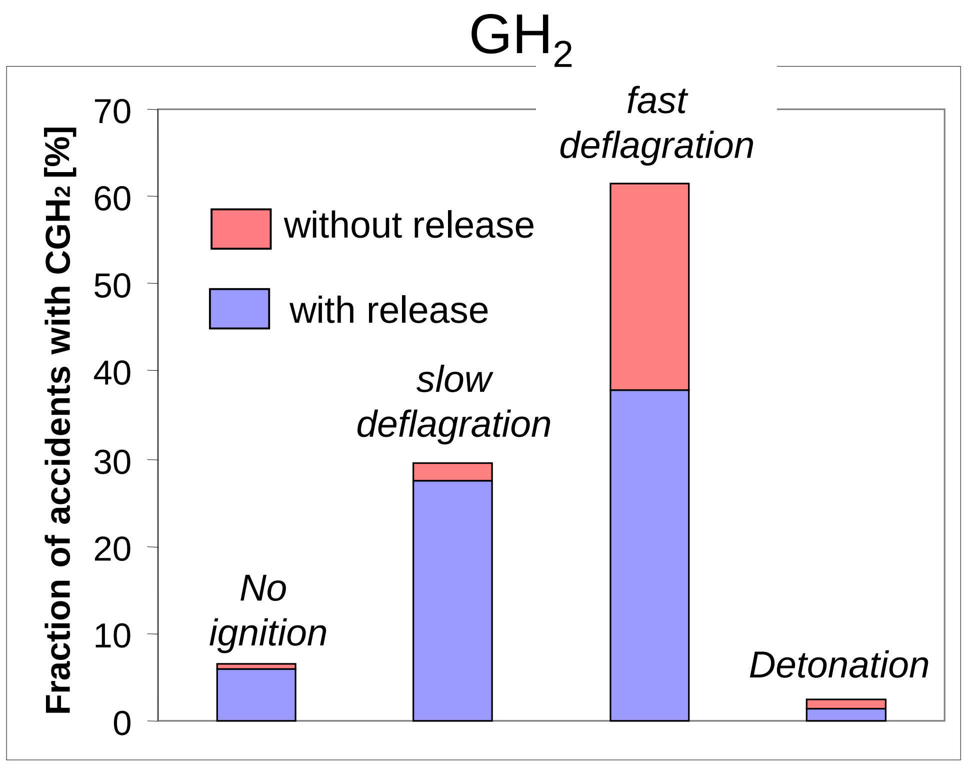
PRESLHY

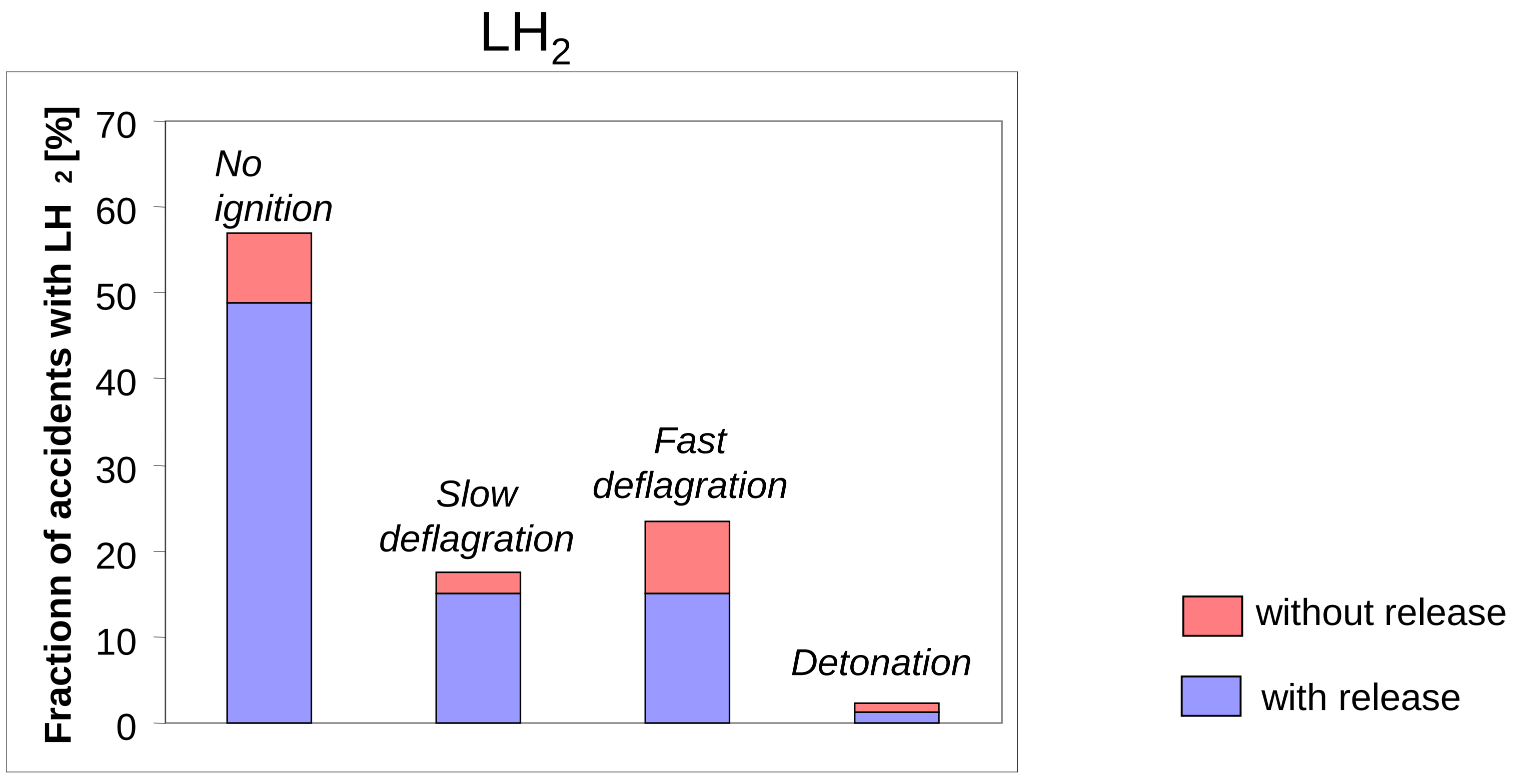
	ITEMS	DISTANCE (M)
1	90 min fire resistive walls	2.5
2	Technical and unoccupied buildings	10
3	Occupied buildings	20
4	Air compressor intakes, air conditioning	20
5	Any combustible liquids	10
6	Any combustible solids	10
7	Other LH2 fixed storage	1.5
8	Other LH2 tanker	3
9	Liquid oxygen storage	6
10	Flammable gas storage	8
11	Open flame, smoking, welding	10
12	Place of public assembly	20
13	Public establishments	60
14	Railroads, roads, property boundaries	10
15	Overhead power lines	10

Comparing CGH2 and LH2 Accident Consequences

PRESLHY

Observed phenomena (based on 287 accident reports analysed by Kreiser IKE 1994)



