Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

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LH2 Research Priorities Workshop

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Author(s):	Frank Markert, IA-HySafe
Reviewer(s):	Thomas Jordan, KIT; Phil Hooker, HSL
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1. Introduction

This publication reports the content and outcome of the PRESLHY research priority workshop (LH2-RPW). The LH2-RPW took place September 18th , 2018 at the HSL premises in Buxton UK. The workshop was scheduled from 14.00 to 17.30. The LH2-RPW attended 39 experts.

The LH2-RPW is part of the PRESLHY work package WP2 programme – Technical Strategy and State-of-the-Art. The detailed objectives and scope or the workshop and its interplay with the PIRT exercise are defined in the task 2.3 description. The research priorities workshop intends:

> "*For assessing the knowledge gaps associated with LH2 safety for energy applications Phenomena Identification and Ranking table (PIRT) method will be used. This approach was successfully applied to nuclear technologies since it was first developed and applied in the late 1980s. The PIRT is a systematic standardized way of gathering information from experts on a specific subject, and ranking the importance of the information, to meet decision-making objective, e.g., determining the highest priority for the research.*
> *The NoE HySafe applied the same methodology in 2005 to priorities hydrogen safety research topic in general. PRESLHY will redo this exercise with focus on LH2 in this task. In advance to the initial open Research Priorities Workshop a PIRT questionnaire will be prepared and widely distributed thanks to the large network of HYSAFE. Then at the workshop the further processed answers of the questionnaire will be presented and discussed. Together with the other material prepared for this workshop, the literature survey and technology description, a risk and knowledge weighted ranking of the respective safety knowledge gaps will be performed.*"

The LH2-RPW further included the outcome of task 2.2 "Analysis of Standards and Regulation" (see the inserted presentation by Andrei Tchouvelev in Table 2). The outcome of the workshop, summarized in deliverable D2.4, will be used in task 2.4 "Refinement of the program". The detailed PIRT results will be published in deliverable D2.5, but the questions and main votings are found in Appendix A here.

In order to attract a large number of experts from industries, government and universities, the LH2-RPW was planned in connection with the biannual Research Priorities Workshop organized by HySafe, US DoE and JRC on general hydrogen safety knowledge gaps and progress. This setup also enabled further expert discussions in connection with related hydrogen safety issues and a dissemination channel for the LH2-RPW findings discussed at this workshop.

2. Participants

Fisrt Name	**Family Namee**	**Company**
Alberto	Agnelotti	Faber
Alexandros	Venetsanos	Demokritos
Andreas	Friedrich	Pro-Science
Andreas	Haberzettl	DLR
Andrei	Tchouvelev	ATV
Benno	Weinberger	INERIS
Bill	Buttner	NREL
Chris	LaFleur	Sandia National Lab.
Christophe	Proust	INERIS
Dag	Bjerketvedt	USN
Dan	Allason	DNV-GL
Daniele	Melideo	JRC Petten
Donatella	Maria Chiara Cirrone	Ulster University
Espen	Steinseth Hamborg	Equinor
Frank	Markert	DTU
Gary	Dobbin	HSE
Hervé	Barthelemy	AirLiquide
Jay	Keller	ZCES
Jennifer	Wen	University Warwick
Jens	Franzen	Daimler
Jonathan	Hall	HSE
Knut	Vagsaether	USN
Lee	Gardner	CNL
Lee	Phillips	Shell
Marco	Carcassi	Univeristy Pisa
Nick	Barillo	PNNL
Nick	Hart	ITM power
Nico	Van den Berg	RWS
Olav	Hansen	Lloyds
Peter	Wilde	BMW
Phil	Hooker	HSE
Pietro	Moretto	JRC Petten
Pratap	Sathiah	Shell
Simon	Jallais	AirLiquide
Simon	Coldrick	HSE
Stuart	Hawksworth	HSE
Thomas	Jordan	KIT
Trygve	Skjold	Gexcon
Ulrich	Schmidtchen	BAM

