Research Priorities Workshop 2022

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Executive Summary

The HySafe standing research committee holds a by invitation only Research Priorities Workshop (RPW) every even year. The 2022 edition was held in Quebec City, Quebec on November 21 – 23, 2022.

The HySafe membership was invited to address the pre-normative research that they are conducting. Speakers at the meeting were asked to discuss their research topics, their perspectives on the present state of the art, where their research is going 5 years into the future, and where their research needs to be 10 years into the future. Presented in the report are the extended abstracts provided by the attendees. At the end of the meeting, participants were asked to prioritize the topics and subtopics.

These data clearly show the level of importance for the different categories addressed here in this workshop. Accident physics of liquid / cryogenic behavior is on top followed closely by Mitigation Sensors, Hazards prevention and Risk. A sharp drop in the priority for Integrated Tools probably represents the fact that many such tools currently exist for use by the industry. While there is still much to be understood about hydrogen effects on materials, the group ranked that about in the middle with a score of 5.5. Accident physics for the Gas Phase ranked pretty low. This is a topic that the pre-normative effort has been spending significant effort on over the past many years. This ranking clearly shows that the topic is reasonably well understood. Applications followed by storage and General Aspects of Safety make up the bottom three levels.

This workshop was excellent in bring out the gaps and directions the research community feels are important.

Introduction

The HySafe standing research committee holds a by invitation only Research Priorities Workshop (RPW) every even year. The 2022 edition was held in Quebec City, Quebec on November 21 – 23, 2022. This report documents that event.

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RPW2022 : UK Hydrogen Context for Regulating Health and Safety

Kate Jeffrey, UK Health and Safety Executive

Current hydrogen market production across the globe is circa 70 billion tonnes, with expected growth to 200 billion tonnes by 2050. Approximately 97% of this hydrogen is consumed at the point of production for refining and ammonia production, methanol and steel production. The UK produces and uses about 700,000 tonnes of hydrogen per annum, the majority of which is 'grey' hydrogen made from natural gas with no carbon capture. The UK Government's 10 Point Plan includes ambitions to drive the growth of low carbon hydrogen, including through significant investment in 'industrial clusters' where heavy industry will convert to use hydrogen in place of fossil fuels. The initial 5GW of low carbon hydrogen in the Hydrogen Strategy in August 2021 has recently been doubled to 10GW of hydrogen production by 2030 in the British Energy Security Strategy. To put into context in 2020 the UK produced less than 30TWh of hydrogen, mainly as grey hydrogen. The UK Government has committed to working with industry to gather evidence to inform a policy decision in 2023 on the potential for up to 20% hydrogen to be blended into the gas distribution grid. Government is also working with industry to undertake 100% hydrogen heating trials (in 2023 and 2025) and make a policy decision on the potential use of 100% hydrogen for heating by 2026. BEIS have made available a number of significant funds to incentivise the hydrogen economy including the £25m for Hy4Heat project looking at the feasibility of converting the gas grid to hydrogen; £23m Hydrogen Transport Programme delivering new hydrogen refuelling stations, £90m into direct research and innovation across the supply chain and the recently announced £240million Net Zero Hydrogen Fund which provides Capex and Devex support to projects. In most cases hydrogen technology is in pilot or early deployment stages. There is a 'chicken and egg' situation between hydrogen supply and hydrogen use where both markets needing to mature at the same time. The current status of development is as follows: A. Hydrogen Production – Onshore i Blue - There are currently no 'blue' hydrogen production sites operating in the UK due to the lack of carbon capture facilities, 8 projects ranging from 200MW to 1 GW were announced in March 2022 to be proceeding to the evaluation stage under Phase 2 of the BEIS Cluster Sequencing process which include links to major Carbon Capture and Storage (CCS) projects ii Green – There are small number of operational electrolysers in the UK, however new projects are being announced including Whitelee Farm, a 20MW hydrogen production and storage facility co-located with onshore wind which aims to be producing hydrogen in 2023. BEIS have also recently announced additional support for electrolytic hydrogen projects. B. Hydrogen Production – Offshore i Offshore hydrogen production is likely to either be co-located with existing oil and gas infrastructure or developed as a hybrid energy model in conjunction with offshore wind. The world's first Hybrid wind models where hydrogen is produced in the column a wind turbine has recently received government funding and is due to be operational in 2025 off the coast of Aberdeen C. Use i Industry – BEIS have been surveying industry to understand the barriers to hydrogen conversion. The Industrial Fuel Switching programme supported projects to look at the feasibility for everything from industrial heating to ceramics and switching baking ovens, oil heaters and steam boilers used in food and drink production to hydrogen. Some strands of the Net Zero Hydrogen Fund (£240m) are looking to support industrial hydrogen projects. ii Transport – Only 15 hydrogen refuelling stations are currently operating in the UK. There are feasibility trials of hydrogen powered vessels being developed in the Thames Estuary and the first hydrogen powered aircraft (which would fly Rotterdam to London) being targeted for 2028. iii Heating – Two trials have been completed on 20% hydrogen blend regulated under exemptions from the provisions of GSMR. BEIS are targeting a policy decision on 100% hydrogen for heating by 2026 D. Storage i The feasibility of large-scale hydrogen storage is being investigated by gas networks who are looking at storage in the gas grid. Others are exploring different types of large-scale storage, including salt caverns ii There are various projects in planning stages including SSE and Equinor proposals for converting the existing Aldborough Gas Storage Facility (capacity 320GW) to hydrogen, which could be operational by 2028. E. Transport of Hydrogen i New hydrogen pipelines associated with industrial clusters are going through the NSIP process to secure planning permission ii Pipelines won’t reach all users and there is an expectation of the use of road, rail and ship for transporting hydrogen.

Hydrogen Sensors Safety Research and Development Advances in the NREL Sensor Laboratory

William Buttner, Matt Post, Kevin Hartmann, Dave Pearman, Ian Palin

The National Renewable Energy Laboratory (NREL) Sensor Laboratory was commissioned in 2010 to serve as a resource for verifying hydrogen sensor performance and for providing guidance on their proper deployment to support the US Department of Energy's (DOE) mission for the safe implementation of hydrogen as an alternative energy source. The Sensor Laboratory is one element of the NREL Hydrogen Research and Development Program (HSR&D), which investigates t e origins and magnitudes of hydrogen releases, and explores strategies to detect and mitigate their occurrence and risk. The HSR&D program structure is illustrated in Figure 1. In addition to hydrogen detection methodologies (e.g., the NREL Sensor Laboratory), the HSR&D program includes the (hydrogen) Component Testing and Reliability task that strives to utilize probabilistic risk mitigation methodologies on a component level to improve hydrogen facility reliability and safety through the integration of failure frequencies with consequence modeling (including quantitation of hydrogen leak rates through failed components) for quantitative risk assessment.

