STATUS OF THE PRE-NORMATIVE RESEARCH PROJECT PRESLHY FOR THE SAFE USE OF LIQUID HYDROGEN

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ABSTRACT

Liquid hydrogen (LH_2) compared to compressed gaseous hydrogen offers advantages for large scale transport and storage of hydrogen with higher densities and potentially better safety performance. Although the gas industry has good experience with LH_2 only little experience is available for the new applications of LH_2 as an energy carrier. Therefore, the European FCH JU funded project PRESLHY conducts pre-normative research for the safe use of cryogenic LH_2 in non-industrial settings. The work program consists of a preparatory phase, where the state of the art before the project has been summarized and where the experimental planning was adjusted to the outcome of a research priorities workshop. The central part of the project consists of 3 phenomena oriented work packages addressing Release, Ignition and Combustion with analytical approaches, experiments and simulations. The results shall improve the general understanding of the behavior of LH_2 in accidents and thereby enhance the state-of-the-art, what will be reflected in appropriate recommendations for development or revision of specific international standards. The paper presents the status of the project at the middle of its terms.

1.0 MOTIVATION AND OBJECTIVES

For scaling up the hydrogen supply infrastructure the transport of liquefied hydrogen is the most effective option due to the energy density. Especially for the transport sector with the planned large bus fleets, the emerging hydrogen fuelled train, boat and truck projects and even for the pre-cooled 70 MPa car refuelling liquid hydrogen (LH_2) offers sufficient densities and gains in efficiency over gaseous transport, storage and supply. However, LH_2 implies specific hazards and risks, which are very different from those associated with the relatively well-known compressed gaseous hydrogen. Although these specific issues are usually well reflected and managed in large-scale industry and aerospace applications of LH_2, experience with LH_2 in a distributed energy system is lacking. Transport and storage of LH_2 in urban areas and the daily use by the untrained general public will require higher levels of safety provisions accounting for the very special properties. The quite different operational conditions compared with the industrial environment and therefore also different potential accident scenarios will put an emphasis on specific related phenomena which are still not well understood. Specific recommendations and harmonised performance-based international standards are lacking for similar reasons.

Therefore, the European pre-normative research project PRESLHY - Pre-normative REsearch for Safe Use of Liquid HYdrogen - is assessing the most relevant and poorly understood phenomena related to high risk scenarios. With the new knowledge generated by this research work science-based and validated tools, which are required for hydrogen safety engineering and risk-informed, performance-based, LH_2 specific, international standards will be developed.

So, the main objectives of PRESLHY are to

- report on the initial state-of-the-art and knowledge gaps with priorities with respect to intended use of LH_2, then
- execute an adjusted experimental program addressing release, ignition and combustion phenomena with highest priorities,
- 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 LH_2 technologies and
- support international SDOs in updating of existing standards or the development of new international performance-based and risk-informed standards.

All activities are supporting an ambitious plan for technical implementation and for dissemination, which includes publication of all generated research data in a findable, accessible, interoperable and reusable (FAIR) way.

2.0 GENERAL ASPECTS OF THE PROJECT

The project formally started on 1st of January 2018 and is funded for a three year duration. However, effectively the activities started only after the kick-off meeting in April 2018.

The general approach, as shown in Fig. 1, reflects the project objectives. Thereby, the project obviously shifts the focus from the initial analysis of the state-of-the-art and the strategic alignment of the work program in work package WP2 to the final exploitation, implementation and dissemination work package WP6 via a central analytical and experimental block. This central block consists of three work packages, addressing the safety critical phenomena Release & Mixing in WP3, Ignition in WP4, and Combustion in WP5.

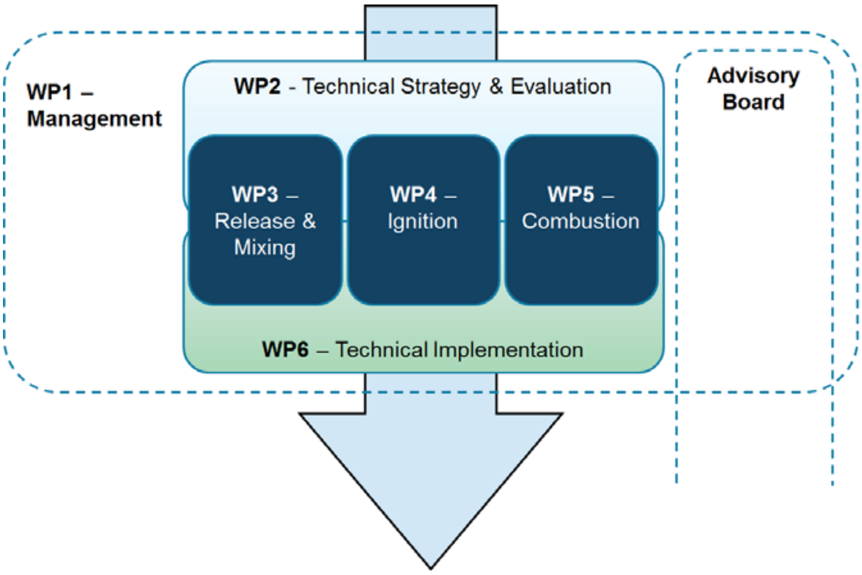


Figure 1: General approach of the PRESLHY project.

The project consortium consists of 9 partners, with the coordinator Karlsruhe Institute of Technology (KIT) and Pro-Science (PS) from Germany, Air Liquide (AL) and INERIS from France, Health &

Safety Laboratory (HSL), University of Ulster (UU) and Warwick University (UWAR) from UK, National Center for Scientific Research Demokritos (NCSRD) from Greece and HySafe from Belgium. The advisory board is composed of international experts from industry and from standards developing organisation, extending the reach of the project's impact to US, Japan and China, i.e. well beyond the borders of Europe. The network is further expanded by the full member HySafe, providing links to most of the hydrogen safety involved institutions and other LH_2 safety relevant projects worldwide. For example, HySafe members SNL and PNNL provide a strong link to the US DoE program H2@scale and the members GexCon, DNV and Equinor initiated a close cooperation with the Norwegian project SH2IFT (see Fig. 2).