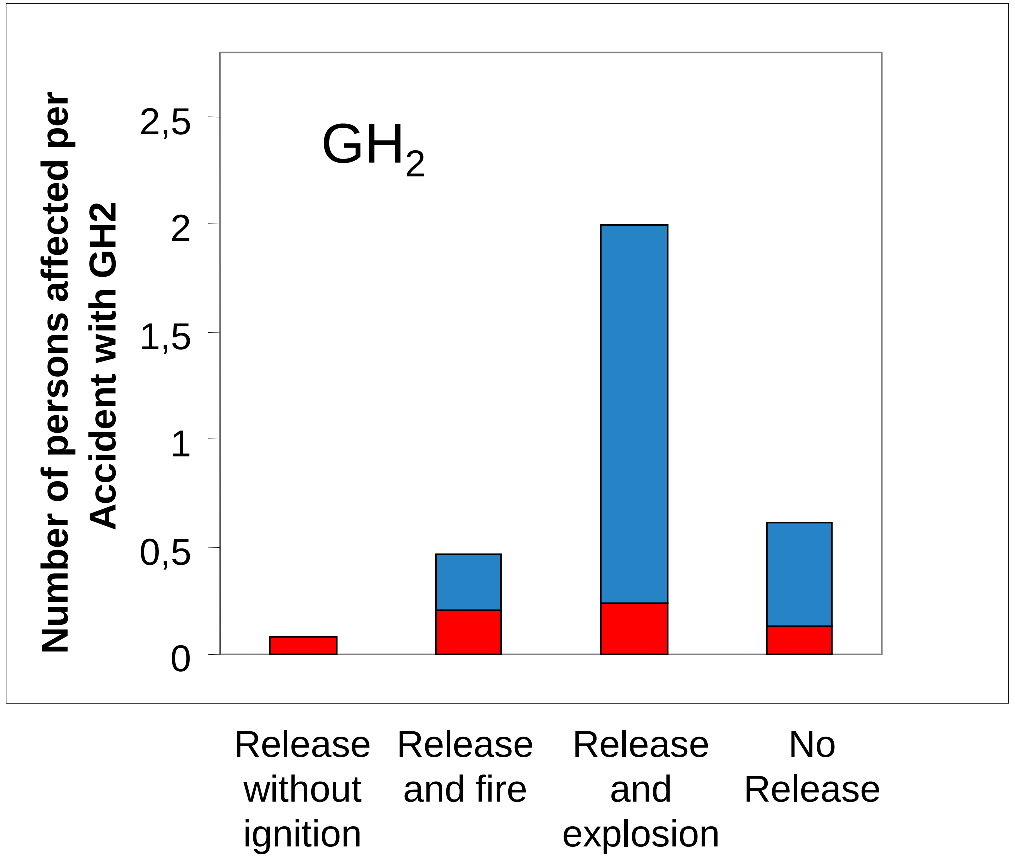


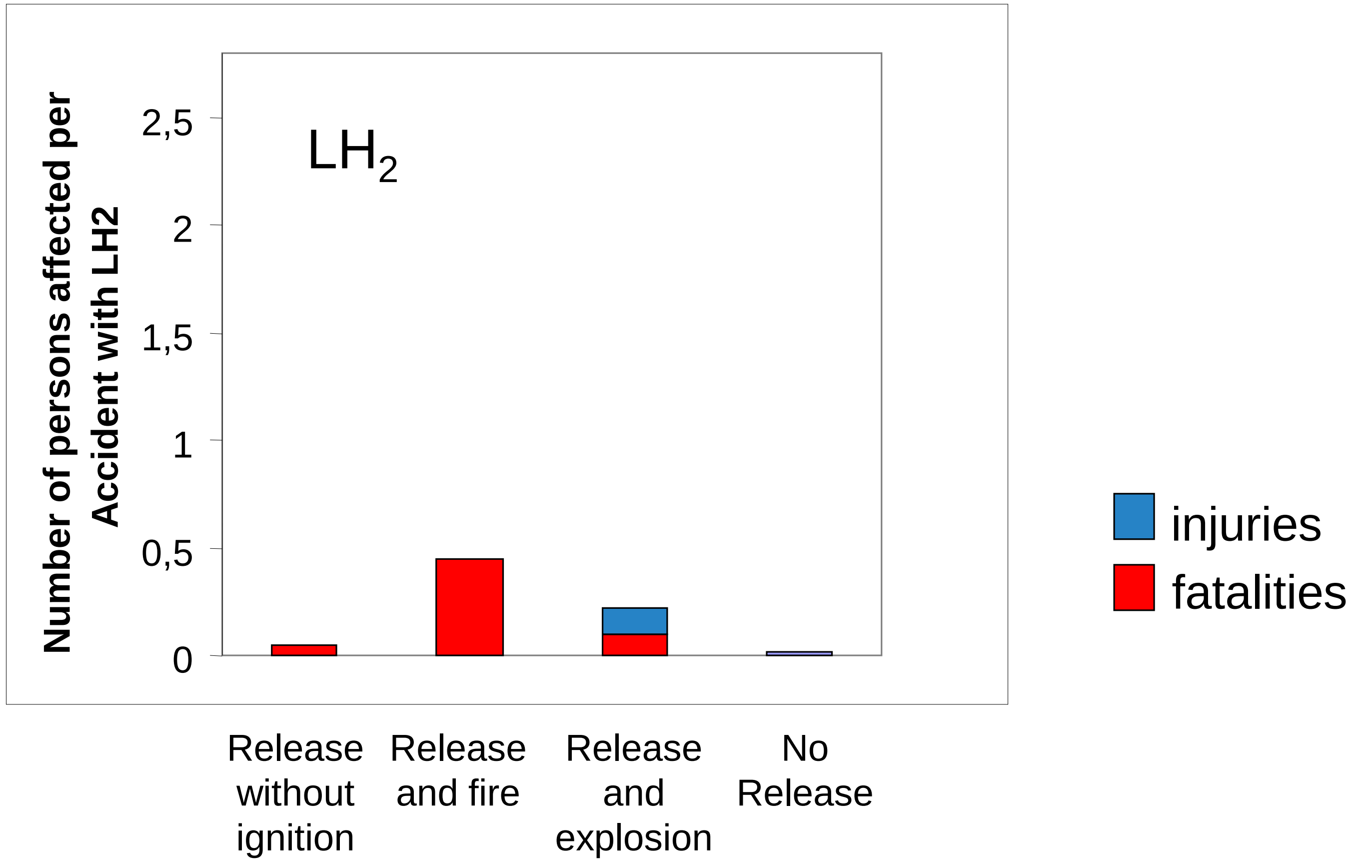
→ Majority of accidents with GH_2 lead to ignition and fast deflagrations
→ Accidents with LH_2 show considerably lower probability for ignition

Comparing CGH2 and LH2 Accident Consequences

PRESLHY

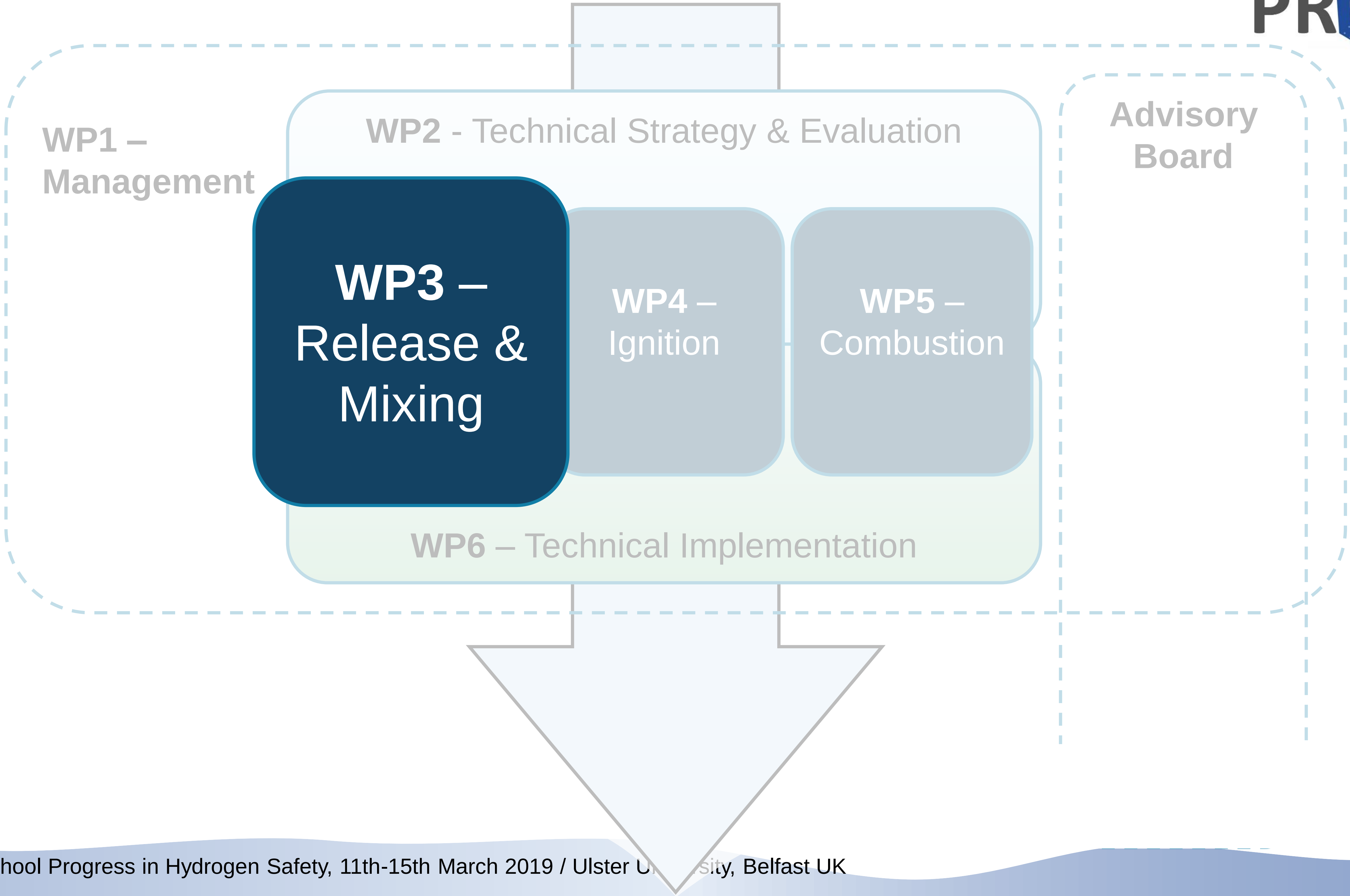
Effect on humans (287 accident reports analysed by Kreiser IKE 1994)





→ Far less injuries, similar amount of fatalaties with LH2

→ More systematic analysis required


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

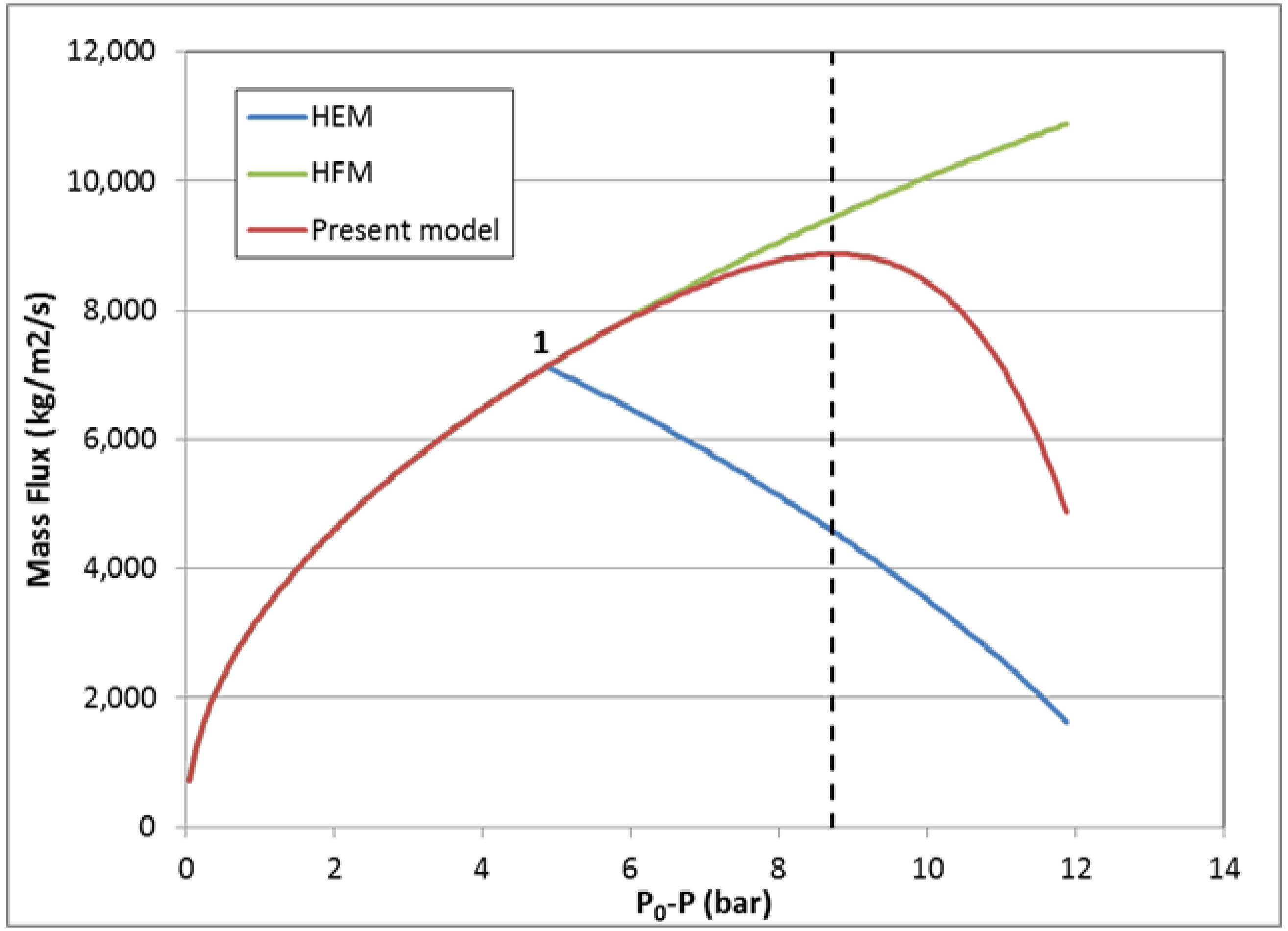
Gaps / Weak points wrt cryogenic H_2 release and dispersion