Figure: Group photo of the RPW-LH2 participants

3. Agenda

	Task	**Responsible**
1	Welcome	Phil Hooker
2	SOA PRESLHY	Thomas Jordan
3	RCS report	Andrei Tchouvelv
4	SOA Release & Mixing	Alexandros Venetsanos
5	SOA ignition phenomena	Phil Hooker
6	SOA Combustion phenomena	Simon Jallais
7	PIRT	Simon Jallais
8	plenary discussion; voting on experimental matrix to adapt in PRESLHY incl. voting on subjects to suggest to the HySafe RPW	all; chair Phil Hooker

Ad 1): Welcome
RPW-LH2 chair Phil Hooker opened the workshop. The RPW-LH2 is prepared in cooperation with IA HySafe represented by the co-chair Frank Markert.

Ad 2): SOA PRESLHY
PRESLHY coordinator Thomas Jordan described the SOA of PRESLHY (see Table 2). The project is a response to a JU call on pre-normative research and the project has a duration of 3 years in the period January 1st , 2018 to December 31st , 2020. The technological development for hydrogen is leading towards liquid hydrogen applications.

Ad 3): RCS report
A survey of RCS and best practices for liquid hydrogen LH2 was performed published in D2.3 IA HySafe expert Andrei Tchouvelev was the author of this deliverable and he presented the outcome of the study. The RCS priority topics are summarized and an example was given on the determination of separation distances using NFPA2 and EIGA. He suggested the priority should be given to establish scientifically based separation distances, identification of hazardous areas, best stack design for cold gas venting and LH2 transport and transfer.
A more detailed critical discussion was provided for the NFPA2:2016 determination of LH2 separation distances and how it compares to EIGA recommendations. The basis for the distances are not identified and need a critical review. Here PRESLHY experiments would give important answers to this. In the longer term the PRESLHY experimental findings could be implemented into the ISO. Work is required to translate the experimental outcomes into input for ISO.
The presentation was thoroughly discussed. It was asked about the application of the safety distances and how could they be possibly implemented into ISO standards. It was also clarified that the NFPA2 separation distances were established back in the 1960s, but today the considerations and reasons for these numbers cannot be traced any more. Using modern calculation methods such as CFD the separation/safety distances are calculated 3 to 4 times longer than the given ones. EIGA has removed numbers on safety distances. Nevertheless, the removed numbers appear still in many other documents.
The project stages for the ISO standard development is the following. A LH2 Preliminary Working Item PWI may be approved December 6th , 2018 at the ISO/TC 197 plenary meeting in Vancouver. The driving force for this is a need for optimizing the footprint of LH2 installations.

Ad 4): SOA Release & Mixing
Alexandros Venetsanos presented the state-of-the-art for cold gas releases and mixing. Some experiments are described in the literature, such as LH2 or LHe two-phase expanded releases and subcooled liquid or gaseous or supercritical under expanded releases. The weak points in the experiments are:

- Unclear release conditions
    - Need to know T, p and vapor quality at nozzle exit
    - Release momentum not measured
    - Some doubts on the discharge rates
- Limited instrumentation
    - Large variability or limited information about meteorological conditions
    - Limited concentration and temperature measurements
    - No velocities or fluctuations measured
    - No rainout or droplet size measurements

The recognized gaps of understanding related to cryogenic H2 are concerned with:

- Under-expanded release & dispersion from LH2 storage (saturated or sub-cooled conditions)
- Storage blowdown
- BLEVE
- Droplet sizes and rainout
- Condensation / freezing of air
- Pool evaporation & ground heat transfer
- Structure of two-phase jets close to the release

- Cryogenic axial decay law versus ambient temperature decay law
- Impinging jets
- Physical properties of multiphase mixtures of hydrogen, oxygen, nitrogen, and water

In order to address the gaps a number of experiments within PRESLHY are planned. HSL will conduct experiments on LH2 expanded two-phase releases and rainout tests in different configurations. KIT is planning for discharge experiments using the DISCHA facility (approach-1) with T > 80 K and p < 200 bar. Also other discharge experiments are possible (approach -2), as releases of LH2 from cryogenic vessel at T > 20 K and p < 5 bar. KIT plans also for LH2 pool experiments to investigate the evaporation rate from a LH2 pool as well as the cold gas mixing phenomena in the near field above the pool. The purpose is the validation of pool models and CFD dispersion models.