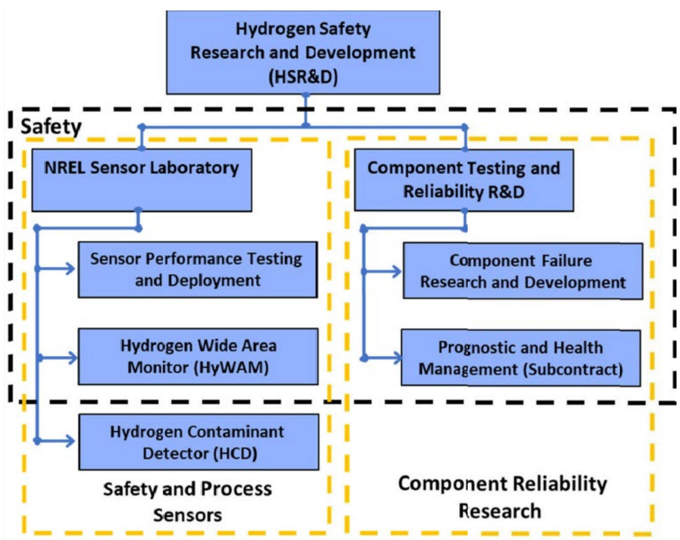

Figure 1: The NREL Hydrogen Safety Research Program.

This talk will focus on hydrogen sensors and detection methodologies. Sensors can play numerous roles in facilitating the use of hydrogen as an energy carrier, including:

- Improved facility safety
- Inventory of product losses along the value stream including both operational and unintentional releases.
- Process control (e.g., verification of fuel quality prior to use in fuel cells or maintaining the composition of natural gas-hydrogen blends)
- Research tools for the elucidation of hydrogen behavior

Hydrogen sensors represent a critical element in a hydrogen facility safety system by enabling the early

detection of unintended hydrogen releases and activation of corrective actions.
Typically, the sensor type can be described as "point sensors" that respond through the direct interaction of hydrogen with a sensing element[1]. The early focus area for the NREL Sensor Laboratory was on assuring the metrological performance of hydrogen point sensors and their proper deployment to optimize their effectiveness as a risk mitigation strategy.

Recently, the Sensor Laboratory R&D program has expanded to exploring advanced hydrogen detection methodologies to accommodate emerging large-scale markets such as those envisioned by the DOE H2@Scale initiative [2] and more recently, the DOE Hydrogen Shot [3]. Point sensors may be inadequate for emerg ng large-scale markets and applications. To address this gap, alternative detection strategies that include wide area monitoring and standoff methods are being explored to meet the safety needs of these emerging markets. The hardware assessment will be supplemented with parallel modelling studies to quantify hydrogen release behavior, which will in turn guide detection deployment strategies. Alternative hydrogen detection methodologies for identifying and characterizing unintended releases include ultrasonic leak detection (ULD), imaging strategies, fiber optic sensor for leak detection, remote interrogation strategies of innovative point sensors, flame detectors, and possibly others not yet included in our investigation. In collaboration with private partners that include both developers of detection systems and operators of hydrogen facilities, the NREL Sensor Laboratory has been characterizing the features and limitations of these methods [4].
Assessment is pending for several of the identified methods, but ULD have been deployed within the NREL Hydrogen Infrastructure Testing and Research Facility. As an illustration, the response of a commercial ULD to an end-fitting failure of a medium pressure storage tank is shown in Figure 2. Deployment of the ULD at a commercial fueling facility is pending.

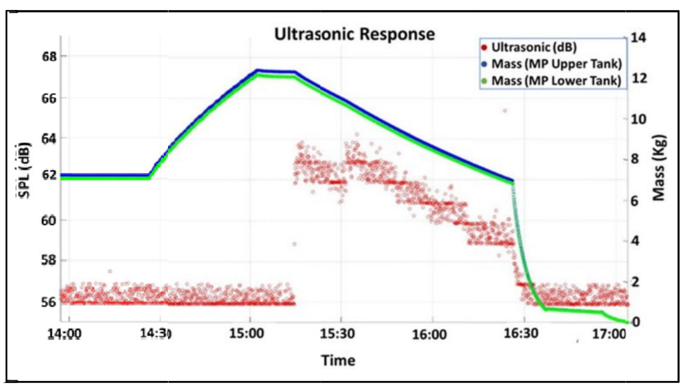

Figure 2: Ultrasonic leak detection (red trace) of the rapid depressurization of two medium pressure hydrogen storage tanks (green and blue trace)

Another emerging area of interest for the Sensor Laboratory is the need to quantify emissions/losses along the hydrogen value chain. Losses may include unintentional releases

[1] A hydrogen sensing element is defined as that component that provides a continuously changing physical quantity in correlation to the surrounding hydrogen volume fraction [1]. (e.g., leaks),

operational releases (e.g., venting or depressurization events), and fugitive releases (e.g., permeation through seals). Losses impact the potential economic success of the hydrogen industry; every molecule lost is one that is not sold to a customer. It has also been postulated that if there are significant losses, hydrogen may have an adverse impact on the environment (e.g., [5]). Vetting of the model and developing the tools to quantify hydrogen emissions is ongoing. Several initiatives exist to support quantifying hydrogen releases, including a recent funding opportunity announcement from DOE to specifically address the need to develop sensors with ppb$_v$ detection limits (see DOE Funding Opportunity Announcement (FOA) Number: DE-FOA-0002792 "Funding Opportunity in Support of the Hydrogen Shot and a University Research Consortium on Grid Resilience", "Topic 2: Development and Validation of Sensor Technology for Monitoring and Measuring Hydrogen Losses"). In response to this development, the NREL sensor laboratory is upgrading testing capability to accommodate sensors with ppbv H_2 range detection limits.

To support the emerging needs for hydrogen detection, the Sensor Laboratory is establishing a hydrogen detection test bed within the NREL Advance Research on Integrated Energy Systems (ARIES) facility [6]. A conceptual illustration of ARIES is given in Figure 3. This facility will be utilized for qualifying the advance hydrogen detection methodologies discussed above for hydrogen safety and to evaluate sensors for emissions monitoring and quantification. ARIES currently has no proximal hydrogen systems, but large scale hydrogen production (1.2 MW electrolyzer), storage, and use (1 MW Fuel Cell) systems will be commissioned within the first quarter of 2023. Background hydrogen measurements at ARIES have been made in collaboration with NOAA. In addition, controlled small, medium, or large scale release of hydrogen can be performed to test detection methodologies and to validate modelling studies.