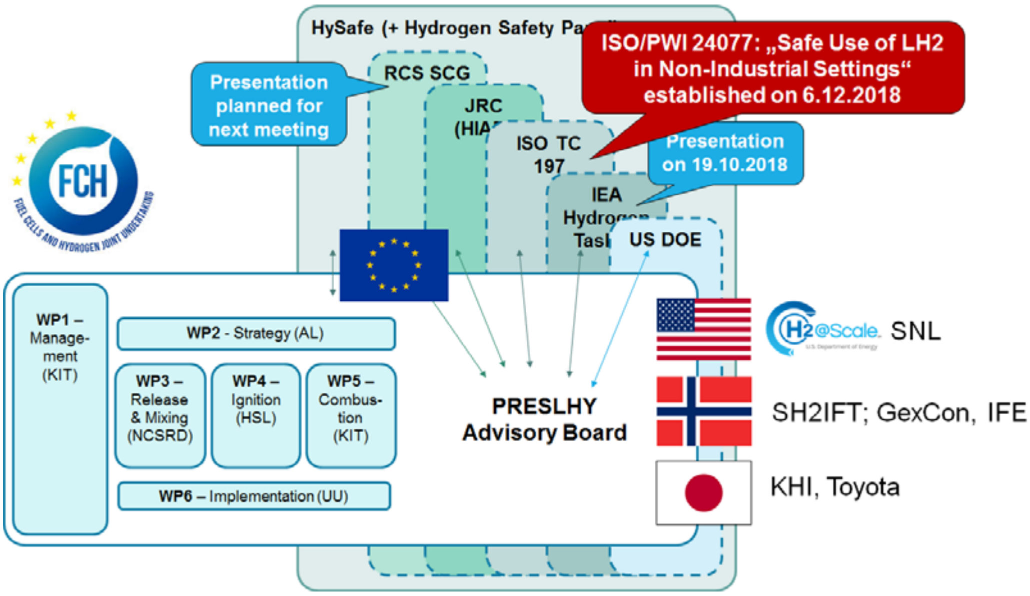
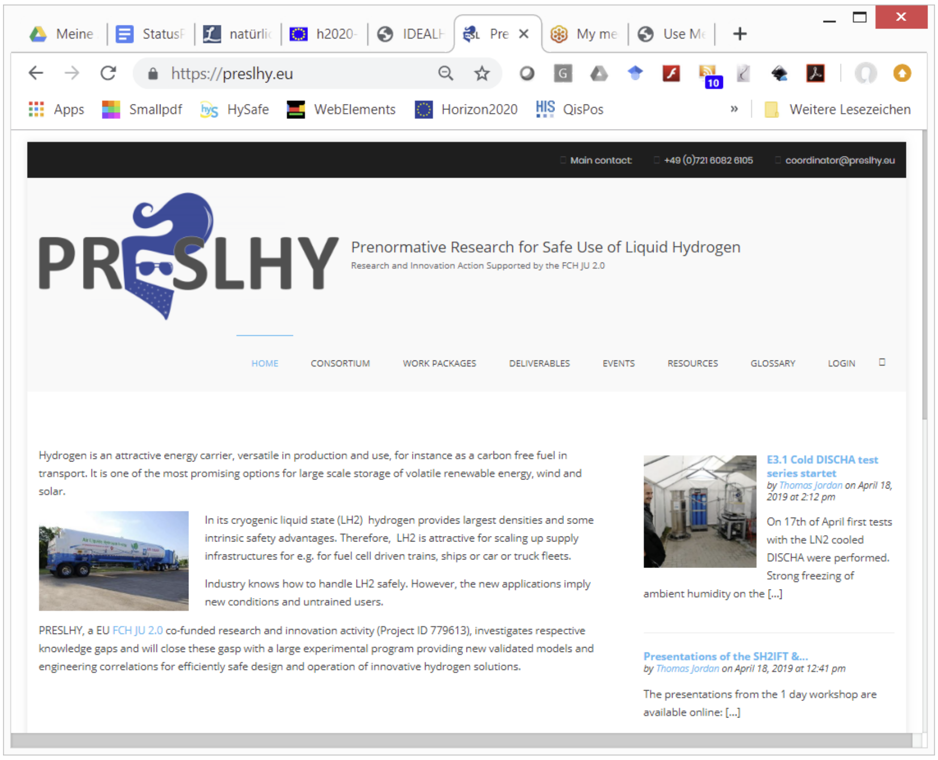


Figure 2: The external network of PRESLHY.

There are two full project meetings organised annually, one in springtime, the other in fall. The first meeting, the kick-off meeting was organised in April 2018 in Karlsruhe by coordinator KIT, the second in Saclay / Paris by partner AL and the third in March 2019 in Bergen by partner HySafe. All the general meetings are combined with special workshops dedicated to exchange of experience in the different fields of experimental techniques related to LH_2 safety. The first workshop was related to optical measurement, the next was addressing low temperature measurement, the one combined with the meeting in Bergen focussed on multi-phase flow measurement. Further workshop topics are CFD and safety for LH_2 experiments, and standardisation processes.

The main tool for internal and external communication is the project website www.preslhy.eu (see Fig. 3). It provides a repository of all deliverables, meeting and workshop documents including respective presentations, and provides access to all dissemination documents and further news regarding the project and LH_2 safety related publications.



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Prenormative Research for Safe Use of Liquid Hydrogen

Research and Innovation Action Supported by the FCH JU 2.0

Hydrogen is an attractive energy carrier, versatile in production and use, for instance as a carbon free fuel in transport. It is one of the most promising options for large scale storage of volatile renewable energy, wind and solar.

In its cryogenic liquid state (LH2) hydrogen provides largest densities and some intrinsic safety advantages. Therefore, LH2 is attractive for scaling up supply infrastructures for e.g. for fuel cell driven trains, ships or car or truck fleets.

Industry knows how to handle LH2 safely. However, the new applications imply new conditions and untrained users.