Ad5): SOA Ignition phenomena
Phil Hooker from HSE presented the SOA on the ignition phenomena. The presentation relates to the PRESLHY deliverable 2.2 and examines existing data relating to ignition of cryo-hydrogen. The potential ignition sources are listed in EN 1127-1:2011. For many of the listed sources data exist for ambient temperatures. This includes existing control measures for routine operations and focus is given on accident scenarios in the PRESLHY project. With regard to LH2 in PRESLHY it needs to be asked if there are any new ignition mechanisms that are not understood. Further, it needs to be questioned if there are significant changes to ignition parameters applicable to cryogenic temperatures. It is not possible within the project scope to address the many ignition mechanisms. Therefore, a selection has to be made and the mechanisms of practical interest are selected. Temperature dependence of the flammability limits, the minimum ignition energy at low temperatures are to be determined. The initiation of ignition due to condensed phase hydrogen and oxygen mixtures will be investigated and testing may start with high energy ignition sources to provide a baseline. In the project, INERIS are planning to measure general ignition parameters, while KIT will test for the electrostatic ignition of cold jets as well as the ignition of LH2 spills. HSL will investigate electrostatic effects during releases, and also the ignition of condensed hydrogen and oxygen phase spills.

Ad 6): SOA Combustion phenomena
Simon Jallais from AirLiquide presented the SOA of the combustion phenomena. Based on small scale experimental studies the classical flame length model seems to be validated at cryogenic jet fire conditions. The fraction of heat radiation is found to be reduced under cryogenic conditions. The known experiment on cryogenic pool fires made by Zabetakis and Burgess was made back in 1961 and LH2 was assumed to behave as classical fuel. There is no clear consensus on the radiative fraction. The laminar flame speeds need to be refreshed with new measurement techniques. The flame propagation regimes, the detonation cell size, unobstructed / obstructed unconfined VCE at low temperature need to be further investigated. Other combustion phenomena involving LH2 BLEVE or LH2 tank failure need to be established. No rapid phase transition with LH2 has been performed. The following seven points are identified as knowledge gaps:

1. Unconfined obstructed explosion of cold mixture (atmospheric vaporizer)
2. Laminar flame speed at low initial temperature & Markstein numbers including possible oxygen enrichment & deficiency

3. Turbulent flame speed at low initial temperature
4. Flame acceleration in tubes for cold mixtures
5. Critical expansion ratio of cold mixtures
6. Detonation cell size for cold mixtures
7. Rapid phase transition with water

There was a longer discussion on the BLEVE whether it is possible or not and on the rapid phase transition. Both phenomena appeared to be of great interest. It was reminded that the Norwegian project SH2IFT has started dedicating considerable efforts to the BLEVE phenomena.

Ad 7) PIRT
Simon Jallais presented the PIRT approach that had been distributed online prior to the meeting. The PIRT-online questionnaire is shown in Table 3 and Table 4 in Appendix A. The summarized outcome is shown in Table 1.

Ad 8): Plenary discussion; voting on priorities
The plenary discussions were done in connection with the presentation of the SOA topics and the voting on the priorities based on the PIRT was done on-line starting before the meeting.

Table 1: PIRT Results indication of the 3 types of scores: Knowledge, Criticality and Global