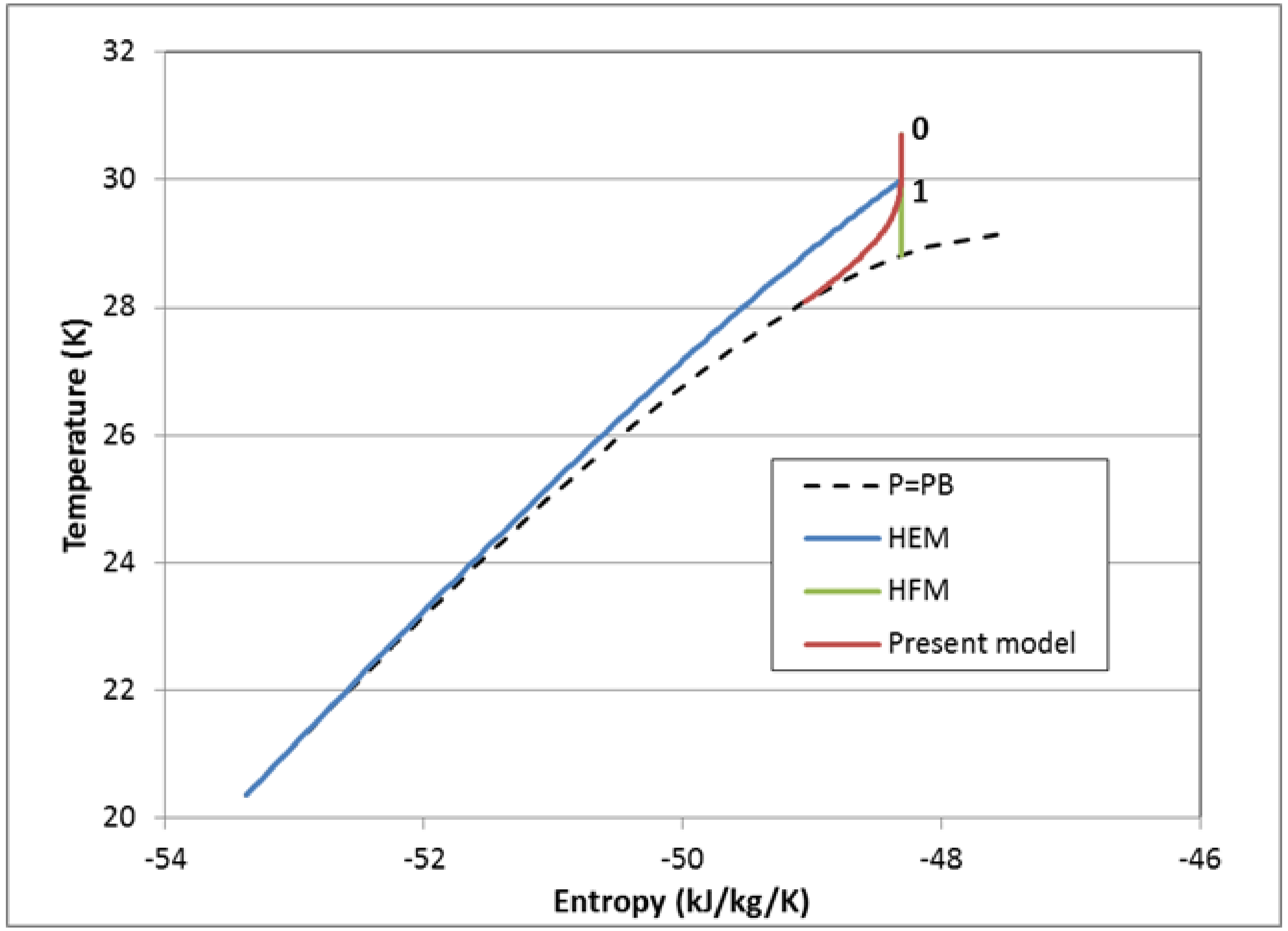
- Gaps
  - No experiments for under-expanded release & dispersion from LH_2 storage (saturated or sub-cooled conditions)
  - No Blowdown
  - No droplet size measurements
  - No velocities or fluctuations
  - Very limited structure of two-phase jets close to the release

- Weak points in many past experiments
  - Release momentum not measured
  - Uncertainty on the discharge rates
  - Large variability or limited info about meteorological conditions
  - Only few concentrations and temperatures

HEM / HNEM Two-Phase Choked Flow Modeling

e.g. NASA test 1197 (P_0=12.9 bar, T_0=30.7 K)





WP3 Experimental Activities

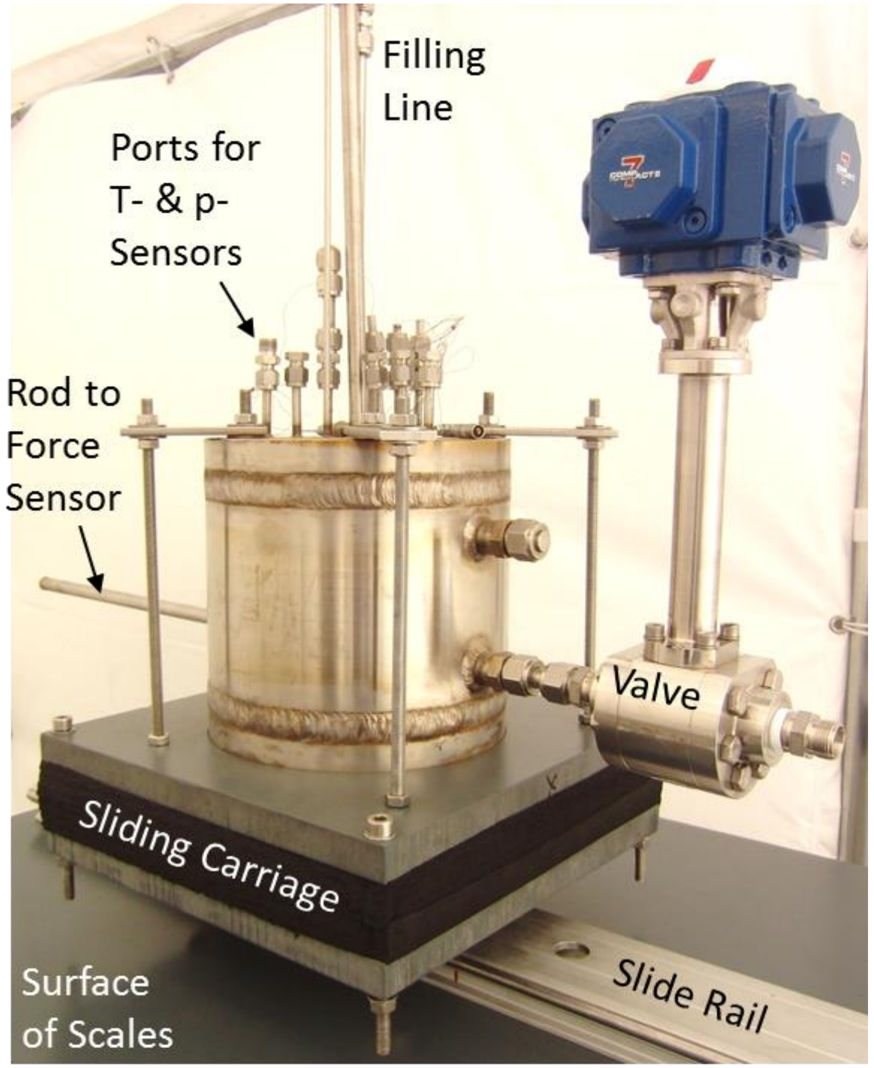
PRESLHY

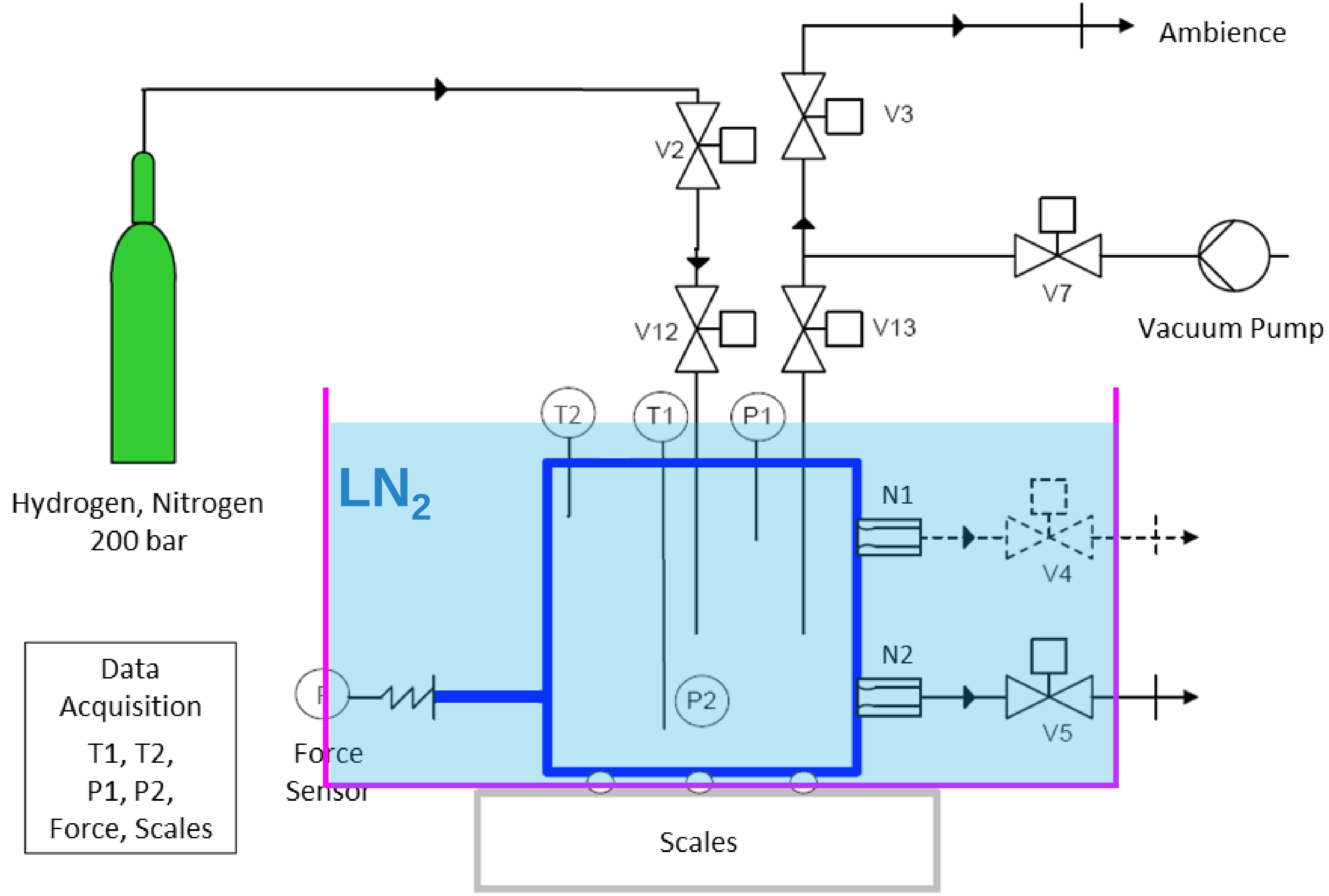
- KIT / PS
  - Design and set-up of tests E3.1, E3.4
- HSL
  - Design of tests E3.5
- INERIS
  - Sharing of existing LHe experiments data
  - Excluded tests
    - test 0 for no humidity info
    - tests 1,2 for too large wind variation
    - tests 7-9 for no H1, H2, L info
  - Tests 3 and 6 selected for validation

Issue n°	duration (s)	Mass flow rate (kg/s)	Wind speed (m/s) at 3 m height	Humidity (%)	Temp (°C)	H1 (m)	H2 (m)	L (m)
0	60	1,5	6	/	16	3	5	20
1	50	1,4	4,0±1,0	86	17	5	17	50
2	52	1,4	5,2±1,0	90	17	5	17	50
3	52	2,1	3,0±0,5	84	12	12	32	80
4	43	2,1	4,0±0,5	84	12	7	35	75
5	34	2,1	5,5±0,5	88	12	7	30	70
6	43	2,1	4,5±0,5	88	11	7	30	70
7	63	1,2	2,0±0,5	85	12			
8	65	1,2	2,0±0,5	85	12			
9	71	2,2	2,0±0,5	85	12			

L the length of the cloud on the ground
H_1 the height of the base of the cloud
H_2 the height at the top of the cloud.