PRESLHY, a EU FCH JU 2.0 co-funded research and innovation activity (Project ID 779613), investigates respective knowledge gaps and will close these gasp with a large experimental program providing new validated models and engineering correlations for efficiently safe design and operation of innovative hydrogen solutions.

E3.1 Cold DISCHA test series startet
by Thomas Jordan on April 18, 2019 at 2:12 pm

On 17th of April first tests with the LN2 cooled DISCHA were performed. Strong freezing of ambient humidity on the […]

Presentations of the SH2IFT &…
by Thomas Jordan on April 18, 2019 at 12:41 pm

The presentations from the 1 day workshop are available online: […]

Figure 3: PRESLHY website www.preslhy.eu .

The following chapters will present the achievements of each work package.

3.0 TECHNICAL STRATEGY AND STATE-OF-THE-ART

Objectives of Work Package 2 are to set the stage of the project by summarising the State-of-the-Art, define the critical knowledge gaps for LH_2 industrial use in energy applications, identify the key scenarios and involved elementary phenomena and provide refined Work Program for the core technical WPs.

First of all, an analysis of the existing Regulations, Code and Standards (RCS) as well as the industry best practices from European and American Gas Association (EIGA) and Compressed Gas Association (CGA) was conducted. The report emphasises the importance of determining science based hazard distances for liquid hydrogen installations and then compare them with the requirements of the published RCS.

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Secondly, a description of the LH_2 installation was written for the partners with a particular interest on the foreseen LH_2 delivery infrastructure: stationary LH_2 large storages, LH_2 road trailers and LH_2-based hydrogen fueling stations. The partners also visited some Air Liquide LH_2 installations (liquefier and refueling station).

Thirdly, a bibliographic State of the Art (SoA) study (open report D2.1) was performed. This SoA focusses on experimental and modelling work on release/mixing phenomena, ignition phenomena and combustion phenomena. The objective of the SoA was to identify the remaining knowledge gaps.

A Phenomena Identification and Ranking Table (PIRT) was also performed in September 2018. The NoE HySafe applied the same methodology in 2005 to prioritise hydrogen safety research topic in general. The PRESLHY project performed again this exercise with a focus on LH_2. The PIRT is a systematic way of gathering information from experts on a specific subject, and ranking the importance of the information, in order to meet some decision-making objectives, e.g., determining what are the highest priorities for research and development on that subject. Few weeks before the Research Priorities Workshop (RPW) in September 2018 (Buxton-UK) a PIRT questionnaire was prepared and widely distributed (via Google Forms) thanks to the large network from HYSAFE and PRESLHY members. For the 3 experimental and modelling WP of PRESLHY a list of associated physical phenomena was developed. For each phenomenon identified, the user gives a value between 1 to 5 regarding : general level of understanding, level of maturity of engineering modelling, level of maturity of CFD modelling, availability of experimental data, and criticality for enabling LH_2in populated areas. Finally, all these values allow to calculate a knowledge score. Globally 24 experts with 8 different nationalities answered the PIRT questionnaire. Their contribution is sincerely acknowledged herewith. More details can be found in the open report D2.4.

The SoA and the PIRT concluded on the need for additional research on the physics of the liquid releases (internal flashing, droplets, rainout, condensation, external flashing, …), on the electrostatic ignition and LH_2 / solid oxygen ignition and on the deflagration, detonation and flame acceleration in cold conditions. Based on these conclusions, the experimental work program for the core technical WPs was updated (D2.6 Public Report).

To anticipate the conclusions of the experimental and modeling WP and in agreement with the RCS analysis, an open consequence analysis is also under progress. Air Liquide suggested risk scenarios (storage failure, liquid and supercritical H_2 leaks) and consequence threshold (overpressure, radiative heat flux, …). This consequence analysis will serve as an internal benchmark. The participants to this open benchmark will then describe their models and calculate the effect distances of the scenarios. This analysis will be useful to assess the level of consensus in the different tools and methods used by the risk and safety actors for LH_2.

4.0 PHENOMENA RELEASE AND MIXING

Objectives of Work Package 3 (Release and Mixing) are to close knowledge gaps, develop and validate suitable models for phenomena relevant to release and mixing of LH_2 as well as develop empirical and semi-empirical correlations when applicable. The work package consists of two major activities: Experiments and Simulations/Model Development.

CFD simulation work was initiated by performing validation of existing modeling approaches against pre-existing experiments [1, 2] not modelled in the past. Four partners participated in the modelling of the SANDIA cryogenic hydrogen vertical jets (UU engineering models and with FLUENT, AL with FLACS, NCSRD with ADREA-HF and KIT with GASFLOW-MPI), while one partner (NCSRD) modelled INERIS-Test 3 large scale liquefied helium release experiment on flat ground. The results of this work are reported within ICHS-8. Figure 4 below shows predicted temperature distribution at 30 s on symmetry plane for INERIS Test-3. Further CFD work will include a) pre-test simulations to help the experimentalists and b) further modelling and validation work based on the new PRESLHY experiments.

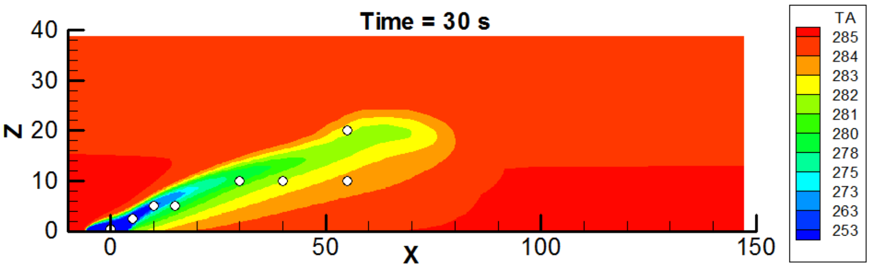

Figure 4: Temperature distribution at 30 s on symmetry plane for INERIS Test-3 predicted with CFD.