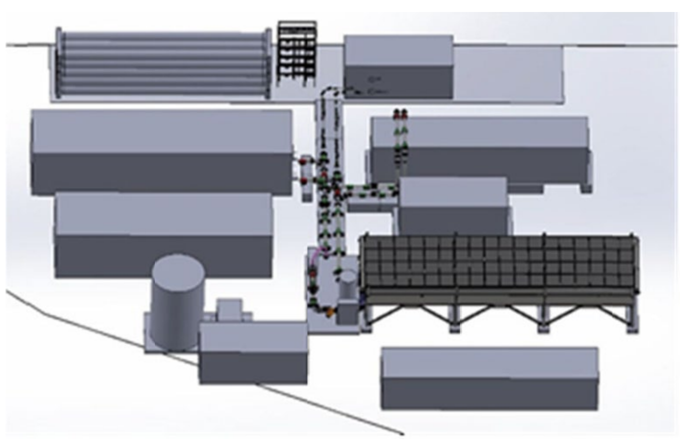

Figure 3: Conceptual illustration of ARIES with on-site hydrogen storage, electrolyzer production, and fuel cell utilization

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6. Ocko, I.B. and Hamburg, S.P., “Climate consequences of hydrogen emissions,” *Atmospheric Chem. Phys.* 22(14):9349–9368, 2022, doi:10.5194/acp-22-9349-2022.
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Progress in Hydrogen Safety at Ulster and Future Research

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The presentation covers progress in hydrogen safety research achieved at Hydrogen Safety Engineering and Research Centre (HySAFER) of Ulster University (UU) within externally funded projects and seeding research, e.g. doctoral studies. The key directions of future research from UU point of view are briefly presented.

The pre-normative research (PNR) project HyTunnel-CS (hytunnel.net) funded by CH JU aimed at allowing hydrogen fuel cell vehicles (HFCV) to enter underground tunnels, car parks and similar confined infrastructure. The safety strategies developed are focused at preventing one of the worst case incident scenarios, i.e. onboard hydrogen storage tank rupture in a fire. The model tank-TPRD system is developed and validated against experiments that allows to design CHSS that excludes flammable mixture formation under the ceiling and thus deflagrations, DDT and detonations. TPRD parameters are investigated that restrict jet flame length to the level sufficient for inherently safer passengers self- evacuation and rescue operations. In particular, numerical and experimental studies demonstrated that a downward release at angle 45° to the vertical through a TPRD of order of 0.5 mm diameter appears to have the best overall performance in terms of flammable cloud formation, flame jet length, combustion products temperatures (it does not exceed 300°C at the ventilation system intake in underground car parks with height 2.1-3.0 m) and adds maximum about 15% to the heat release rate (HRR) in case of light-duty HFCV fire during a short duration. This optimised TPRD diameter has to be validated against fire resistance of CHSS. The breakthrough safety technology of microleak-no-burst (LNB) self-venting (TPRD-less) tanks is a solution of practically all safety concerns of hydrogen storage systems use in confined spaces. It could be efficiently used for safety of hydrogen storage rooms onboard of ships, planes and trains. QRA conducted in the project demonstrated that the risk can be reduced to acceptable level when the fire resistance rating of onboard storage is increased to the order 80-100 min, which can be easily provided by self-venting (TPRD-less) tanks. The presentation reports key closed knowledge gaps and developed/validated models, including blast wave decay correlation in the tunnel developed at Ulster and validated against tests in real tunnel performed by CEA. The outstanding safety issues are named, e.g. hydrogen transport using LH2 tanker in tunnels, accidental release and fire incidents with hydrogen fuelled rail transport in tunnels for CHSS with TPRD, etc.

Unique CFD model of hydrogen refuelling accounting for the entire station components is briefly presented. The validated model is able to simulate the fuelling of compressed gaseous hydrogen for arbitrary parameters and develop fuelling protocols. The CFD simulations reproduced experimental data by Kuroki et al. (2021) accurately predicting hydrogen temperature and pressure through the entire hydrogen refuelling station equipment, including Joule-Thompson effect at PCV, pre-cooler, etc.

LH2 and ammonia storage safety is being addressed via ELVHYS project and seeding research on two- phase flows:

- The development of a CFD model able to predict multi-peaks pressure dynamics in the blast wave after the LH2 storage tank rupture in a fire;
- Modelling and validation of simulations for ammonia evaporation/condensation in a storage

tank during loss of containment or bunkering and effect of ammonia dispersion on hazard distances defined by toxicity and flammability limits of ammonia;
- Modelling and validation of simulations for LH2 evaporation/condensation in a storage tank during loss of containment or bunkering, etc.

Safety of hydrogen-natural gas blends is of particular interest for natural gas providers. The presentation outlines identified knowledge gaps and research needs relevant to distribution and end-use of hydrogen blends in gas networks.

Safety of conformable hydrogen tanks is being investigated in SH2APED project**.** The findings include lower fire resistance of conformable "standard" onboard hydrogen storage tanks with TPRD, significant temperature non-uniformity during refuelling up to 40 C. The issue is solved by LNB tanks.

Coupled CFD+FEM is discussed in the framework of hazards for road, maritime, aviation and rail transport. The accounting the fluid-structure interaction is important for prediction of storage room integrity in the case of incidents with tank rupture.

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Current Status of Hydrogen Materials Compatibility Research in the U.S.

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Historically, the U.S. Department of Energy (DOE) has funded hydrogen materials compatibility research through the Hydrogen and Fuel Cell Technologies Office (HFTO), particularly the Safety, Codes and Standards subprogram. In recent years, several multi-national lab projects have also been funded by DOE- EERE-HFTO to develop a deeper understanding of hydrogen effects on materials, including the Hydrogen Materials Compatibility Consortium (H- Mat) and the Pipeline Blending CRADA (a HyBlendTM project). Other DOE offices have also included materials compatibility aspects in larger programs, most notably in the Subsurface Hydrogen Assessment, Storage and Technology Acceleration (SHASTA) program. Other U.S. government agencies are also funding related work, such as the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA). The PHMSA funding continues to support work on fatigue and fracture testing at the National Institute of Standards and Technology (NIST) as well as pipeline risk work at various universities through the Competitive Academic Agreement Program (CAAP). The remainder of this overview will focus on HFTO-funded work.

The H-Mat consortium is a national laboratory-led project that started in 2019 and focuses on understanding fundamental materials degradation mechanisms in hydrogen. The focus has been primarily around structural materials (such as steel) and polymer materials (often used as seals). H-Mat addresses the challenges of hydrogen degradation by elucidating the mechanisms of hydrogen-materials interactions with the goal of providing science-based strategies that enable (1) the microstructural design of metallic materials for enhanced resistance to hydrogen- assisted fatigue and fracture; and (2) the development of polymeric materials with improved resistance to hydrogen-induced degradation. These two elements are led by Sandia National Laboratories

(SNL) and Pacific Northwest National Laboratory (PNNL) respectively. The consortium aspect of H-Mat extends beyond the national laboratories and includes competitively funded projects, which are expected to leverage the unique capabilities for hydrogen studies at the national laboratories.

The Pipeline Blending CRADA (a HyBlendTM project) assembles a multi-lab, multi-industry team to address high-priority research topics related to the blending of hydrogen into the U.S. natural gas pipeline network. This project is led by the National Renewable Energy Laboratory (NREL) and includes materials compatibility studies at SNL and PNNL. One of the main objectives of this CRADA is to develop general principles for operation of blended delivery systems in the context of structural integrity and assess the role of gas impurities on degradation of transmission (metal) pipelines and distribution (principally polymer) piping.