code	**Question**	**Knowledge**	**Criticality**	**Global**
Q1 WP3	Thermophysical properties for LH2 and mixtures with air (including ortho / para conversion) *	53	3.6	15
Q2 WP3	Source term - discharge rate *	42	4.1	10
Q3 WP3	Internal heat transfer and flashing in pipes *	18	3.3	5
Q4 WP3	Droplet size / distribution / evaporation *	22	3.4	6
Q5 WP3	External flashing *	28	3.6	8
Q6 WP3	Rainout *	25	3.1	8
Q7 WP3	Cold heavy gas atmospheric dispersion / transition to buoyant *	77	4.2	18
Q8 WP3	Pool spreading on different surfaces including water *	60	3.4	17
Q9 WP3	Cryogenic spillage interaction with materials cold embrittlement *	24	2.9	8
Q10 WP3	Pool evaporation on different surfaces including water *	46	3.4	13
Q11 WP3	Condensation and freezing of air & CO2 & humidity *	17	3.4	5
Q12 WP3	Interaction with rain, water sprays, water deluge, water curtains & foams *	6	3.1	2
Q13 WP3	High pressure release concentration decay and concentration fluctuations *	88	3.6	25
Q14 WP3	High pressure release velocity, fluctuation & turbulence scale *	76	3.6	21
Q15 WP3	High pressure release in complex environment obstacles, impingement, surface... *	21	3.7	6

code	Question	Knowledge	Criticality	Global
Q16 WP3	Buoyant low velocity releases *	68	3.5	19
Q17 WP3	H2 build-up in confined / semi-confined areas (natural/forced ventilation) *	132	3.2	34
Q18 WP4	Flammability limits at low temperatures (horizontal, upward and downward) *	26	3.6	7
Q19 WP4	Ignition energy at low temperatures *	16	3.1	5
Q20 WP4	Ignition in cryogenic jet releases *	21	3.4	6
Q21 WP4	Ignition above pools *	18	3.4	5
Q22 WP4	Shock diffusion ignition at low temperatures *	8	2.9	3
Q23 WP4	LH2 - condensed O2 mixtures ignition *	5	3.6	1
Q24 WP4	Electrostatic properties of LH2 releases *	9	3.4	3
Q25 WP4	Electrostatic charging and ignition in cryogenic jets *	6	3.4	1
Q26 WP4	Electrostatic charging and ignition above LH2 pools *	5	3.2	2
Q27 WP5	Cryogenic free jet fire *	15	3.9	15
Q28 WP5	Cryogenic impinging jet fire *	18	3.8	5
Q29 WP5	Cryogenic surface jet fire *	57	3.4	4
Q30 WP5	Pool fire *	39	3.6	11
Q31 WP5	Laminar flame speed at low initial temperature including possible O2 enrichment & deficiency *	8	3	3
Q32 WP5	Quenching diameter and safe gap for cold mixtures *	5	2.9	2
Q33 WP5	Turbulent flame speed at low initial temperature *	7	3.2	2
Q34 WP5	Flame acceleration in tubes for cold mixtures *	10	3	3
Q35 WP5	Critical expansion ratio of cold mixtures *	10	3	3
Q36 WP5	Run-up distances and DDT for cold mixtures *	5	3.4	1
Q37 WP5	Detonation cell size for cold mixtures *	6	2.9	2
Q38 WP5	Unconfined Unobstructed Cold Vapour Cloud Explosion *	31	4	8
Q39 WP5	Unconfined Obstructed Explosion of cold mixture (atmospheric vaporizer) *	13	3.9	3
Q40 WP5	Vented explosion for cold mixtures *	28	3.6	8
Q41 WP5	LH2 insulated vessel heat up in fire *	33	3.7	9
Q42 WP5	BLEVE (hot and cold) - Boiling Liquid Expanding Vapor Explosion *	16	3.6	4
Q43 WP5	Rapid Phase Transition (RPT) with water *	6	2.9	2

The conclusions from the PIRT may be summarized as follows. PIRT analysis is a powerful tool to prioritize the needed R&D. This PIRT analysis will be used to adjust the PRESLHY experimental program.
Some trends could be highlighted :

– WP3 : need of R&D on the physics of the liquid releases (internal flashing, droplets, rainout, condensation, external flashing, …)
– WP4 : need of R&D on electrostatic ignition and LH2 / solid oxygen ignition
– WP5 : need of R&D on deflagration, detonation and flame acceleration in cold conditions

4 Results

The evaluation of the results showed that the activities of the PRESLHY project are, in general, well in line with the experts view. However, there were three topics which induced some discussion and could imply adjusting the work program:

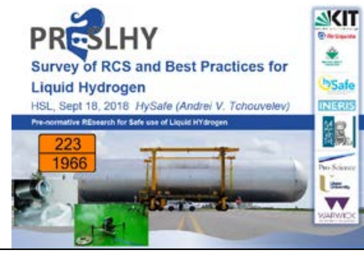
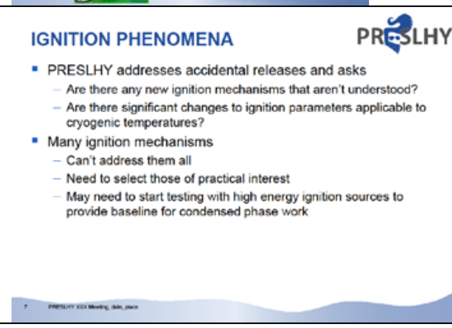
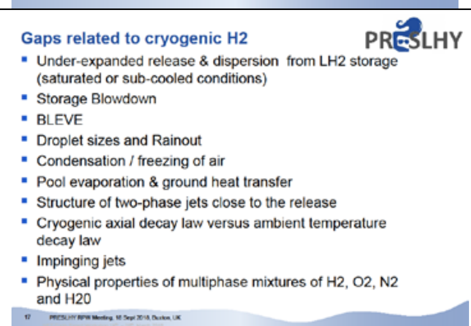
1. BLEVE. This phenomenon has been ranked relatively high. On one hand there is some justification for claiming, that for well heat insulated cryo-vessels, as used for LH2, this phenomenon is less relevant than for LPG, for instance. However, a few historic accident cases showed that there is a potential for such energetic scenarios.
   As there is a recently started small dedicated project on BLEVE phenomenon with PRESLHY partners and advisors involved, no experiments on the BLEVE topic will be planned in PRESLHY. Moreover, it should be noted, that due to scaling constraints a relevant test program would induce considerable costs.
2. MATERIAL COMPATIBILITY. Also this topic was ranked relatively high. However, from the very beginning PRESLHY explicitly excluded this quite huge domain from the work content for budgetary constraints. It is recommended to treat this topic in a separate dedicated project.
3. JET FIRES. This topic was ranked surprisingly low. In the discussion it turned out that there is the general assumption that the quite well established models for “warm” releases will work well also in the low temperature domain.

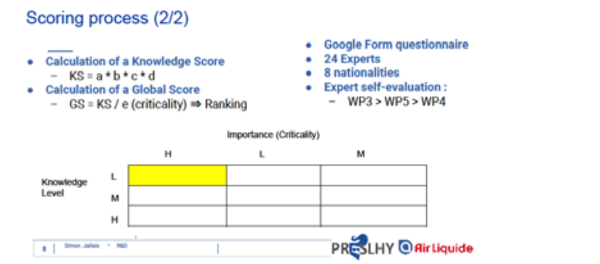
The project will seek to slim down the experimental program for jet fires and rather focus on a few validation cases.

Important note: the proposed case studies are examples. Thus, they can be modified with inclusion of other relevant information. Also, other similar case studies could be added to the project portfolio.
The approach will be to compare and / or overlay the numbers coming from the existing documents vs hazard distances obtained within the PRN scope of work (modeling and experiments).

List of Presentations

Table 2 List of presentations

SOA PRESLHY - Thomas Jordan	
RCS - Andrei Tchouvelev	
Ignition Phenomena Phil Hooker	
Dispersion and Mixing Alexandros Venetsanos	
Combustion Phenomena Simon Jallais	

PIRT analysis Simon Jallais	

References

1. Linde BMW brochure promoting cryo-compressed technology, 2017.
2. PRESLHY application, 2017.
3. PRESLHY report D 2.3 on RCS
4. PRESLHY report D 2.2 on existing data relating to ignition of cryo-hydrogen.
5. EN 1127-1:2011 on potential ignition sources

Appendix A - PRESLHY FCHJU LH2 RISK AND SAFETY PIRT

Phenomena Identification Ranking Table for LH2 use in hydrogen energy applications

WP3 : Release and mixing phenomena
WP4 : Ignition phenomena
WP5 : Combustion phenomena

.Please plan a little time (30'), you have 43 questions to answer...