In the framework of developing simplified engineering models a new homogeneous non-equilibrium model (HNEM) has been developed by NCSRD to predict isentropic choked two phase releases in the bubbly flow regime [3]. The model does not exhibit any sound speed discontinuity when crossing the liquid binodal curve. The model was implemented using hydrogen EoS explicit in terms of the Helmholtz free energy (HFE) and successfully applied against the pre-existing NASA experiments [4] producing better agreement to the experiments for low mass fluxes compared to the classical HEM.

In parallel, in the same engineering modeling framework, a 1D computational tool was developed by NCSRD to simulate steady state choked flow through a discharge line of variable cross section. The model solves the mass, momentum and energy balance equations and finds choked flow using PIF algorithm. For the flashing inside the discharge line, three modeling approaches were implemented: HEM, Homogeneous Relaxation Model (HRM) and Delayed Equilibrium Model (DEM). Physical properties are calculated using HFE based EoS. Given the current absence of relevant hydrogen data, preliminary validation work was performed against experimental data from the old Super Moby Dick experiments with water, while future validation will be based on the discharge experiments performed within PRESLHY. Fig. 5 below shows on the left the pipe diameter evolution along the discharge line and on the right the predicted void fraction evolution, for liquid water at stagnation state 20 bar, 212.3°C compared against the experimental data.

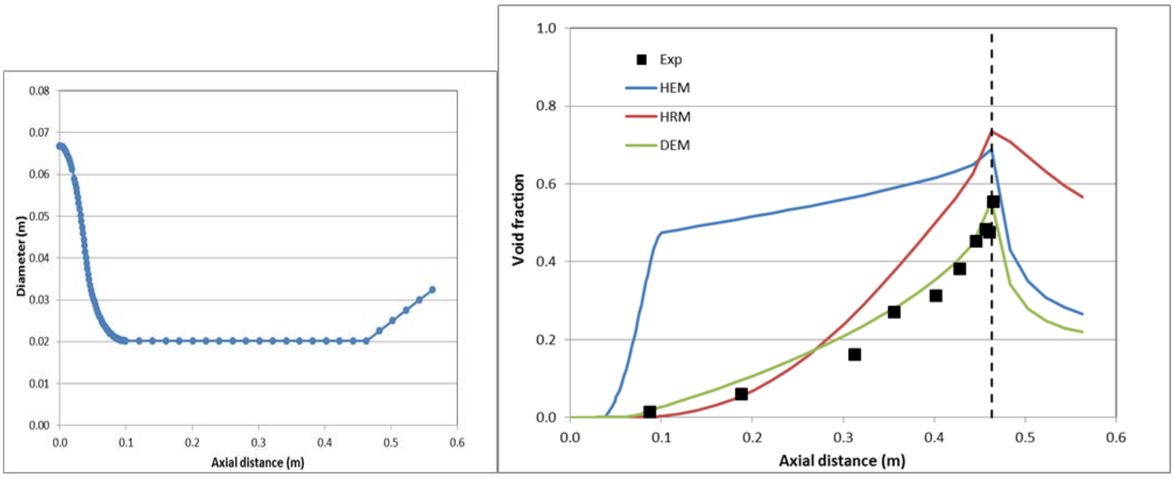

Figure 5: Left: pipe diameter variation along the discharge line. Right: predicted void fraction evolution, for liquid water at stagnation state 20 bar, 212.3°C compared against the Super Moby Dick experimental data.

The Ulster's under-expanded jet theory was applied by UU to calculate parameters at the nozzle exit for the experiments performed by Sandia National Laboratories (SNL) on jets from storage temperature in the range 46-295 K and pressure up to 6 bar abs [2, 5]. The experimental mass flow rate was found to be well represented for over 100 tests within ±10% accuracy with the exception of a test with T=37 K and p=2 bar abs. The similarity law for concentration decay in momentum-dominated jets by [6] was shown to be capable to reproduce experimental data of SNL on 9 unignited cryogenic releases. It was noted that the accuracy of the similarity law to reproduce the axial concentration decay measured in experiments improves with the increase of the release diameter. Results are reported within ICHS-8.

Further engineering modelling work will include development of correlations based on the acquired new experimental data.

Experimental work within this work package includes a) the DISCHA experiments by PS/KIT b) the CRYOSTAT experiments by PS/KIT c) the pool experiments by PS/KIT and the rainout experiments by HSL, all performed with cryogenic hydrogen.

HSL experimental matrix and experimental setup close to the release are presented below. The experiments will focus on dispersion / source term. Main objective is to investigate LH_2 vaporization / pool formation for elevated release points. Release conditions are expected to be two-phase.

Table 1: Experimental matrix of the HSL rainout tests

Work Package	Experimental Subtask	Test No.	Experiment Title	Release Orientation	Release Height	Orifice Diameter
3	3.5	3.5.1	Rainout experiments	Horizontal	0.50 m	1"
3	3.5	3.5.2	Rainout experiments	Horizontal	0.50 m	½"
3	3.5	3.5.3	Rainout experiments	Horizontal	0.50 m	¼"
3	3.5	3.5.4	Rainout experiments	Horizontal	1.50 m	1"
3	3.5	3.5.5	Rainout experiments	Horizontal	1.50 m	½"
3	3.5	3.5.6	Rainout experiments	Horizontal	1.50 m	¼"
3	3.5	3.5.7	Rainout experiments	Vertically upward	NA	½"
3	3.5	3.5.8	Rainout experiments	Vertically downward	0.50 m	½"
3	3.5	3.5.9	Rainout experiments	Horizontal into baffle	0.50 m	½"

PS/KIT DISCHA experimental setup is presented below. Experiments were performed at ambient temperature and at a temperature of approx. 80 K. For the cold tests vessel and valve are cooled from outside by a bath of LN_2 at approximately 77 K. Vessel temperature is expected to decrease from 77 K during blowdown. It is to be verified whether compressed gaseous hydrogen will liquefy inside the tank during the blowdown.

All releases are documented by photo-series' that are processed offline using a BOS-algorithm. An example for an original and a processed image of a cold experiment (T ≈ 80 K) with the 4 mm nozzle and an initial pressure of 200 bar is shown in the right part of the following figure 6.