E3.1 DISCHA-Facility Setup

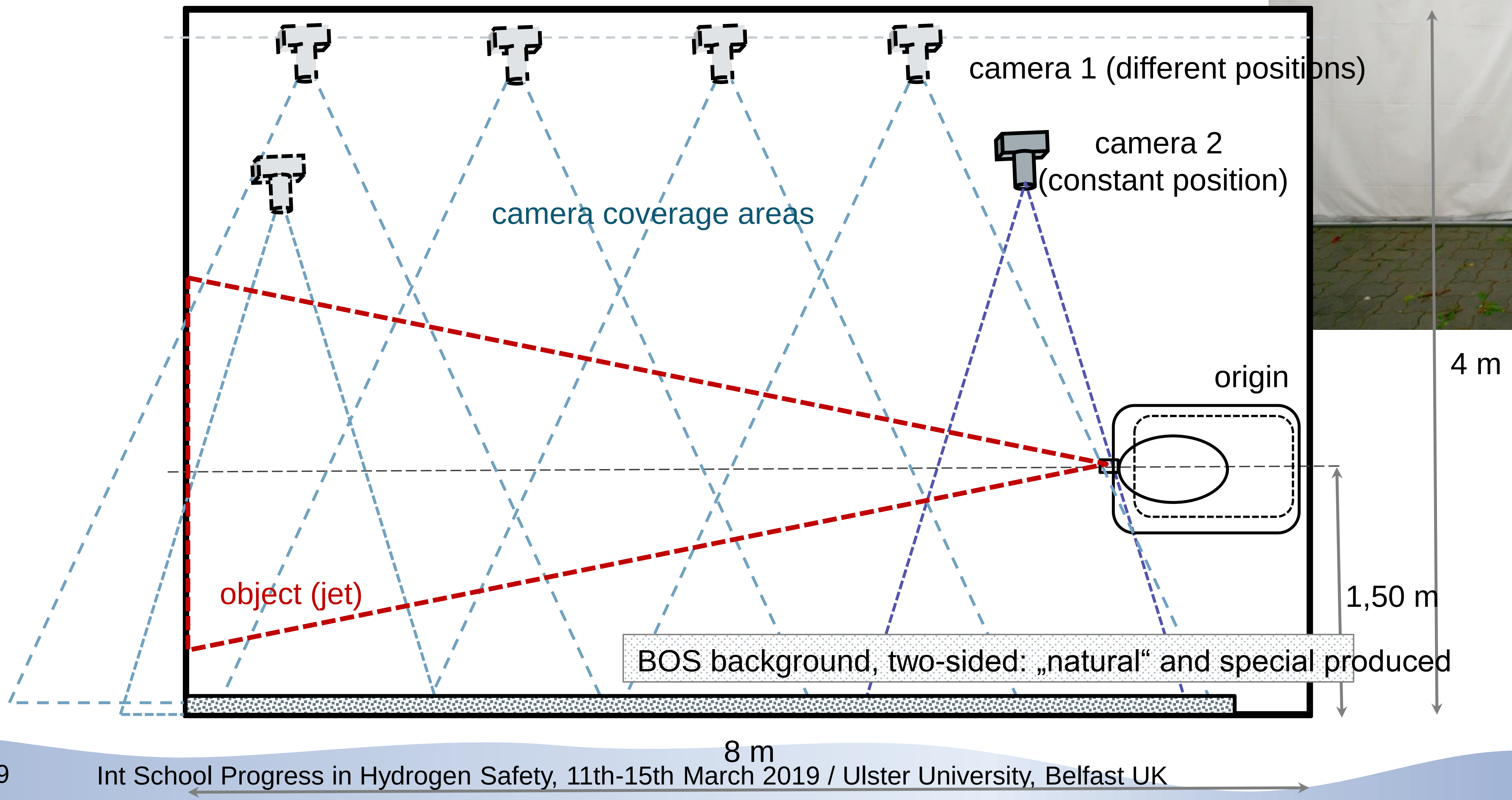




- Vessel and valve will be cooled from outside by LN2 pool (T_{min} = 77K)
- Release of cold CGH2 and LN2 from up to 20 MPa

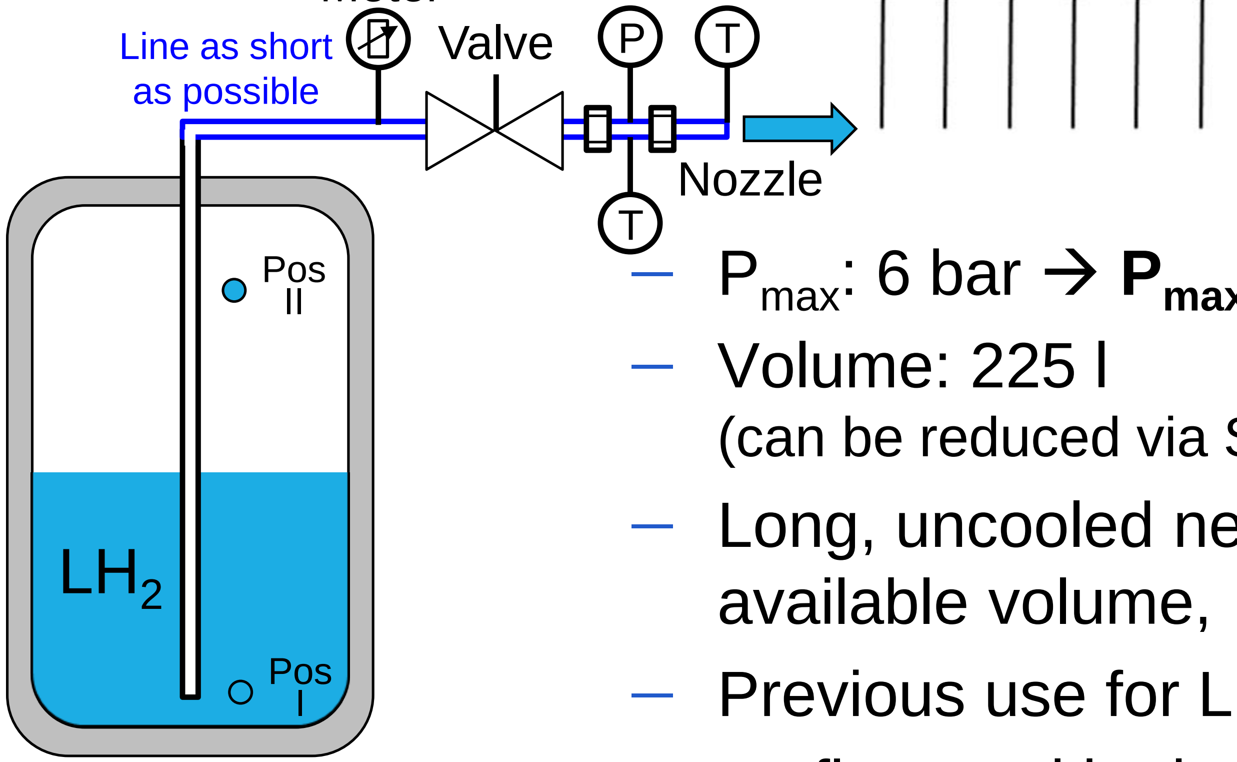
E3.1 DISCHA-Facility

Release experiments combined with near- and far-field optical measurements (BOS, laser, shadow,..) of mixing



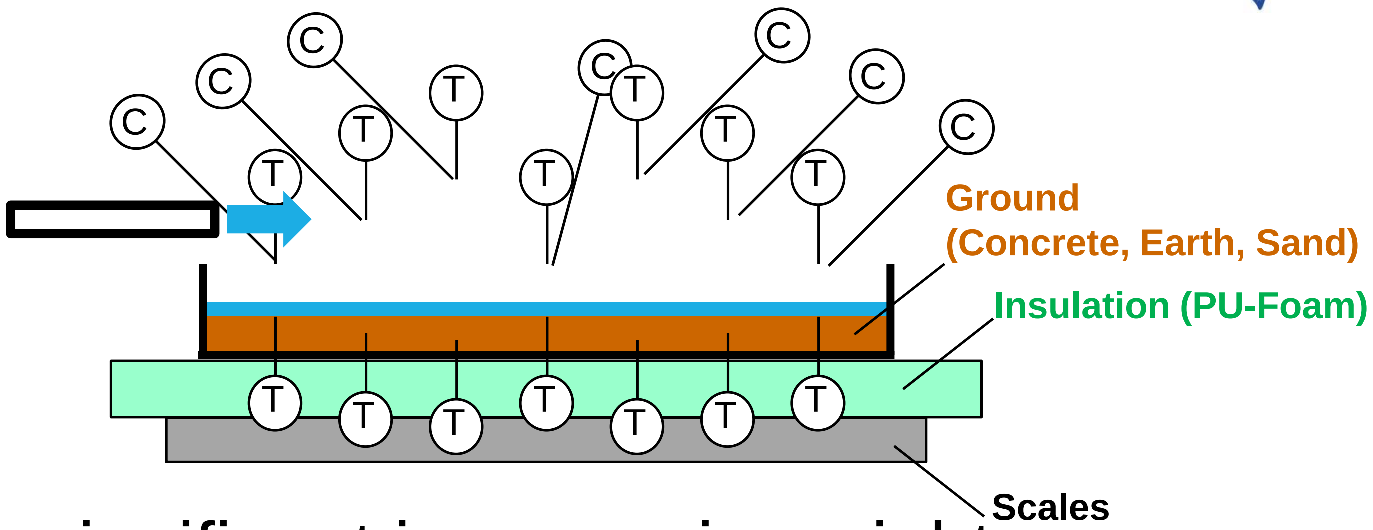
E3.1 CRYO-Vessel

- LN_2-shielded Cryo-vessel:

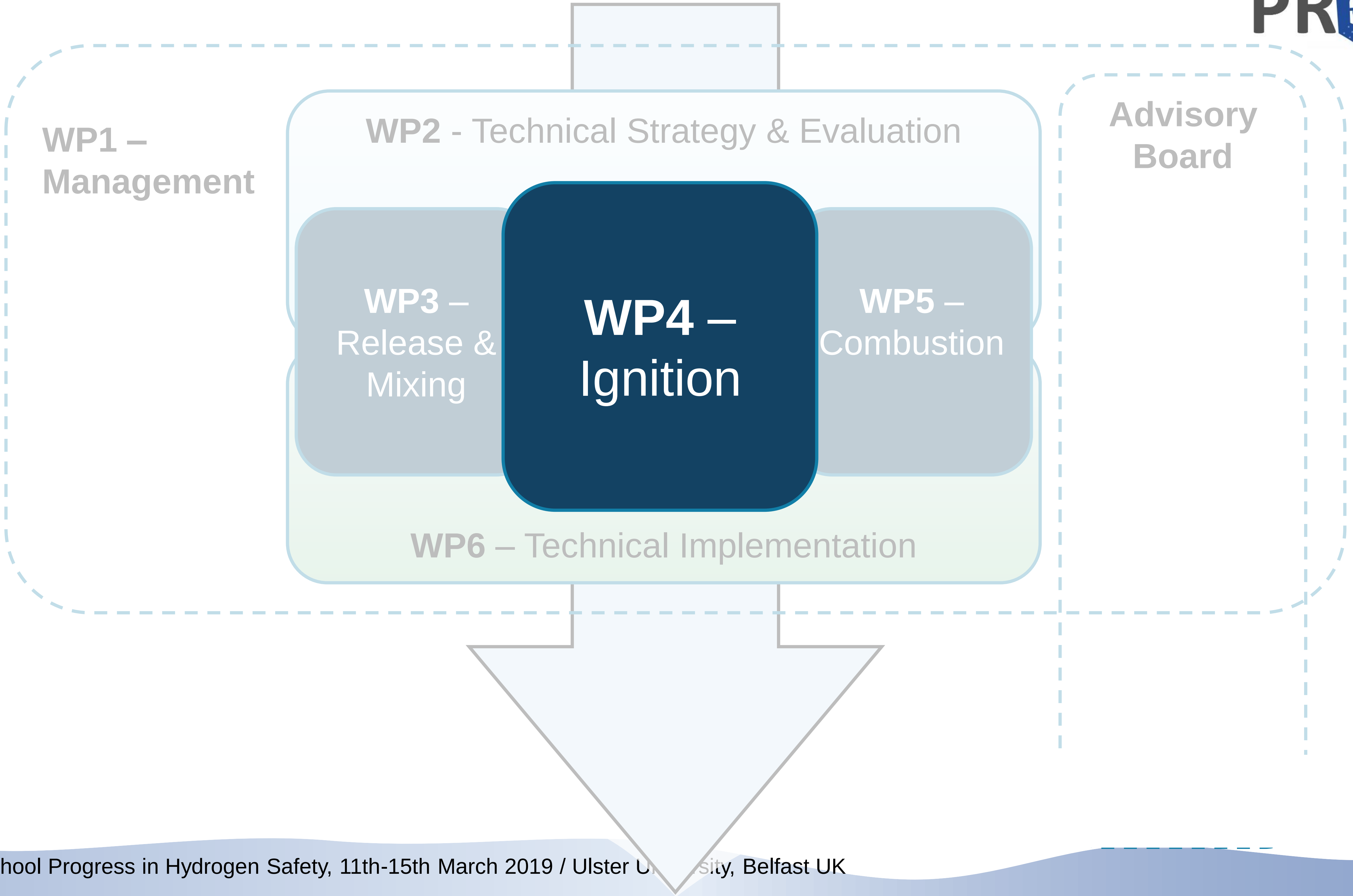


  - P_{max}: 6 bar → **P_{max}(exp): 5 bar**
  - Volume: 225 l (can be reduced via Styrofoam rings),
  - Long, uncooled neck further reduces available volume,
  - Previous use for LHe
  - top flange with pipework, controls under construction,
  - safety valves replaced,
  - safety check by TÜV Süd scheduled.

E3.4 Pool-Facility / Planned Experiments

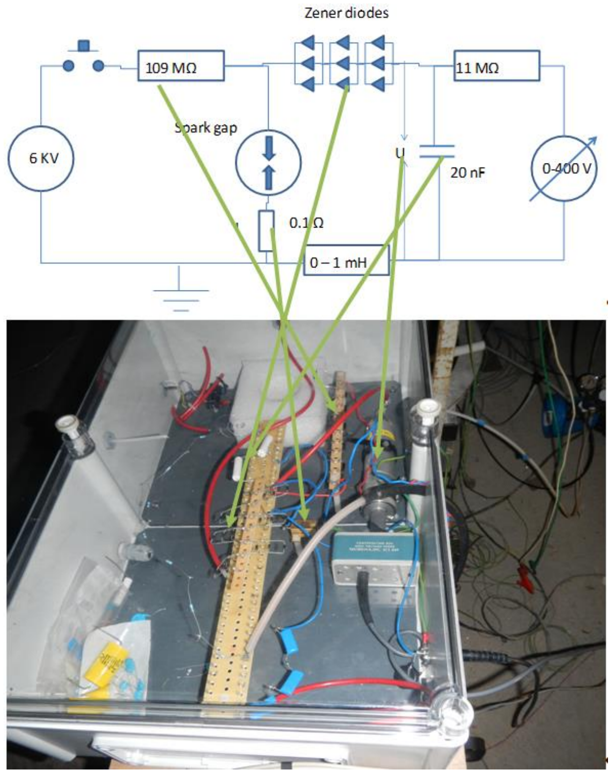


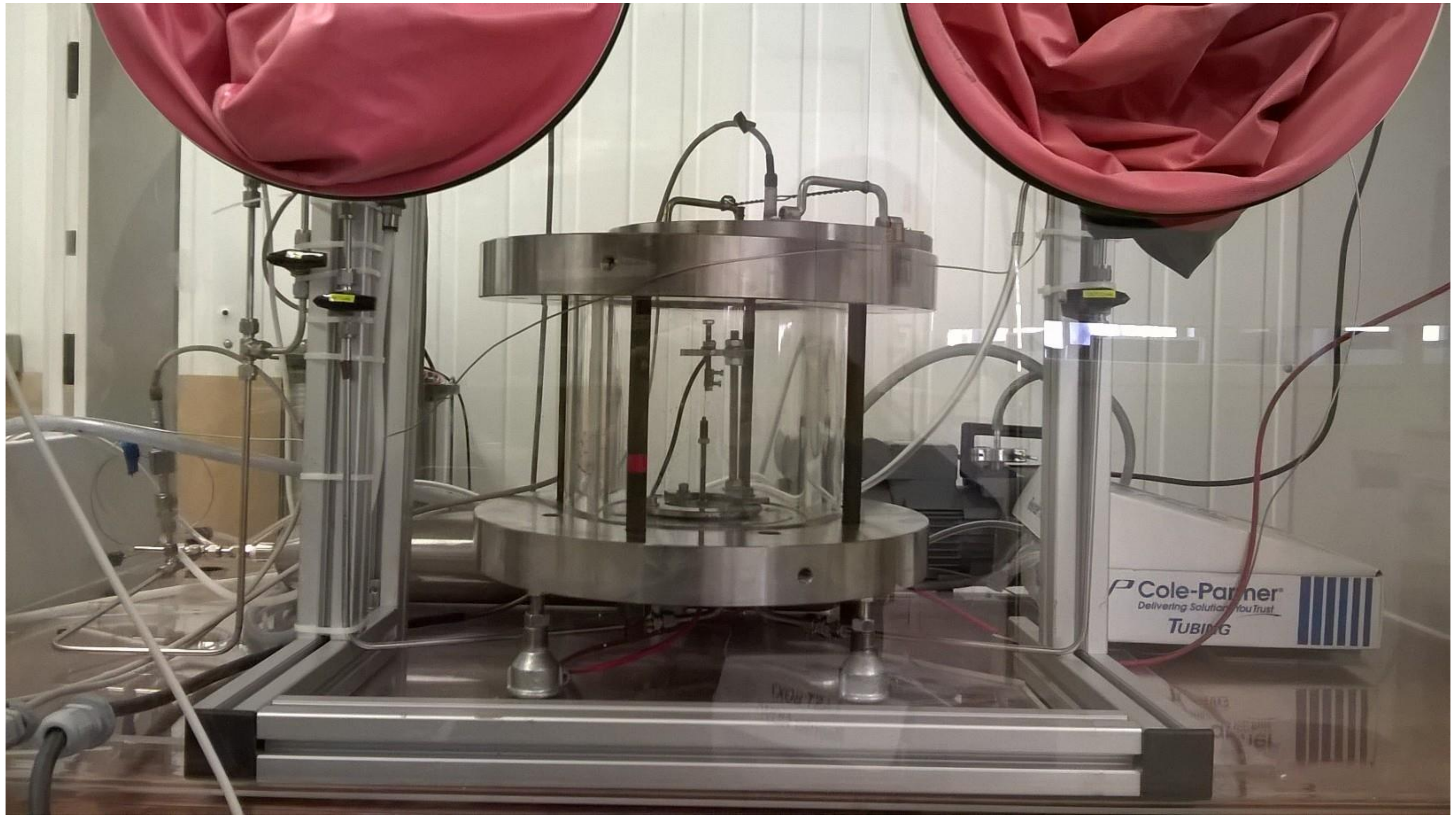
- Basin with size 50 x 50 cm with variation of ground material (e.g. concrete, earth or sand, to be defined!)
- LH2 release on surface in basin,
- As long as no LH2-pool is formed no significant increase in weight,
- LH2-release until weight increases (or LH2-reservoir is empty),
- When pool has formed LH2 supply is stopped,
- All frozen gases evaporate ➔ loss of weight,
- In correlation with ground surface temperature evaporation of different species (LH2, LN2, LO2) might be distinguished (distillation),
- Using loss of weight over time for surface temperatures below 80 K might give evaporation rate for LH2.


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

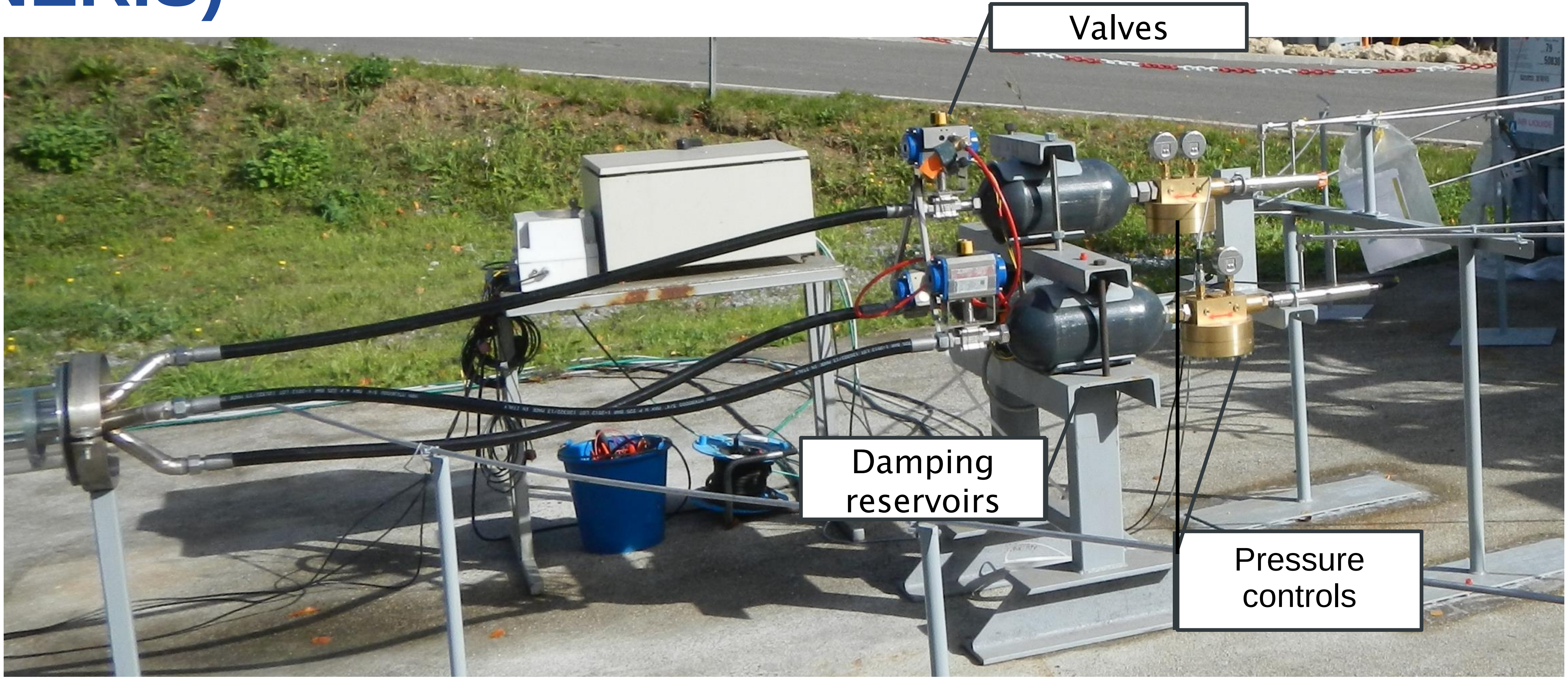
E4.1 MIE Device (INERIS)