The third major research program with significant elements of materials compatibility research is the Safety, Codes & Standards (SCS) subprogram (which also includes other topics). The hydrogen compatible materials and components activity has several broad objectives: 1) optimize the reliability and efficiency of test methods for structural materials and components in hydrogen gas; 2) Generate critical hydrogen compatibility data for structural materials to enable technology deployment; 3) Create and maintain information resources such as the "Technical Reference for Hydrogen Compatibility of Materials"[1]; and 4) Demonstrate leadership in the international harmonization of codes. Existing codes and standards in the U.S. with materials compatibility requirements or guidance invariably trace back to the SCS program. Additionally, significant knowledge of trends in hydrogen materials compatibility has roots in the SCS program, including definitive informational resources such as the Technical Reference for Hydrogen Compatibility of Materials[1]. Moreover, the other programs in materials were generally born from and contribute to the SCS program; for example, test methods developed in the SCS program are used to improve testing efficiency in both H-Mat and HyBlend™ projects, whereas results from these programs provide foundational information that form the scientific basis for the SCS code coordination activities.

The SCS materials program has historically made significant contributions to safety, codes and standards and these contributions continue to influence the codes. Fatigue crack growth rate measurements in high- pressure gaseous hydrogen of steels used for stationary storage vessels recently led to development of an ASME Code Case 2938, which reduced the test burden by developing fatigue design curves which were shown to extend life by 3X, based on case studies. In addition, analysis was performed to demonstrate the benefits and methods of cycle counting to maximize the usable life of pressure vessels. National laboratory leadership in international committees and working groups has led to harmonization of test method requirements and language in ISO working groups, SAE, and GTR around materials compatibility with hydrogen.

In the Pipeline Blending CRADA (HyBlend™project), fatigue and fracture testing in gaseous hydrogen has been performed on a variety of pipeline grades and welding techniques from modern and vintage (1940- 1960s) pipes. From a high level, the behavior of vintage pipes is quite similar to modern pipes in terms of their susceptibility to hydrogen embrittlement. Broadly speaking, there does not appear to be a significant effect of microstructure, strength, or age of the pipe when evaluating fatigue properties for the range of grades evaluated (e.g. X52 to X80). Fracture toughness of pipeline steels appears to be sensitive to strength, especially at higher tensile strengths (>700 MPa). Complementary work within the H-Mat project independently revealed dependence of fracture performance on strength for pressure

[1] [1]https://www.sandia.gov/matlstechref/

vessel steels and the lack of significant microstructural influence on hydrogen-assisted fracture. Similar results from the SCS program had already influenced the ASME codes, and these more recent discoveries will likely influence future code developments.

Future research areas in hydrogen compatibility of materials include:

- Revision of ASME B31.12 Hydrogen Piping and Pipelines Code, as the world looks to this code in navigating hydrogen blends in pipelines and testing requirements.
- Evaluation of materials used in existing infrastructure where blended gases are being proposed, with particular consideration for materials not intended for hydrogen service, including both hydrogen storage and hydrogen conveyance.
- Quantification of the influence of gas impurities on hydrogen-assisted fatigue andfracture; as small amounts of impurities can mask the effects of hydrogen in accelerated testing, but these accelerated results may not be indicative of long-term effects in infrastructure.
- Bridging the gap between laboratory-accelerated test methods and real-world environmental response by clarifying the role of time in accelerated testing methods.
- Elucidation of aging behavior of soft materials in hydrogen environments to identify long-term potential hydrogen-induced failure modes in polymeric materials
- Provide physics-based description of hydrogen-assisted fatigue and fracture to aid development of predictive engineering design tools and strategies for materials design to accommodate the influence of hydrogen degradation
- Development of probabilistic frameworks for materials evaluation and structural integrity assessment to complement physics-based QRA frameworks, such as HyRAM+
- Clarification of the phenomenology of hydrogen-assisted fracture at low temperature to inform potential long-term structural degradation mechanisms at LH2 temperature
- Quantification of hydrogen-assisted fatigue and fracture at elevated temperature to enable high-temperature applications such as hydrogen combustion for power generation, solid-oxide fuel cells and electrolyzers

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Project STACY - Towards Safe Storage and Transportation of Cryogenic Hydrogen

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World-wide efforts aim at the decarbonization of the energy sector with an increasing fraction of renewable energies in the energy mix. Energy storage technologies are required to store excess energy generated from fluctuating sources to making it accessible on demand. In this context, the large-scale storage and transportation of liquefied (cryogenic) hydrogen (LH2) can be expected to play a fundamental role in a potential future hydrogen economy due to its high storage density. Ensuring safe implementation of LH2 storage and transportation technologies is mandatory with regard to economic benefit and public acceptance.

The European Interest Group (EIG) CONCERT-Japan joins 13 science, technology and innovation (STI) funding agencies from 11 European countries and Japan (JST), strengthening Japanese-European research collaboration in a variety of fields. In the framework of the recent call "Sustainable Hydrogen Technology as Affordable and Clean Energy", the EIG supports sustainable and multilateral research cooperation, especially promoting the transnational mobility between European and Japanese researchers.

The overall aim of the STACY project is to contribute to the safety of LH2 storage and transportation by

(1) experimentally determining fundamental safety-related parameters of hydrogen combustion not yet available for very low temperatures,

Combustion of hydrogen and the phenomena behind the initiation of an explosion have been the subject of studies for several decades. While there is numerous data about hydrogen explosion at standard conditions of pressure and temperature, little is known about the explosion propensity of hydrogen at cryogenic conditions, which are responsible for a large change in the combustion properties. Among others, three fundamental combustion parameters – the flammability domain, the laminar flame speed, the expansion ratio – will be determined at cryogenic temperatures.

(2) developing and qualifying novel catalysts for catalytic recombiners to prevent the formation of flammable gas mixtures in case of LH2 leakages,

Dilution and ventilation of hydrogen releases in closed or semi-confined environments are the most efficient means to avoid the formation of flammable mixtures. However, in specific low- ventilated areas, e.g. on a maritime hydrogen carrier, catalytic recombiners can provide a relevant hydrogen sink. While recombiners have been qualified for elevated temperatures and pressures, no knowledge exists on the operational performance at low temperatures. The specific objective is to develop and qualify a novel catalyst to operate under the typical conditions of LH2 applications.

(3) applying advanced numerical tools to study scenarios of potential hydrogen leakages and

assessing the efficiency of mitigation measures.

Although hydrogen leakages and formation of flammable gas mixtures has been studied since a long time, the specific conditions of LH2 applications, such as low temperature, specifics of the geometry, natural ventilation, still represent challenging boundary conditions. The specific objective is to apply well-proved codes on the simulation of hydrogen distribution and mixing to identify potential modelling gaps, study potential accident scenarios and provide information on potential boundary conditions and locations for additional mitigation measures.

In an interdisciplinary approach, STACY brings together high-level experts from internationally recognized institutions in the fields of combustion (CNRS-ICARE), recombination (FZJ), catalyst development (KGU), and safety assessment (IRSN). The relevance of the scientific research is to be ensured by the Industrial Advisory Board (IAB), which is constituted of experts from high-level industries and institutions: Kawasaki Heavy Industries (Japan, LH2 carrier builder), Daihatsu Motor Co., Ltd. (Japan, LH2 storage, car catalyst), Air Liquide (France, production, storage, and distribution of GH2 and LH2), Chemical Consulting Dornseiffer (Germany, prototyping catalytic systems), Japan Atomic Energy Agency (Japan, hydrogen safety, catalytic recombiners), EnerSys-Hawker (Germany, catalytic recombiners).