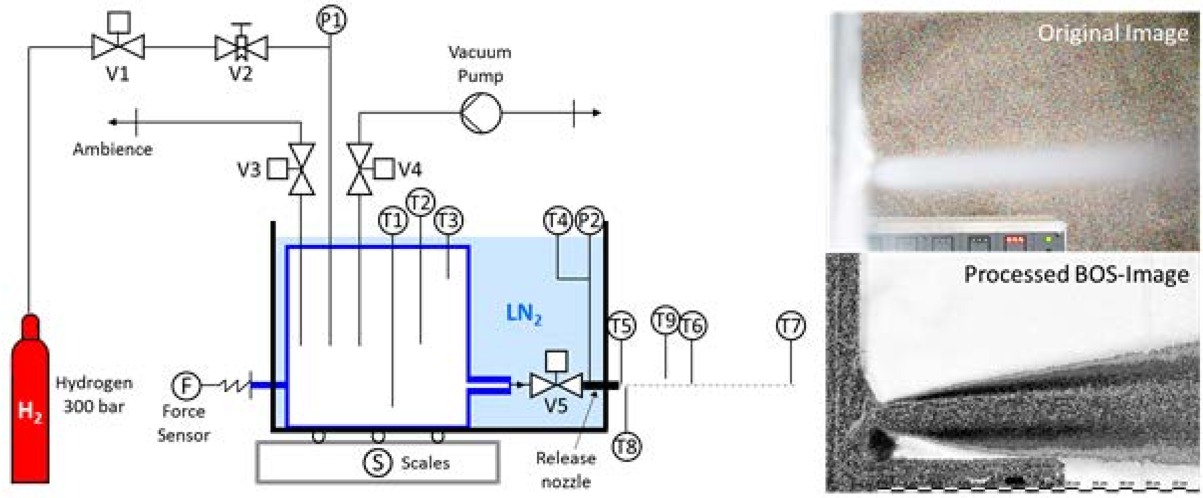

Figure 6: PID of the cold DISCHA tests and photos of a cold experiment (T ≈ 80 K) with the 4 mm nozzle and an initial pressure of 200 bar

In the DISCHA experiments four nozzle diameters (dN = 0.5, 1, 2, 4 mm) were investigated at seven initial pressure stages (pini = 5, 10, 20, 50, 100, 150, 200 bar). Every experiment was repeated at least two times to ensure reproducibility. Selected temperature as well as pressure and H_2-concentration histories for a cold experiment (T ≈ 80 K) with the 4 mm nozzle and an initial pressure of 200 bar are shown in the following graph.

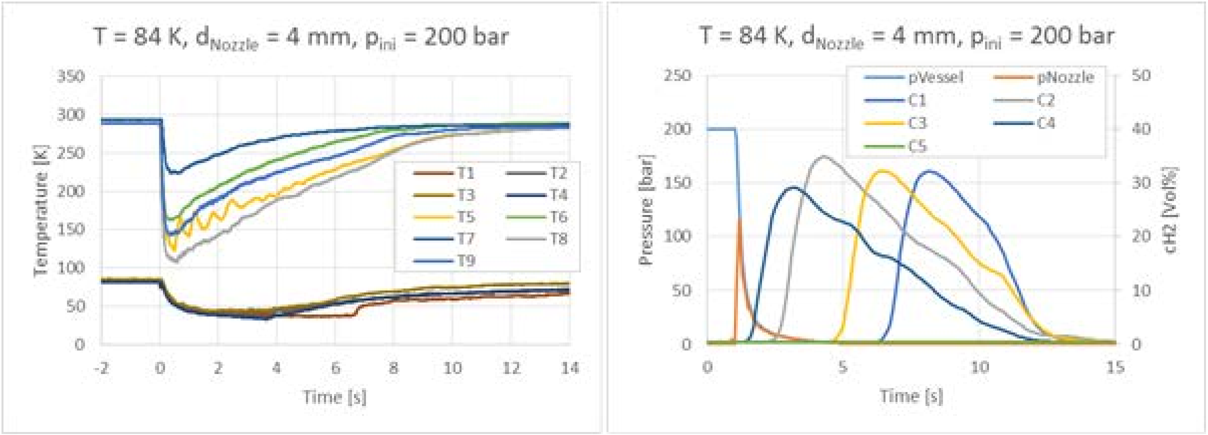

Figure 7: Temperature (left), pressure and H_2-concentration histories (right) for a cold experiment (T ≈ 80 K) with the 4 mm nozzle and an initial pressure of 200 bar.

The experimental setup for the PS/KIT CRYOVESSEL experiments and the pool experiments are shown below. In both of these experiments temperatures near 20K and two-phase release conditions will be reached.

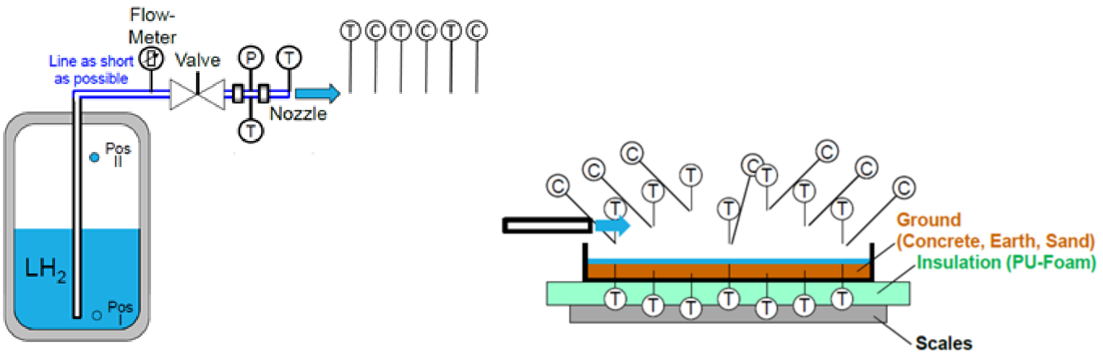

Figure 8: Left: Planned CRYOVESSEL experiments. Right: pool experiments with cross-wind.