- Triggered spark
- Current and voltage measured in the spark gap
- Inductance = 1 mH or zero
- Capacitance : variable
- From a few microjoules to 1 joule





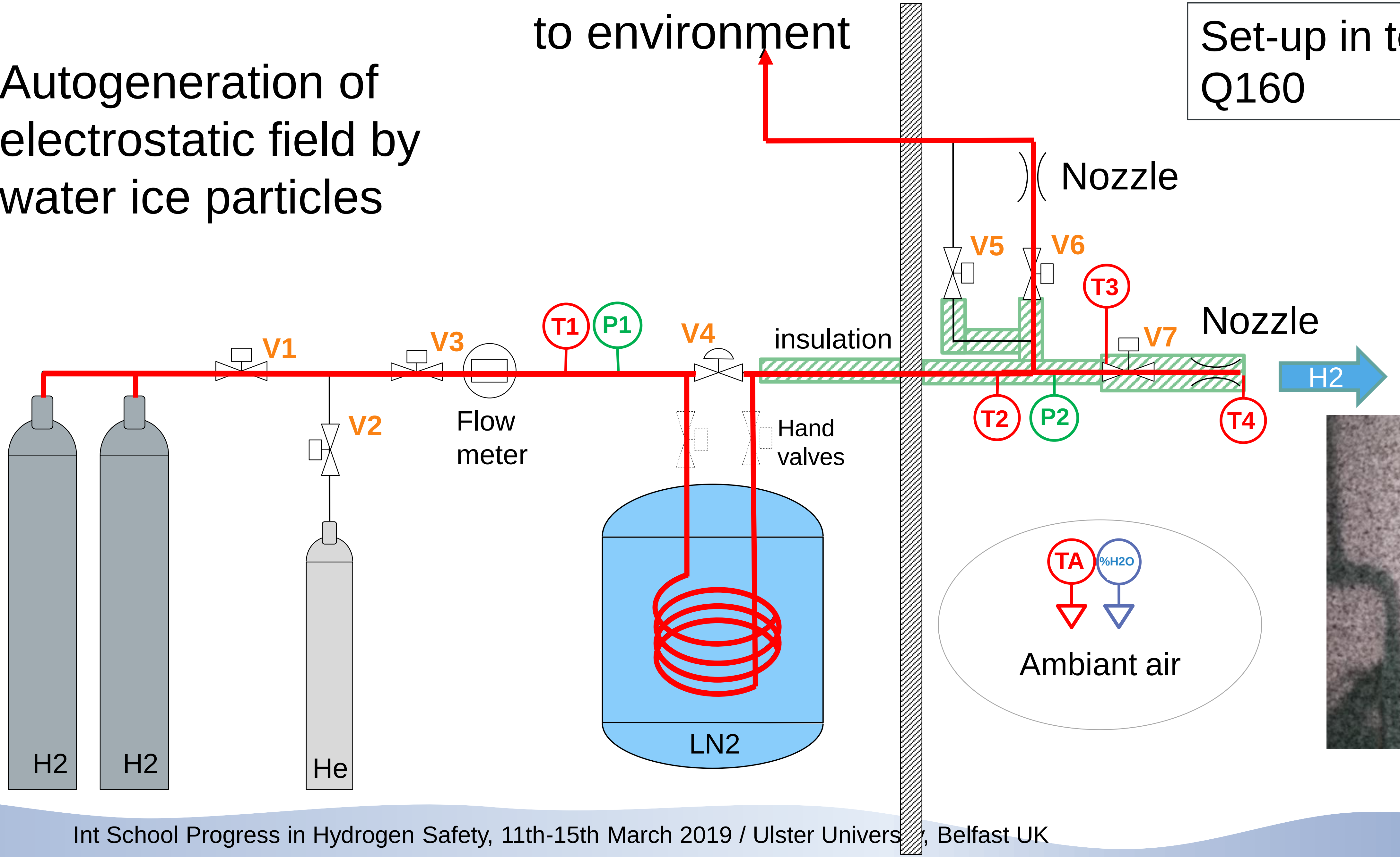
E4.1 Ignition by hot surfaces/power (INERIS)



E4.2 Electrostatic Ignition in jet (KIT)