Bringing well-established safety knowhow and technology from nuclear hydrogen safety to hydrogen storage and transportation in the non-nuclear energy sector represents a knowledge transfer across artificial borders, contributing to tear down traditional walls between nuclear and non-nuclear research. Dissemination activities include Young Generation Workshops in the three participating countries involving national and international students as well as the connection with networks such as the International Association HySafe to ensure reaching a wide audience beyond Europe and Japan.

Risk and Environmental Impact Assessment for a Salt Cavern Hydrogen Storage

Benno Weinberger, Ineris

1 RESEARCH TOPIC

The EU aims to be climate-neutral by 2050[i] with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment[ii] to global climate action under the Paris Agreement[iii].

Hydrogen underground storage is seen as a key solution to tackle the storage problem related to the intermittence of renewable energy that is necessary to get climate neutral.

The concept would be using hydrogen as energy carrier produced by (excess) renewable electricity and then stored in underground storage and coupled with the existing natural gas pipe networks.

For the same investment a gas pipe can transport 10-20 times more energy than an electricity cable[iv]. Moreover, most industrial high-temperature heat demand, currently served by natural gas and other new appliances in steel and concrete industry can be provided by hydrogen. Regarding the safety the following topics should get addressed:

- Leak detection and loss technics of hydrogen for the underground storage
- Early leak detection mesh of the huge hydrogen installations on the top
- Microbiologic transforming of hydrogen in other substances
- Physical stability of the underground storage related to the higher pressures and higher number of pressure cycles compared to natural gas
- Better understanding of the phenomena that occurs during large hydrogen releases that could occur with accidental scenarios with underground storages

2 PRESENT STATE OF THE ART

Today six underground pure hydrogen storage salt caverns are in operation over the world, in the U.K. and the U.S.A.[v]:

- In Teesside in the United Kingdom, where for more than 30 years, 3 salt caverns of 70,000 m3. Each can store 1 million Nm3 of almost pure hydrogen (95% H2 and 3-4% CO2). These salt caverns are located at an average depth of 370 m.
- At Clemens Dome, Lake Jackson in Texas (USA) where, since 1986, Conoco Philips has stored 30.2 Mm3 of hydrogen from synthesis gas (95% hydrogen) in a salt cavern. The salt cavern has a geometric volume of 580,000 m3 and is operated between 7-13.5 MPa with a minimum calorific value of 92 MWh.
- In Moss Bluff, Liberty County, Texas (USA), where, since 2007, Praxair has stored 70.8 Mm3 of industrial hydrogen in a salt cavern. The cavern has a geometric volume of 566,000 m3 and is operated between 7.6 and 13.4 MPa with a minimum calorific value of 80 GWh.
- At Spindletop Dome, in Beaumont, Texas (USA), Air Liquide recently commissioned the largest underground hydrogen storage facility in a salt cavern in the world. The saline cavern is located at a depth of 1500 m and about 70 m in diameter.

Although these salt caverns are in operation since long time, very little information is available regarding subsurface equipment design and material selection versus the specific issues to be addressed with hydrogen and lessons learned.

3 WHERE RESEARCH SHOULD BE INTO THE FUTURE

Giving a timeline about the research topics that must be obtained in the future are somehow like a look into the crystal ball, taking in account the very fast changing political agenda.

What must be obtained is a very well understanding of all hazardous phenomena that could occur with massive hydrogen storage in salt caverns. Regarding the huge storage capacity that is need according to the actual political agenda to decarbonize Europe, possible mitigation measures that address all hazardous phenomena must be checked on their reliability and effectiveness.

Further these research results need to find acceptance by all stakeholders (NGOs, industrials, regulators…).

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[i] 2050 long-term strategy; Source: 2050 long-term strategy (europa.eu)

[ii] A European Green Deal Striving to be the first climate-neutral continent; Source: A European Green Deal (europa.eu)

[iii] The Paris Agreement, Source: https://unfccc.int/process-and-meetings/the-paris-agreement

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[v] Michael Ball, Angelo Basile and T. Nejat Veziroğlu., Compendium of Hydrogen Energy, 2016, ISBN: 9781782423645

Status of Hydrogen Release Behavior and Quantitative Risk Research

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Sandia National Laboratories has had a program to support science-based codes and standards for hydrogen since 2003. Significant efforts have been made to develop both models and data for the behavior and quantitative risk assessment (QRA) of hydrogen, as well as the application of these models and data to better inform safety codes and standards. These data and models are incorporated into the publicly-available and open-source Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) software toolkit. HyRAM+ contains fast running models for hydrogen behavior including dispersion, accumulation in enclosures, flames, and overpressure from delayed ignition as well as a rigorous, repeatable quantitative risk assessment method that incorporates leak frequency data specific to hydrogen.

Hydrogen is non-toxic but flammable, and therefore the hazards associated with the use of hydrogen are related to its flammability, flames, and other combustion-related phenomena (e.g., overpressure). HyRAM+ contains a one-dimensional dispersion model and a one- dimensional flame model, both of which can account for buoyancy, predicting average concentration (dispersion) or mixture fraction (flame), velocity, and temperature profiles for releases from low to high pressure, and from cryogenic to ambient temperatures. Small leaks of liquid hydrogen (saturated liquid or saturated vapor) are modeled assuming that the fuel vaporizes close to the leak point due to the heat from entrained air before dispersing and mixing with air as a (cryogenic but warming) gas. Recent updates to HyRAM+ improved the flow modeling for liquid hydrogen through an orifice, implementing a homogeneous equilibrium flow model that searches for a maximum mass flux rather than relying on the uncertain speed of sound for a two-phase flow. Flowrates were recently compared to two liquid hydrogen experimental data sets and generally predicted either accurate or much higher flowrates than were measured experimentally. The model has also been validated for ambient temperature high-pressure flow through an orifice. A second key piece to modeling is in the expansion of fluid that can remain above ambient pressure at the orifice to ambient pressure in the downstream dispersion model. Several models in the literature can result in a range of distribution profiles; a universal notional nozzle model could improve predictions. Current experimental work is obtaining laboratory-scale dispersion data for hydrogen/methane mixtures relevant for natural gas blends.

QRAs are constructed for a system based on the specified fuel state, pressure, temperature, typical pipe size, and comprising components. Based on the fuel type and fuel phase, component leak frequencies are estimated using Bayesian statistical models for a range of leak sizes relative to the system's pipe size. Recent work has estimated leak frequencies for liquid hydrogen components via proxy data sets, but more information specific to liquid hydrogen is needed. Coupling consequence probability and leak frequencies, all derived based on the system configuration, results in risk estimates. The probability of immediate or delayed ignition of a hydrogen leak is critical to these risk estimates, although the current basis for these probabilities lacks validation with real-world data. Through implementation uncertainty quantification, sensitivity analysis will also become possible, which will provide quantification of the impact of uncertainties sources on predicted quantities. The data-basis for component leak frequencies is expected to improve as additional systems come online and recorded operational time expands exponentially.