5.0 IGNITION PHENOMENA

The primary aim of WP4 is to understand scenarios that are unique to LH_2, which may not have been previously addressed and which may introduce novel, previously unobserved and poorly understood pathways to ignition. These scenarios will be studied through a combination of theoretical, numerical and experimental work. Initial theoretical studies have been undertaken to establish how relevant ignition parameters, such as minimum ignition energy (MIE), relate to practical ignition sources such as electrical devices, electrostatics or hot surfaces. Based on the theoretical studies and identified gaps in understanding of related physical phenomena and their control, the WP4 experimental programme has been developed. In particular, the following areas have been identified:

- The influence of cryogenic temperatures on the evolution of the standard ignition parameters as a function of the temperature;
- The potential for electrical charge generation and accumulation from flowing LH_2 and relevance to foreseen activities;
- The behaviour of multiphase cryogenic mixtures to help understand their capacity to form flammable energetic or explosive hazards.

To complement the theoretical and experimental aspects, University of Ulster have been developing numerical modelling techniques for the evaluation of MIE on spark ignition in H_2-air mixtures. A computational fluid dynamics (CFD) model has been developed to determine the MIE by spark for mixtures at ambient temperature with 10%-55% H_2 content in air. Preliminary results have shown good agreement with experiment and the model will be further developed to numerically evaluate the MIE in mixtures at cryogenic temperature.

The experimental work is underway through programs at INERIS, HSL and KIT. These include:

- Experiments to determine the MIE and flammability domain for low temperature hydrogen (INERIS);
- Hot surface ignition experiments using a vacuum insulated transparent mixing tube, Fig. 9 (INERIS). These experiments are complete and the results have been obtained;
- Electrostatic measurements in a small scale cold jet applying the DISCHA facility, Fig. 11 (KIT/PS);
- Electrostatic measurements in a large scale LH_2 release, Fig. 10 (HSL).

Further experiments are in the planning stage and will be executed later in the project:

- Ignition of a spill of LH_2 (KIT);
- Ignition of H_2/condensed O_2 phase (HSL).

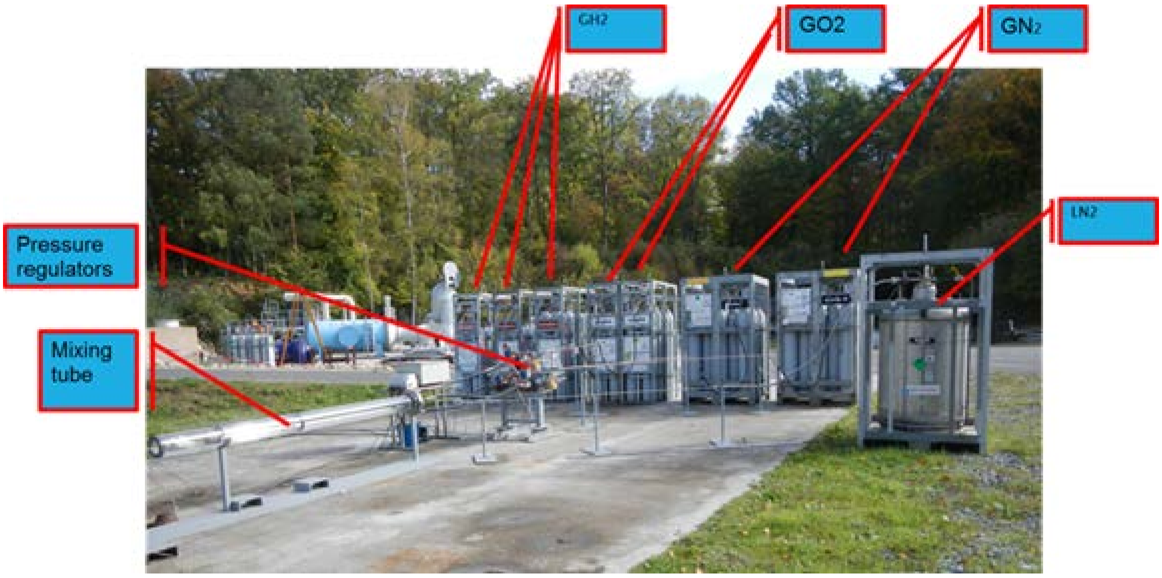

Figure 9: Hot surface ignition apparatus.

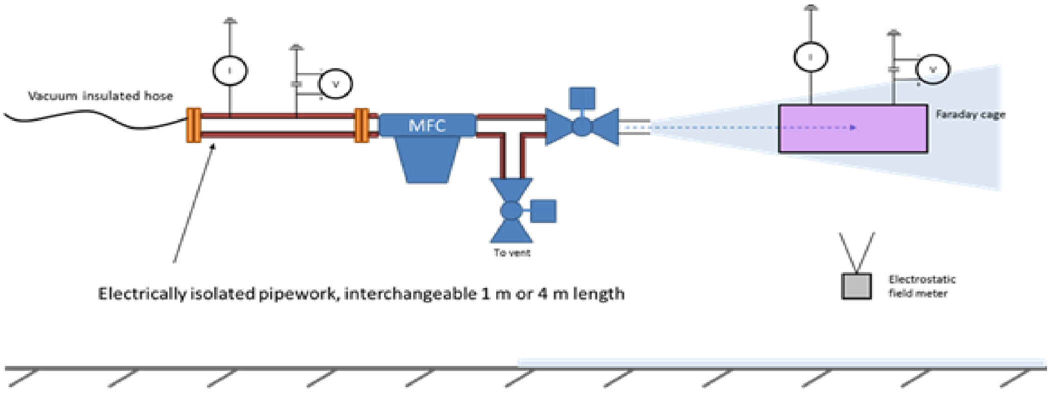

Figure 10: Schematic of the HSL release facility set up for electrostatic measurements.

6.0 PHENOMENA COMBUSTION

There is a big lack of experimental data and numerical simulations on cryogenic hydrogen safety analysis. The only fragmentary experimental and accidental data are known at cryogenic initial conditions. Main objective of WP5 (Combustion) is to perform a complex experimental and analytical study on cryogenic LH_2 combustion, including laminar and turbulent combustion and detonation of LH_2 and gaseous hydrogen in air at cryogenic temperatures and different geometries; then, to analyze experimental data in order to develop and validate existing or to generate new models for LH_2 combustion and, finally, to develop empirical and semi-empirical engineering correlations for practical applications.