Autogeneration of electrostatic field by water ice particles

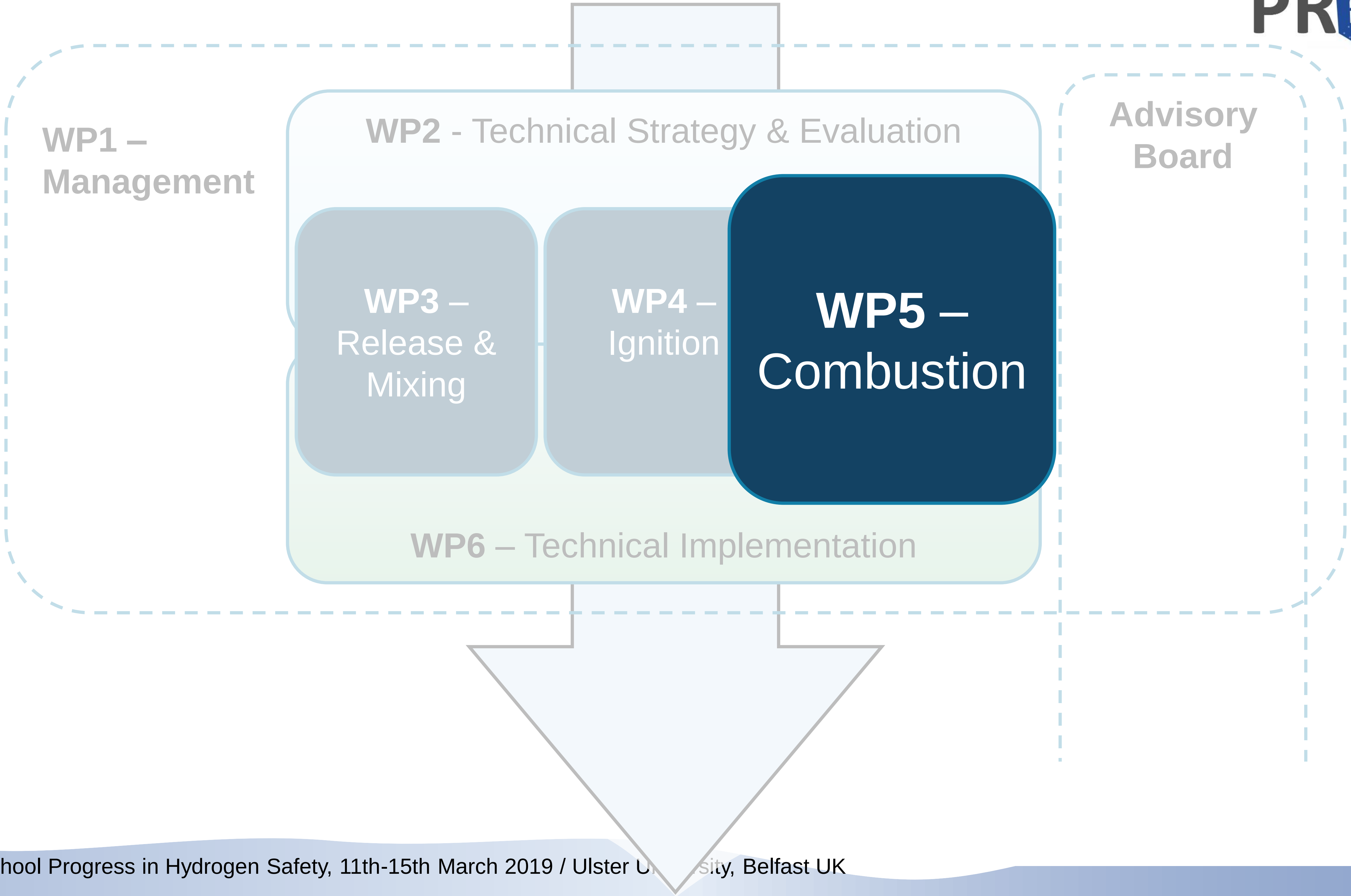
Set-up in test chamber Q160



Field mill

Further ignition experiments

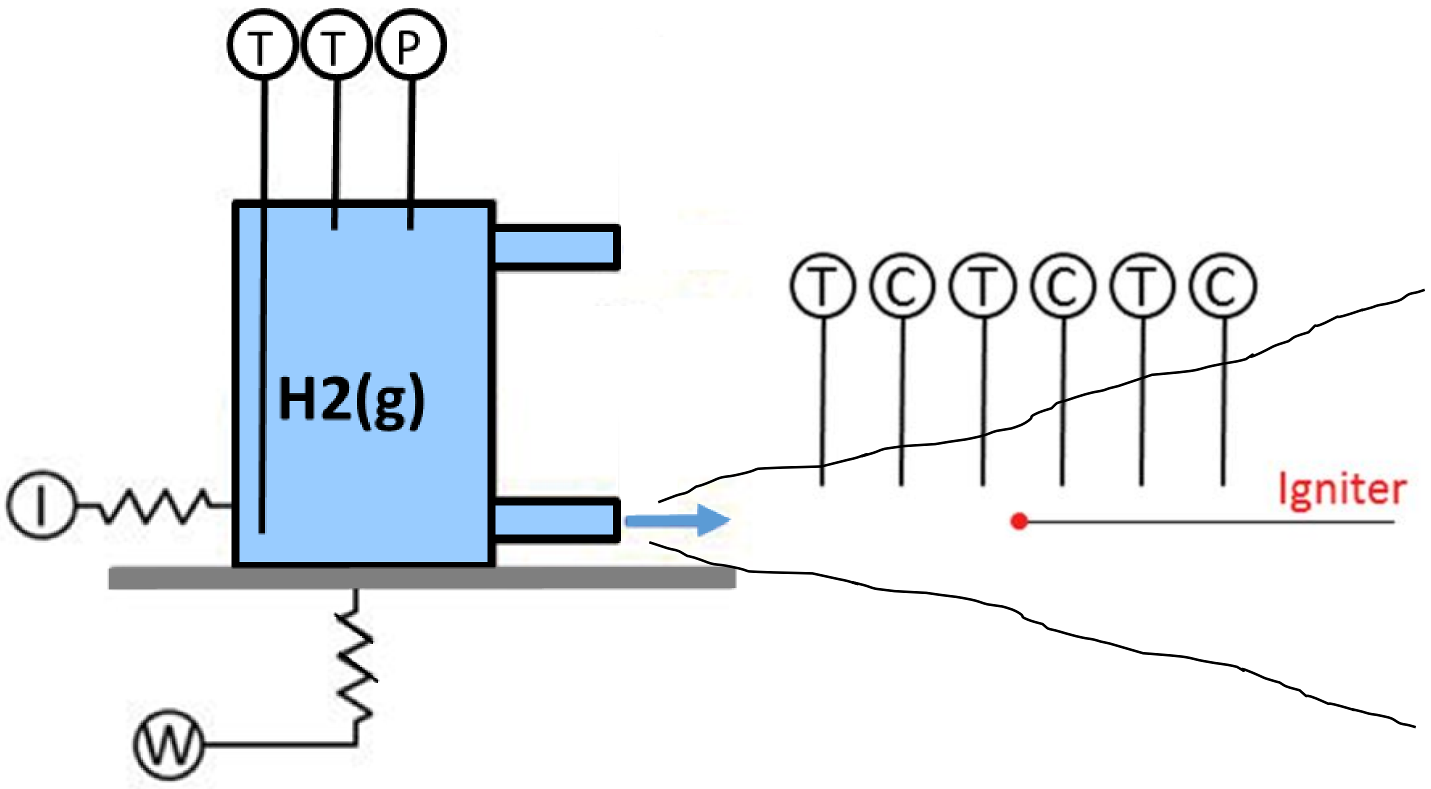
- E4.3 Electrostatic Ignition in plume (HSL)
- E4.4 Ignition above pool (KIT)
- E4.5 Condensed phase ignition (HSL)


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

E5.1: DISCHA Ignited Jet

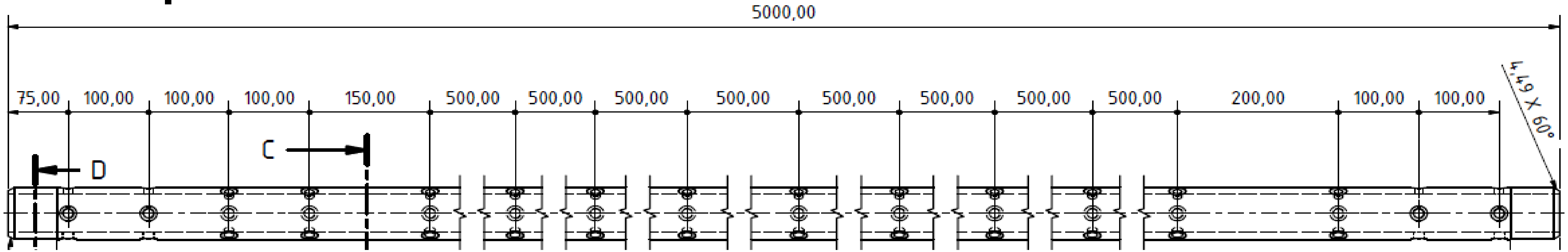
Flammability, pressure and heat flux for ignited cold jet

- For the ignited experiments an ignition device will be added to the existing facilities.
- Selected experiments of the unignited series will be repeated with ignition,
- Parameters to be varied include:
  - Ignition position,
  - Ignition time.

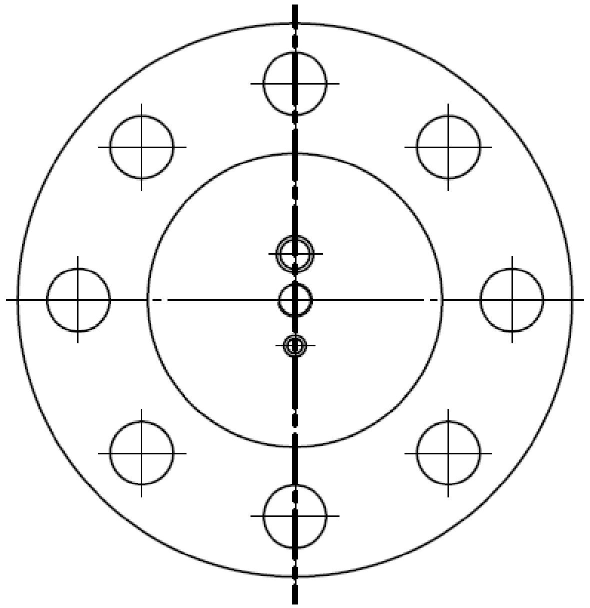


E5.2: Combustion-Tube-Facility

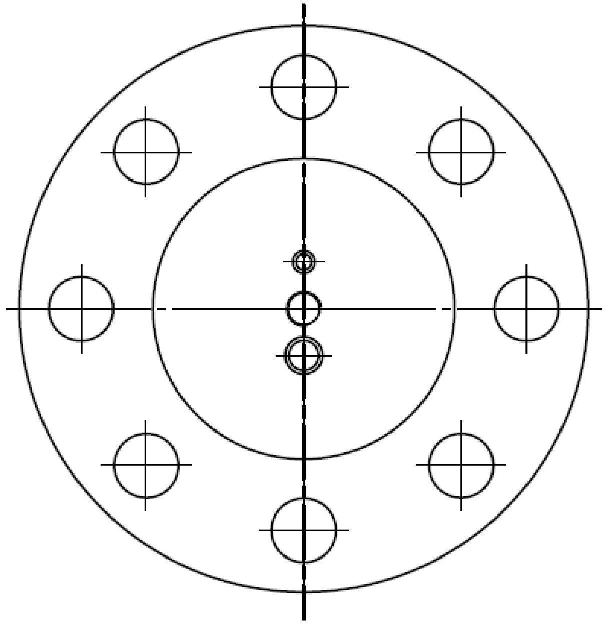
Tube experiments for FA and DDT criteria for T down to 80K