Both behavior and risk models were recently used to justify revisions to bulk liquid hydrogen storage setback distances in the NFPA 2 code. A representative storage system was analyzed using the QRA and behavior models in HyRAM+. Equivalent fractional hole sizes were obtained that would lead to the same separation distances as risk-based. A sensitivity study on these equivalent hole sizes was performed, and this led to the selection of a 5% of pipe flow area as the basis for separation distance calculations. Physical hazard criteria for different exposure types were then used with the behavior models in HyRAM+ to obtain different setback distances for different exposure types. This risk-informed methodology is a good example of how a combination of risk calculations, behavior models, and sensitivity analyses can be used to account for uncertainty and variability in the calculations themselves, and can still produce actionable insights to inform code requirements.

In the next five years, an experimentally-validated liquid pooling model should be developed. Additionally, better quantification for the use of barrier walls (and other leak mitigations) can enable these to be used more widely as appropriate. As a community, evaluation of different models for the same phenomena (e.g., notional nozzle models, overpressure models) should be undertaken and a universal model should be developed (or the proper selection of a model under the right conditions). Empirical component leak frequency models should be developed based on a significant in-field data basis. Physics based ignition probability characterizations will become available as experiments able to inform such characterizations are developed.

Longer term (5-10 years), an understanding of the condensation of oxygen and nitrogen into liquid hydrogen through experimentation is needed as well as models for this phenomenon. As large-scale hydrogen storage is developed, an understanding of permeation and dispersion through soil will be important to the safety of these systems. Additional operating data for different applications should allow not just for additional risk-relevant data, but also for more nuanced databases for components and applications of different types. Finally, a more consistent consensus about risk assessment methodologies for different applications, including spatial awareness for barrier walls and overpressure effects, should allow for more consistent assessments for similar types of systems.

Safety of Cryogenic 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. 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.

Since the previous RPW in 2020 the European FCH JU funded project PRESLHY and the Norwegian project SH2IFT accomplished their ambitious experimental programs dedicated to prioritised fundamental issues related to the accidental behaviour of liquid or cryogenic hydrogen.

For the release phenomena, data for determining discharge coefficients for cryo- and cryo- compressed releases have been determined, the mixing behaviour and rainout phenomena are now better understood.

With regard to ignition MIE and hot surface temperature have been determined for cryogenic conditions. In hundreds of discharge experiments of PRESLHY no spontaneous ignitions have been observed. The electrostatic fields generated by the cryogenic releases increase with discharge pressure, however, obviously do not suffice to ignite the released inventories. The variation of the dedicated ignition location and timing has delivered a correlation for worst effects in a transient release of small inventories. Empirical tests for RPT and BLEVE in the SH2IFT project have shown that both phenomena occur under realistic conditions. In the RPT tests, spilling LH2 into water, even a reliable ignition above the injection point was observed. So, these phenomena should be further investigated and considered in corresponding safety assessments, and finally in the safe design and operation.

In the combustion domain existing flame length correlations have been validated also for the cryogenic domain and σ, σ_crit and run-up distance for DDT have been determined at cryogenic conditions.

Part of these new learnings are currently injected in a revision of the ISO TR 15916 and stimulated follow-up projects like ELVHYS (Enhancing Liquid and Vapourised HYdrogen Safety, a Clean Hydrogen Partnership supported project 01/2024-12/2026). ELVHYS will focus on the safe transfer of LH2 and therefore is more applied.

Besides the following knowledge gaps are considered important: material compatibility with cryogenic hydrogen, improved thermodynamic modelling in multiphase, non- equilibrium, close to critical conditions and reaction kinetics, induction times and detonation cell sizes for cryogenic conditions. Also, the multiphase effects on large scale dispersion and the combustions transients with obstruction and/or (partial) confinement need better understanding. The better understanding of the fundamental behaviour shall help solving more applied open issues, like proper design and approval of e.g. safety valves and heat insulation and improve the quality of associated risk assessments and mitigation strategies (sensor placement, ventilation,...). Other quite applied open issues are crash testing of LH_2 tanks and quenching behaviour of LH_2 cooled high temperature superconductors.

Research Priorities on Hydrogen Safety at BAM

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BAM is already active in different fields of in hydrogen safety research for more than 125 years. In 2020, BAM decided to coordinate its various competencies and research activities on hydrogen safety in the competence center H2Safety@BAM. The center is structured in five competence areas:

- Material properties and compatibility
- Component testing, component safety and approval
- Sensor technology, analytics and certified reference materials
- Process and plant safety
- Cross-cutting topics

Following some of the main issues addressed in the different fields of research for the next years are summarized separately.

The compatibility of metallic materials, polymers, composites and lubricants with hydrogen is investigated. Mainly two fields of application are addressed:

- Compression, transport and storage of high pressure (1000 bar) and purity hydrogen such as in filling stations
- Transport and storage of hydrogen in existing natural gas infrastructure (pipe- lines, underground storage, etc.) in moderate pressures blended with natural gas

Information on material compatibility is partially available for the majority of materials. The influence of hydrogen on different materials is strongly depending on the conditions and also on the history of the materials, especially in existing gas infrastructure. Validated testing methods are developed in lab-scale as well as in real scale in order to allow reliable statements on the compatibility transferable to real conditions. The main focus is given to the development of the hollow tensile technique. In parallel a modular test facility for investigation of components in real scale is developed. This facility allows the conditioning of pipeline segments and components, considering also critical conditions, exceedance of boundary conditions and bursting of components. The overall goal is to provide conclusive information on the suitability of various materials under process conditions and also a deeper understanding of failure mechanisms by applying analytical methods. Scientific and practical criteria for the use of materials with hydrogen shall be delivered. In this context the influence of the pipeline material on the gas quality is another research topic that is planned to be addressed.

Consequences of accidental scenarios are investigated considering infrastructures with large inventories of hydrogen in the public domain. Mainly the following areas are focused:

- Release and ignition of hydrogen or hydrogen-mixtures, especially at high pressure
- Accidental scenarios in context with LH2
- Specific safety concepts

Various models for hydrogen releases are available. Comprehensive and reliable experimental data for the validation of the models considering specific conditions is scarce. The experimental possibilities for investigating the release of hydrogen at real scale are extended to obtain reliable experimental data for the validation and development of models for free jet releases and the ignition of free jets considering also constant high-pressure releases with varying directions.

In context with LH2, recently the accidental LH2 release in water during ship transport was investigated experimentally. Based on this work spontaneous ignition phenomena in the gas phase, that were observed reproducibly shall be further investigated in future to understand the nature of the ignition source and possibly derive mitigation strategies. Moreover, the behaviour of LH2-tanks and especially the multi-layer insulations involved in fire is further investigated focussing on the behaviour of the multi-layer insulations and the tanks under thermal load.