The theory and analysis of cryogenic hydrogen combustion is based on general theory of combustion with a difference that because of cryogenic temperature and high pressure the state of combustible matters is condensed, heterogeneous and essentially non-ideal. Independent of the low, cryogenic temperature, the danger of cryogenic hydrogen combustion could be even worse than that at ambient temperature and pressure because of 5-10 times higher density of combustible matters. It compensates for the lower hydrogen reactivity at cryogenic temperatures.

Analytical and numerical models for CFD calculations will be validated against the new and existing experimental data. The feedback between experimental results and recent models and numerical simulations should lead to better understanding of the process, capability to predict characteristics of the processes for LH_2 combustion and to produce a set of simplified engineering correlations to assess a danger of LH_2 combustion with respect to hydrogen safety in general.

Special attention will be paid to the next physical matters:

- Combustion under cryogenic temperatures, at the conditions of real gas state, close to condensed phase density;
- Heterogeneous combustion in presence of condensed (liquid or solid) oxygen, nitrogen, CO_2 and H_2O, an effect of hydrogen rainout should also be taken into account under combustion process;
- Effect of cryogenic temperatures on thermodynamics and kinetics of combustion process leading to several times lower speed of sound and viscosity of the gas;
- Simultaneous combustion and flush evaporation and rapid Phase Transition (RPT) of hydrogen above the spill of LH_2;
- Effect of inverse hydrogen concentration gradient (higher hydrogen concentration at the ground level) on combustion dynamics in a layer geometry;
- Radiation characteristics of LH_2 combustion.

A competitive comparison between partners' CFD-simulations will be performed before ("blind") and after the experiments to choose the most advanced numerical models to be shared between all participants. Best-fitted numerical simulations can then be used to generate the engineering correlations for practical use in safety analysis.

Several series of principal combustion experiments to be done within the WP5 experimental campaign are to close existing knowledge gaps. The major characteristics to be investigated should be the pressure, temperature, heat flux, and characteristic velocity of the processes. Effects of scale and turbulence should also be considered as parameters of the processes. Similar to LH_2 distribution, the combustion analysis shall include confinement geometry and obstructions.

LH_2 jet fire behaviour, including scaling and radiation properties will be investigated again with the DISCHA facility. This facility is already in operation at the preliminary stage of the study with regard to investigation of cryogenic hydrogen release characteristics: mass flow rate and hydrogen distribution as a function of initial pressure and temperature. Main goal is to investigate two phase jet ignition and then jet fire behaviour with respect to maximum combustion pressure, temperature and heat flux radiation for model validation on hazard distances. A side view and principal scheme of the tests is shown in Fig. 11.

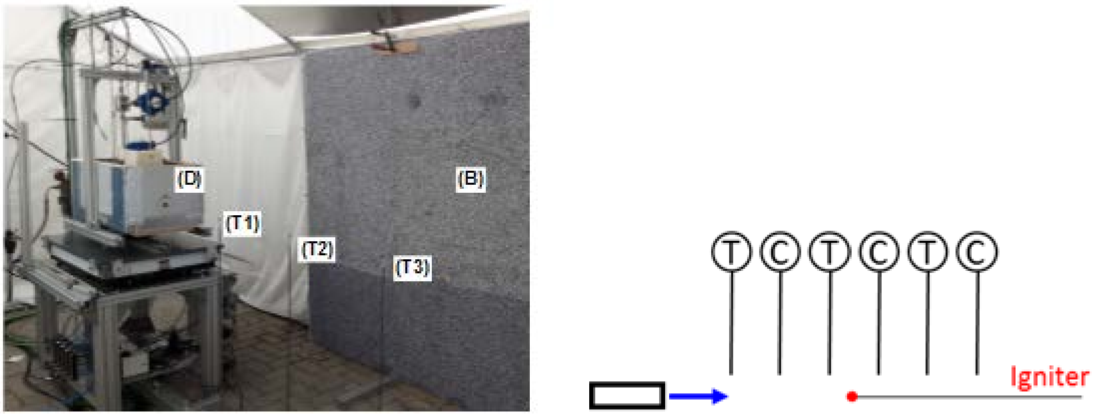

Figure 11: Side view of DISCHA facility (right) and principal scheme (left) of jet fire experiments.

The facility consists of a high pressure vessel with hydrogen exposed at cryogenic temperature of 80K (D) with varied vent orifices (1-4 mm id); (B) stochastic background for BOS imaging; (T1…T3) thermocouples. A side view camera for BOS imaging and a heat flux sensor are out of view zone. Hydrogen inventory will be changed depending on the initial pressure from 4.4 to 138 g H_2 with initial pressure changes from 5 to 200 bar. At the same time, characteristic release time will be changed from 12.1 s to 0.19 s with nozzle changing from 0.5 to 4 mm id. This gives a big chance to reach two-phase flow at 200 bar and 4 mm id. for LH_2-air release.

Then, based on experimental data and calculations, radial safety distances as a function of exposure time can be calculated for different damage degrees as shown in Fig. 12.

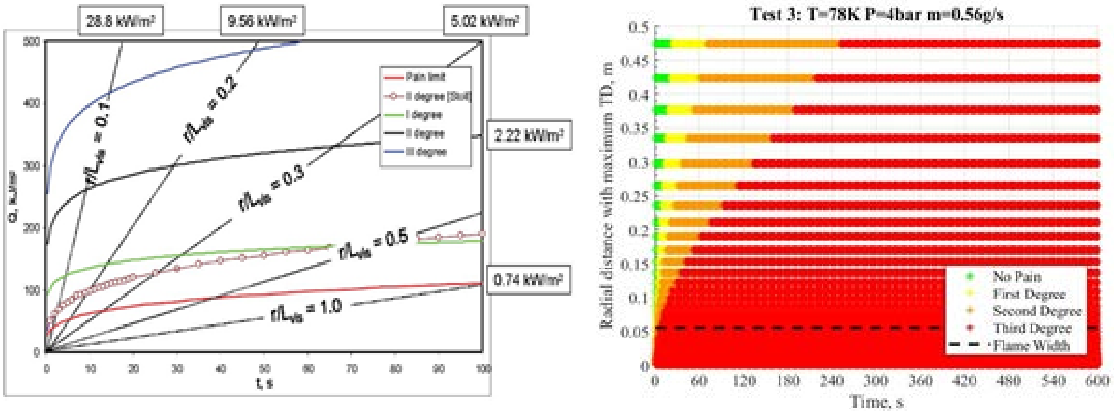

Figure 12: Maximum exposure times for different degrees of skin damage from thermal radiation of cryogenic hydrogen gas jet fires calculated for known experimental data by KIT (left) and UU (right).