- Front-Flange with ports for:
  - Gas-Inlet
  - Glow-Plug
  - Thermocouple

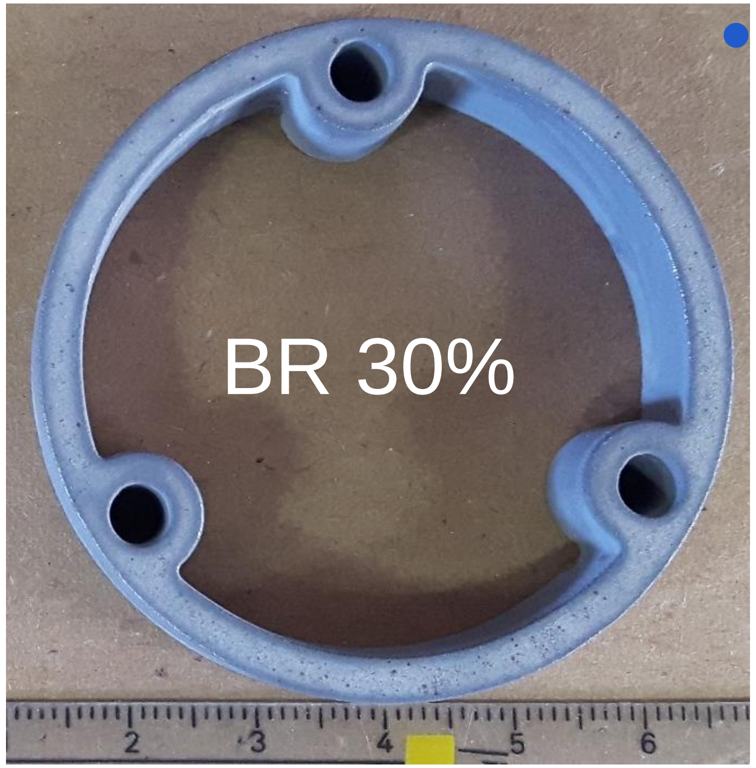


- End-Flange with ports for:
  - Thermocouple
  - Pressure-Sensor
  - Gas-Outlet

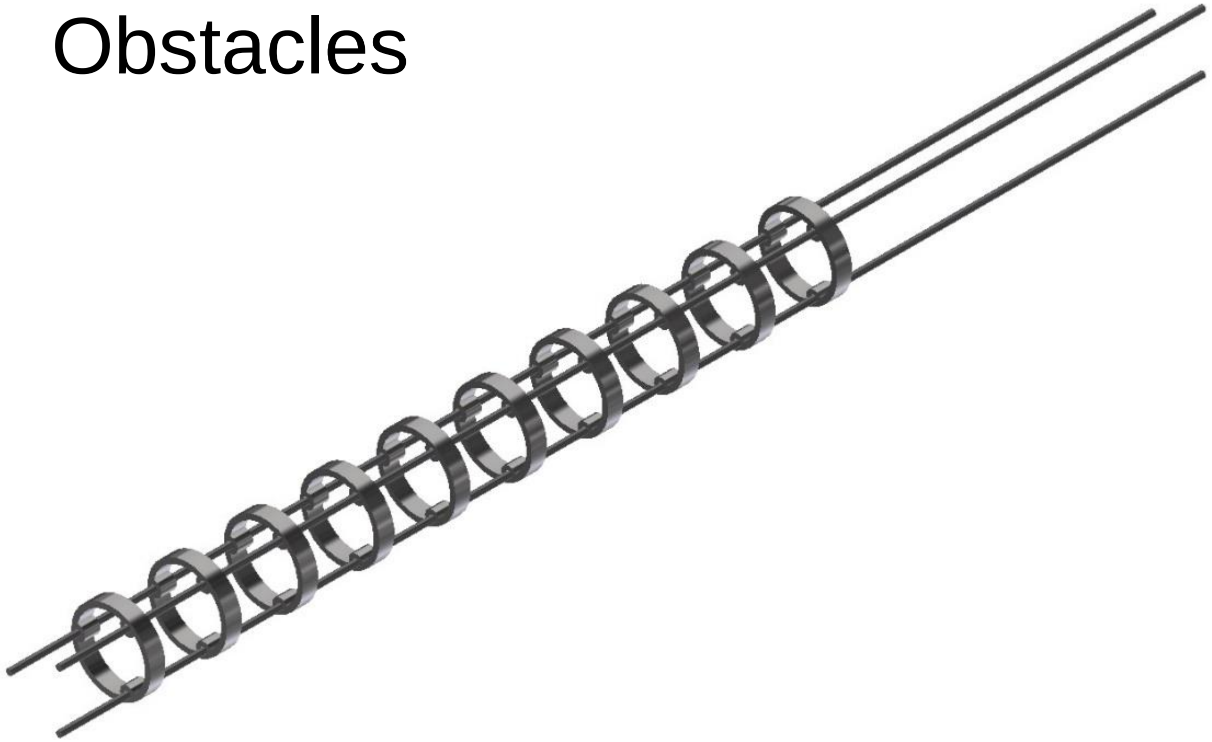


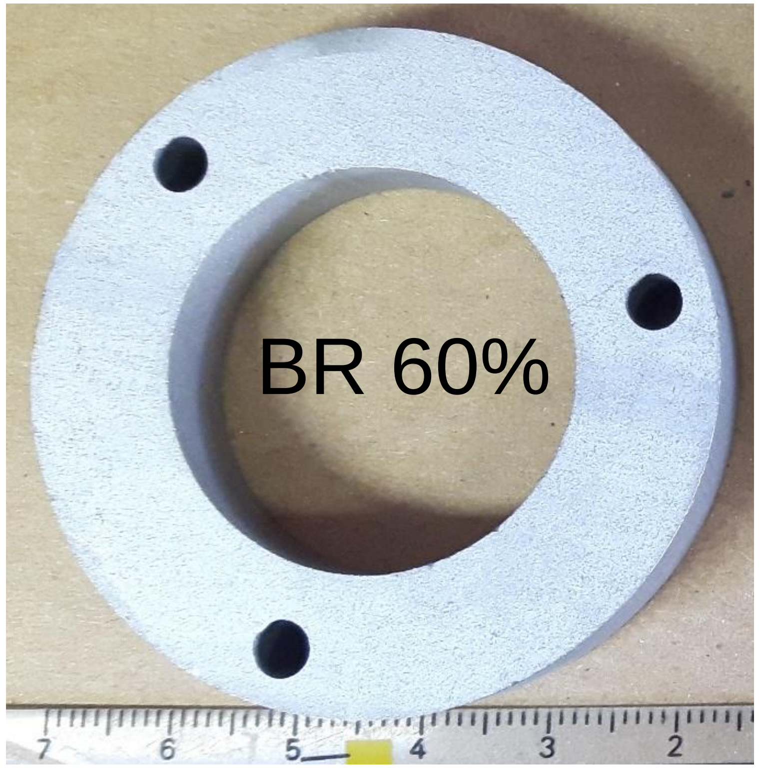
- Along the tube 52 ports for:
  - Pressure Sensors (2 different types),
  - Phototransistors

E5.2: Combustion-Tube-Facility



- Obstacles





- 2 different obstacles (BR 30% and BR 60%),
- obstacles will be positioned evenly along the complete tube length (spacing: 1 inner diameter of tube) via three thin threaded rods,
- obstacles were manufactured externally (already delivered).

E5.5: Integral test in congested space

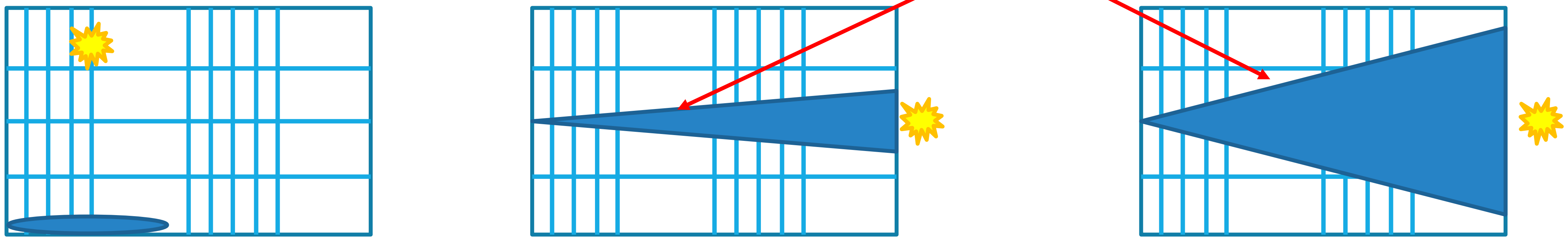
Variables:

- LH2 pool or jet
- Congestion level
- Confinement level
- LH2 jet flow rate

Ignition source located just downstream of rig to limit inventory of unburnt gas prior to entry into the congestion rig, this is to limit noise

Jet opening angle? (24 deg)

Blockage ratio?

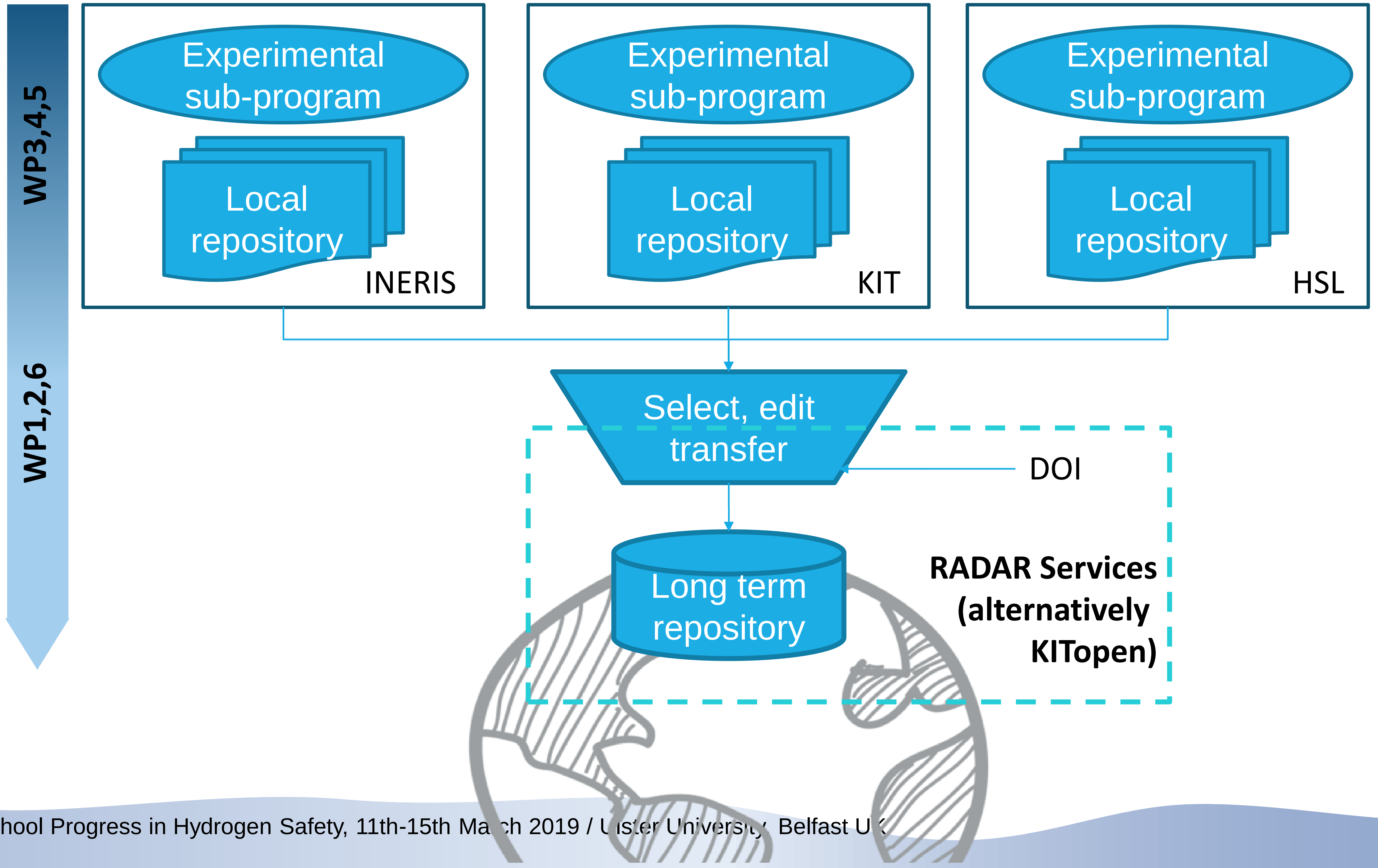


Pool in congestion rig

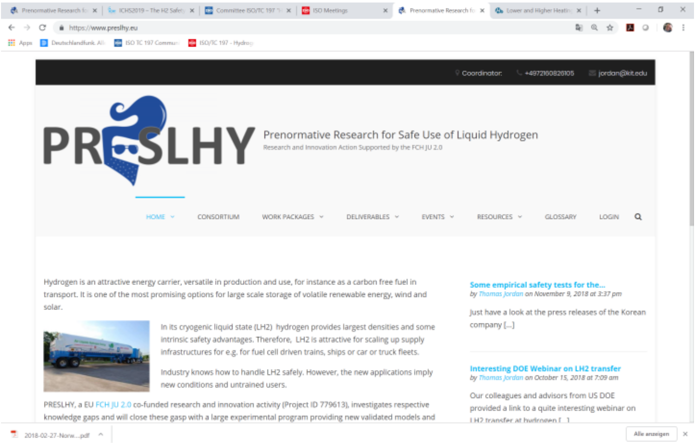
Jet release into congestion rig

Higher flow rate release into rig, larger orifice

FAIR Data Management



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 Dissemination Conference

Deliverables on www.preslhy.eu

Number	Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (month)
D1	D1.1	Kick-off Meeting	1	KIT	OTHER	CO	1
D2	D1.2	Website including internal communication tools	1	KIT	DEC	PU	3
D12	D2.1	RCS Analysis	2	HySafe	REPORT	PU	3
D13	D2.2	State of the Art Report	2	AL	REPORT	PU	3
D14	D2.3	LH2 installation description	2	AL	REPORT	PU	4
D15	D2.4	LH2 Research Priorities Workshop	2	HySafe	OTHER	PU	4
D16	D2.5	Phenomena Identification and Ranking Table Analysis	2	AL	REPORT	PU	4
D17	D2.6	Refined Work Program	2	AL	REPORT	PU	5
D3	D1.3	Data Management Plan Version 1.0 - Draft	1	KIT	ORDP	PU	6
D44	D6.6	Plan for Dissemination, Communication and Exploitation	6	ULster	REPORT	PU	6

Number	Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (month)
D4	D1.4	2nd Project Meeting	1	KIT	OTHER	CO	9
D21	D3.4	Summary of experiment series E3.1 (Discharge) results	3	PS	REPORT	CO	11
D27	D4.4	Summary of experiment series E4.1 (General ignition) results	4	INERIS	REPORT	CO	11
D9	D1.9	1st Annual Data Reporting	1	KIT	REPORT	CO	12
D5	D1.5	3rd Project Meeting	1	KIT	OTHER	CO	14
D36	D5.5	Summary of experiment series E5.2 results	5	PS	REPORT	CO	14
D35	D5.4	Summary of experiment series E5.1 results	5	PS	REPORT	CO	15
D18	D3.1	Theory and Analysis of cryogenic hydrogen release and dispersion	3	NCSRD	REPORT	PU	18
D24	D4.1	Theory and Analysis of Ignition with specific conditions related to cryogenic hydrogen	4	HSE	REPORT	PU	18

today

Invitation to ICHS www.ichs2019.com

ICHS®
International Conference on Hydrogen Safety
2019
ADELAIDE AUSTRALIA

ENDORSEMENTS

COLLABORATION

HOSTING

European Commission

IPHE International Partnership for Hydrogen and Fuel Cells in the Economy

U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy FUEL CELL TECHNOLOGIES OFFICE

Vigili del Fuoco Corpo Nazionale – Ministry of Interiors The National Fire Corps ITALY

ISO – ISO/TC 197 HYDROGEN TECHNOLOGIES

HySafe INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY

Government of South Australia

SOUTH AUSTRALIA

PRESLHY

Acknowledgement

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

FCH
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

European Commission

Horizon 2020
European Union funding
for Research & Innovation