Safety concepts for the safe use of hydrogen are established especially in the industrial sector. A direct transfer of these safety concepts on technologies and applications in the non-industrial sector handling large amounts of hydrogen is not possible considering the feasibility of organizational safety measures and the extent of losses. More PNR is necessary as a basis for the development and advancement of more specific safety concepts and practical methods considering these circumstances. In this light, it is further intended to investigate specific safety concepts and accidental scenarios for example in context with PtX-plants.

Predictive Tools for Consequence Analysis of Liquid Hydrogen–Achievement and Knowledge Gaps

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This presentation will provide an overview of the efforts and achievement of my team in developing computational fluid dynamics (CFD) based consequence models. The development was conducted within the frame of open source CFD code OpenFOAM. They are implemented in our in-house modified version of the code, for the release, dispersion, jet fires, explosion incorporating deflagration to detonation transition (DDT). The individual new solvers developed within the frame of OpenFOAM have been consolidated into HyFOAM, which is a proprietary code for in-house research and work for our sponsors.

The focus of the presentation will be the more recent developments for predicting the loss of containment (LOC) scenarios of liquid hydrogen (LH_2), covering the formation and dispersion of LH_2 vapour cloud from sudden catastrophic release, LH_2 vapour cloud from jet release, flash fires and vapour cloud explosions (VCE). Some brief comments will be provided along with validation, highlighting the gaps I see in experimental data as well as underlying physics in the model.

As most of the work has not been published. Some critical details will be omitted from the presentation.

Safety Distance Methodologies

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Determining safety distances have always been of paramount importance, but, as new installations are being built closer to densely populated areas, the relevance of accurate safety distances has risen even more. Safety distance determination on several occasions been identified as one of the major challenges for the wide implementation of hydrogen in society.

There exist primarily two ways to determine the safety distance in practice today – either deterministic determination based on a credible worst-case or a probabilistic based on quantitative risk analysis (QRA). Both these approaches suffer from their own limitations.

For QRA, there is always a lack of appropriate data leading to quite disparate results between users even when given the same case. To tackle this from a legislator's perspective, some countries (e.g. the Netherlands) have prescribed what input data to use.
Standardization is, however, a two-edged sword and the benefits and limitations of such an approach are currently a topic of a PhD at Lund University. To reduce the uncertainty regarding frequencies, there are several international efforts currently being performed, including SAFEN and IEA Task 43 part E, that will provide vital information in the near future.

The main limitation of the deterministic approach is that the selection of credible worst- case is subjective, resulting in disparate results between countries. It is also difficult to account for active protection systems where neither perfect nor zero reliability is a viable assumption. In this presentation, a third approach will be put forward which is between these two extremes. In the method, the percentile of the credible worst case is varied depending on the gravity of the consequence, in line with the F-N-curve of QRA. This also allows for accounting for active protection systems since they reduce the leak size for each percentile.

However, no method is without its limitations, and, in parallel to the deterministic approach, subjective assumptions are needed, and the frequency assessment is, by necessity, much simplified compared to a QRA. Despite this, the method is believed to be useful, especially in countries without a tradition of QRA and where the authorities are skeptical about this approach (e.g. Sweden). The method needs further development and validation in the coming years before being used.

Apart from methodological challenges, there is also a range of different specific research needs that should be investigated during the coming 5-year-period.

- Model for predicting momentum and buoyancy dominated regimes for combustion products – similar to what is available for unignited releases.
- Further investigate the "lower hazardous limit" as an alternative to "lower flammability limit" in different situations.
- Models for ground diffusion of underground pipeline leaks.
- Model safety distance determination scheme for new applications (e.g. liquid,

pipelines).
- Investigation of unconfined detonations for impinging jets (following the accident in Sandvika Norway 2019)
- Influence of mild (~10-15 kW/m^2) heat radiation on type-IV-tanks over long durations (e.g. 30-60 min).
- Interaction between droplets (e.g. rain and sprinkler) and deflagrations.
- Pressure from delayed ignition of jets in different situations
- Design of barriers for hydrogen jets.
- A predictive model for emitted radiation, including wavelength spectra accounting for, for example, air humidity and particles.
- Investigating the effect of UV-radiation on sensitive human organs (e.g. the eyes).
- Investigating the ignition of combustible materials exposed to hydrogen jet flames.

When the challenges above are solved, more accurate safety distances can be determined, resulting in that both safer and, potentially, shorter distances when less conservatism is needed.

Hydrogen Safety Research at the University of Bergen

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Introduction

The research activities related to hydrogen safety at the University of Bergen (UiB) focus on various aspects of the Strength of Knowledge (SoK) in risk assessments, with special emphasis on maritime applications. Conventional risk assessments entail the estimation of expectation values that combine event frequencies and associated consequences for the hazards identified for a specific system. There is, however, increasing awareness and recognition of the importance of reflecting knowledge and expressing uncertainty in the understanding, analysis, assessment, management, and communication of risk (Flage & Aven, 2009; Aven, 2010).

Since the explosion at the hydrogen refuelling station in Sandvika on 10 June 2019, most of the refuelling stations in Norway remain closed, plans for new stations have been abandoned, and there is limited focus on the use of hydrogen for road transport. There are, however, numerous initiatives towards maritime applications of hydrogen in Norway. One example is MF Hydra, the first ferry fuelled by liquid hydrogen (LH2).

One of the main challenges associated with the use of hydrogen as a fuel for ships is to achieve and document compliance with the general goals and functional requirements outlined in Part A of the IGF Code (IMO, 2016), such as §3.2.1:

> *"The safety, reliability and dependability of the systems shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery."*

International legislation specifies that the flash point for the bunker oils used by ships must be at least 60 °C. This is an effective means of preventing the formation of explosive atmospheres after loss of containment. Furthermore, §4.3 of the IGF Code specifies strict limitations with respect to the 'permissible' consequences of explosions on merchant ships fuelled by low-flashpoint fuels (LFFs), including hydrogen. To this end, it is essential to critically assess the knowledge and uncertainty behind the risk assessments used for documenting compliance with the IGF Code, since this ultimately may prevent serious accidents that will delay or terminate further development and deployment of hydrogen technologies in the maritime sector.

The starting point for the research activities at UiB related to the SoK for hydrogen systems is the crude direct grading approach proposed by Aven (2013), where the SoK is considered *weak* if one or more of the conditions below are met:

1. The assumptions made represent strong simplifications.
2. Data are not available or are unreliable.
3. There is lack of agreement/consensus among experts.
4. The phenomena involved are not well understood and/or models are non-existent or known/believed to give poor predictions.

On the other hand, the SoK is considered *strong* if all the following conditions are met:

1. The assumptions made are seen as very reasonable.
2. Much reliable data are available.
3. There is broad agreement/consensus among experts.
4. The phenomena involved are well understood and the models used are known to give predictions

with the required accuracy.

Some of the research projects also address aspects such as:

5. The framing of hydrogen safety in the public discourse (Bentsen *et al.*, 2023).
6. The awareness of critical safety-related properties of hydrogen and hydrogen-based fuels amongst relevant stakeholders, including the public.
7. Researcher training and education.