In a similar manner other experimental series should be done within the project

- Burning LH_2 pool behaviour, radiation characteristics;
- Cryogenic hydrogen combustion in a layer geometry relevant to flame spread over the spill of LH_2;
- Flame acceleration and deflagration-detonation-transition for cryogenic hydrogen-air clouds in an enclosure. The experiments can also be modified to varied enclosure and blockage degrees, including an open geometry;
- BLEVE associated with distant thermal and pressure loads.

7.0 IMPLEMENTATION - EXPLOITATION AND DISSEMINATION

PRESLHY scientific findings and advancement of knowledge beyond the state-of-the-art are extracted and translated into suitable information and tools for international SDOs, regulatory bodies and industry, so that they can be implemented into performance-based Regulations, Codes and Standards (RCS). This is the main reference for legislative regulations, as suggested by the "modern approach" shown in Figure 13. Moving in this direction, PRESLHY project was presented to the ISO TC 197 committee at the plenary meeting in Vancouver on 6 December 2018. A Preliminary Working Item (PWI) on "Safe Use of Liquid Hydrogen in Non-industrial Settings" was proposed and set up with unanimous support by the committee (PWI N. 24077). Dr. Thomas Jordan, PRESLHY coordinator, was nominated "project manager" of the PWI.

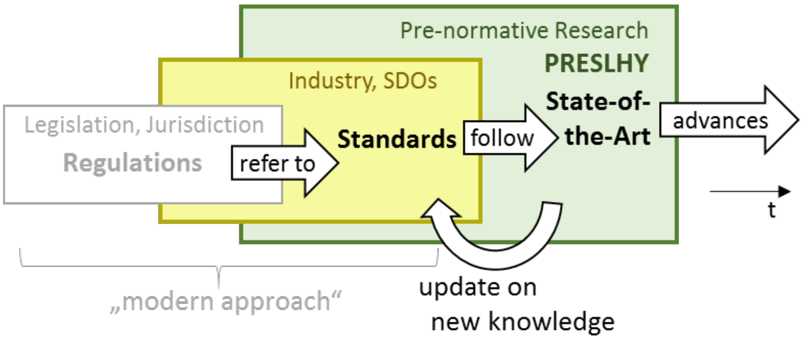

Figure 13: Impact areas and connections among PRESLHY pre-normative research, standardisation and regulation (impact areas of PRESLHY in green and yellow).

The outcomes of the pre-normative research are multiple. The new unique experimental data generated within WP3-5 will be stored in digital format through the KIT open research data repositories [5]. The service assures the data open access to the research community or any interested party for review, verification and validation of analytical and numerical models, etc. Data fulfil Horizon 2020 requirements of being findable, accessible, interoperable and reusable (FAIR).

The generated experimental data are employed to develop and validate analytical models, and to generate empirical and semi-empirical engineering correlations. The purpose is to provide tools for quantifying consequences from possible accident scenarios and associated hazard distance to support inherently safer design of LH_2 systems.

The up-to-date knowledge generated during PRESLHY is gathered in the form of a chapter on safety of liquid and cryo-compressed hydrogen, providing a review of the state-of-the-art, RCS, a description of LH_2 relevant phenomena and key experimental results, developed models and engineering correlations, prevention and mitigation techniques, etc. The chapter complements the Handbook of Hydrogen Safety, originally established by the European Network of Excellence (NoE HySafe) "Safety of hydrogen as an energy carrier" (2004-2009) [6]. The table of contents of the chapter was prepared in December 2018.

The guidelines underpin the inherently safer design and operation of LH_2 systems and infrastructure, addressing the areas where specific RCS have not been established yet or where they are not suitable for use in public space. The innovative strategies and engineering solutions developed during the project will be included in the guidelines following a structure and format resembling established standards, such as [7]. The structure and contents of the guidelines were established in February 2019. The relevant part of the developed guidelines, including the engineering correlations, will be extracted and expressed in concise language for use by SDOs as recommendations for RCS.

The potential benefits of LH_2 systems and infrastructure deployment in the FCH sector, particularly with regards to the mobility sector, will be analysed and reported in a White Paper, to impact the policy making process and influence the development and spread of FCH technology employing liquid or cryo-compressed hydrogen.

PRESLHY programme and outcomes have been extensively presented and disseminated at international meetings and events relevant to several aspects of hydrogen safety, such as IEA HIA Task 37 meeting (October 2018, Saclay, France), Research Priorities Workshop by HySafe (September 2018, Buxton, UK), ISO/TC 197 Hydrogen Technologies meeting (December 2018, Vancouver, Canada), the LH_2 Safety workshop (March 2019, Bergen, Norway), the International School Progress in Hydrogen Safety (March 2019, Belfast, UK), etc. A flyer of the project was developed in November 2018 and distributed at several dissemination events. The project key results and progresses achieved up to date are disseminated through PRESLHY newsletter. The plan includes 4 issues to be released by the end of the project. PRESLHY dissemination activities will culminate with the project conference to be held towards the end of the project in 2020. The conference will involve invited speakers from outside the consortium and participation of collaborators and experts from and beyond Europe. This is thought to increase the impact of the project outputs on the international community working in the field of hydrogen technologies.

8.0 ACKNOWLEDGEMENT

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9.0 LITERATURE

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