(* *Required field)*

Mailadresse *
Surname *
Name *
Position *
Affiliation *

Table 3 Ranking table for each of the questions.

	1	**2**	**3**	**4**	**5**
a) General level of understanding					
b) Level of maturity of engineering modelling					
c) Level of maturity of CFD modelling					
d) Availability of experimental data					
e) Criticality for enabling LH2 in populated areas					
f) Expert Level (not used)					

5 corresponds to a very good level of understanding / very good maturity / numerous high quality experimental data / highly critical for applications or a very good personal expertise on this topic/phenomena.
1 corresponds to a very low level of understanding / very low maturity / no experimental data / absolutely not critical for applications or a very low personal expertise on this topic/phenomena

Table 3 is used to calculate a score to estimate the knowledge of the expert answering the questions. Each of the scores a) to e) in the table are ranked form 1 to 5 with 5 being the best score. The formulas to calculate the scores for Knowledge, Criticality and Global are as follows:

- Calculation of knowledge score: KS = a*b*c*d
- Calculation of a global score: GS = KS /e

Table 4 Questions for WP3, WP4 and WP5

Q1 WP3	Thermophysical properties for LH2 and mixtures with air (including ortho / para conversion) *
Q2 WP3	Source term - discharge rate *
Q3 WP3	Internal heat transfer and flashing in pipes *
Q4 WP3	Droplet size / distribution / evaporation *

Q5 WP3	External flashing *
Q6 WP3	Rainout *
Q7 WP3	Cold heavy gas atmospheric dispersion / transition to buoyant *
Q8 WP3	Pool spreading on different surfaces including water *
Q9 WP3	Cryogenic spillage interaction with materials cold embrittlement *
Q10 WP3	Pool evaporation on different surfaces including water *
Q11 WP3	Condensation and freezing of air & CO2 & humidity *
Q12 WP3	Interaction with rain, water sprays, water deluge, water curtains & foams *
Q13 WP3	High pressure release concentration decay and concentration fluctuations *
Q14 WP3	High pressure release velocity, fluctuation & turbulence scale *
Q15 WP3	High pressure release in complex environment obstacles, impingement, surface... *
Q16 WP3	Buoyant low velocity releases *
Q17 WP3	H2 build-up in confined / semi-confined areas (natural/forced ventilation) *
Q18 WP4	Flammability limits at low temperatures (horizontal, upward and downward) *
Q19 WP4	Ignition energy at low temperatures *
Q20 WP4	Ignition in cryogenic jet releases *
Q21 WP4	Ignition above pools *
Q22 WP4	Shock diffusion ignition at low temperatures *
Q23 WP4	LH2 - condensed O2 mixtures ignition *
Q24 WP4	Electrostatic properties of LH2 releases *
Q25 WP4	Electrostatic charging and ignition in cryogenic jets *
Q26 WP4	Electrostatic charging and ignition above LH2 pools *
Q27 WP5	Cryogenic free jet fire *
Q28 WP5	Cryogenic impinging jet fire *
Q29 WP5	Cryogenic surface jet fire *
Q30 WP5	Pool fire *
Q31 WP5	Laminar flame speed at low initial temperature including possible O2 enrichment & deficiency *
Q32 WP5	Quenching diameter and safe gap for cold mixtures *
Q33 WP5	Turbulent flame speed at low initial temperature *
Q34 WP5	Flame acceleration in tubes for cold mixtures *
Q35 WP5	Critical expansion ratio of cold mixtures *
Q36 WP5	Run-up distances and DDT for cold mixtures *
Q37 WP5	Detonation cell size for cold mixtures *
Q38 WP5	Unconfined Unobstructed Cold Vapour Cloud Explosion *
Q39 WP5	Unconfined Obstructed Explosion of cold mixture (atmospheric vaporizer) *
Q40 WP5	Vented explosion for cold mixtures *
Q41 WP5	LH2 insulated vessel heat up in fire *
Q42 WP5	BLEVE (hot and cold) - Boiling Liquid Expanding Vapor Explosion *
Q43 WP5	Rapid Phase Transition (RPT) with water *