Research projects and international collaboration

The following sections provide a brief overview of the main research projects and international networks related to hydrogen safety where UiB will be involved in the coming years.

Norwegian Centre for Hydrogen Research (HyValue) is one of two new *Centres for Environment-friendly Energy Research* (FMEs), granted by the Research Council of Norway (RCN) for the period 2022-2030. NORCE coordinates HyValue, and SINTEF coordinates FME HYDROGENi. Both centres address the entire value chain for hydrogen and hydrogen-based fuels, including safety. As part of the research activities in HyValue, UiB will organise a blind-prediction benchmark study for consequence models in 2026, followed by large-scale hydrogen explosion experiments in 2027.

Norwegian Research School on Hydrogen and Hydrogen-Based Fuels (HySchool) is a *National Research School for Quality and Relevance,* granted by RCN for the period 2022-2030. This is a joint initiative from seven Norwegian universities: UiB, UiO, UiT, UiS, USN, NMBU and NTNU. The thematic areas in HySchool cover the entire value chain for hydrogen and hydrogen-based fuels, including societal aspects and safety. The primary objective is to contribute to the global energy transition by enhancing the quality of Norwegian doctoral training on the use of hydrogen and hydrogen-based fuel as energy carriers, and doctoral candidates from all universities and university colleges in Norway can be admitted.

Safe Hydrogen Fuel Handling and Use for Efficient Implementation 2 (SH2IFT-2) is a *Collaborative and Knowledge-building Project* (KPN) coordinated by SINTEF, with support from RCN and industry partners (2021-2027). The overall objective is to develop new knowledge on critical aspects of hydrogen safety, and at the same time facilitate the competence building required for supporting widespread use of hydrogen in society.

Safe Hydrogen Implementation: Pre-normative research for Ships (SH2IPS) is a *Researcher Project for Scientific Renewal* (FRIPRO) at UiB, supported by RCN (2021-2027). The primary objective of SH2IPS is to provide science-based recommendations for an international regulatory framework that can facilitate the safe deployment of merchant ships powered by hydrogen and hydrogen-based fuels.

Large-Scale Offshore Hydrogen Storage for Green Energy Transition (Hy4GET) is a *Collaborative and Knowledge-Building Project* (KSP) coordinated by SINTEF, with support from RCN and industry partners (2023-2027). This project focuses on hydrogen storage in offshore salt caverns on the Norwegian Continental Shelf, including the safety of offshore platforms for processing hydrogen.

Risk-Reduction for Hydrogen Installations by Partial Suppression of Explosions (HyRISE) is a *Joint Industry Project* (JIP) supported by Total E&P Norge and Shell (2021-2027). The main objective is to develop fundamental knowledge to support practical solutions for mitigating hydrogen explosions in congested and/or confined environments by means of active systems for chemical inhibition.

Hydrogen as an Energy Carrier in Society: Risk Picture, Risk Awareness and Public Acceptance (HySociety) is a collaborative project funded by UiB and the University of Stavanger (2021-2027). The overall goal is to analyse drivers and barriers for the implementation of hydrogen as an energy carrier in society.

Improved Modelling of Hydrogen Explosions is part of the *Industrial PhD scheme* of RCN (2020-2025). The main objective of the PhD project is to improve the predictive capabilities of the computational fluid dynamics (CFD) tool FLACS from Gexcon (Lucas *et al.*, 2021; Lucas *et al.*, 2023).

Hydrogen Safety Laboratory (HySALA) is an *Internal Infrastructure Project* at UiB. The project started in 2021 and the initial aim is to establish a state-of-the-art laboratory facility for investigating ignition and combustion phenomena for hydrogen-air mixtures. In a longer perspective, the ambition for HySALA is to establish a large-scale test facility as part of the national infrastructure in Norway. This would allow researchers to investigate safety-critical phenomena at spatial scales that resemble actual applications in industry and society.

The research activities at UiB are intimately connected with the international research community on hydrogen safety through organisations such as *International Association for Hydrogen Safety* (IA HySafe), *IEA Hydrogen TCP Task 43 on Hydrogen Safety*, the *Fire and Blast Information Group* (FABIG), the *European Hydrogen Safety Panel* (EHSP), and the *International Hydrogen Energy Centre* (IHEC) under the auspices of the United Nations Industrial Development Organization (UNIDO).

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Hazards Associated with Maritime

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The IMO acknowledges the need to reduce greenhouse gas emissions and targets a 40% reduction in CO_2 by 2030 and a 70% reduction by 2050 compared with 2008 levels. Although hydrogen has been produced and used by industry for many years the marine sector introduces new issues requiring practicable solutions to enable commercial success. There is currently a perception by some stakeholders in the marine sector that hydrogen is too dangerous a fuel to handle.

In 2021, Shell undertook a study to identify all the possible scenarios for the use of liquid and compressed hydrogen on commercial shipping:

- 'Concepts'
  all vessel types (including container, cruise, tanker, ferries etc.) for which a need to decarbonise is envisaged, this also included such factors as the vessel configuration, capacity, range, cargo etc. as well as fuel consumption estimates
- 'Operations'
  activities associated with operating these vessels (e.g., refuelling, cargo operations, propulsion, onboard processing)

For each Concept and Operation, the most likely causes of loss of containment and resultant hazardous phenomena were captured and the current knowledge position was assessed for existing and decarbonised fleets. The 'Causes of LoC' and 'Hazardous Phenomena' were ranked using a score of 1-5, where 5 = high level of understanding within marine applications. The following was observed:

	Positions for existing fleet	**Positions for decarbonised fleet**
Causes of LoC	should be understood to a level 5 Knowledge Position: "Well understood in maritime context, good standardisation".	All Causes of LoC scored a Knowledge Position of 3 or higher
Hazardous Phenomena	Knowledge Position of level 4 reasonably assumed for all Hazardous Phenomena i.e. "*Validated models and significant experience in maritime*" OR "*Models exist, some experimental data and / or some experience in maritime*".	significant number of phenomena at Knowledge Position level 3 or below, i.e., "*Models exist for phenomena as a minimum. Needs validation for new fuels*" OR "*Models exist, no experimental data but some operational experience in a different sector*".

The current state of published research for the identified Hazardous Phenomena was assessed and combined with the ranking output to identify the following research priorities:

1. Explosions in Open or Partially Confined Spaces
2. limited data on conditions which cause Deflagration to Detonation Transition (DDT). As such it is challenging to ensure ships are designed to avoid a Detonation scenario.
3. Explosions in Confined Spaces

4. limited knowledge how to design machinery enclosures on vessels to prevent explosion and whether current venting design of these spaces is adequate.
5. Dense Gas Dispersion from LH2 Releases
6. limited knowledge on how dense vapour from a liquid hydrogen release will dissipate through a machinery space. This makes designing machinery spaces for equipment such as reliquefication technology challenging.
7. Effects of LH2 Spillage on Structures/Materials including Steel
8. limited data on the size of liquid hydrogen pool that could occur and damage to the vessel structure. Also, the amount of Liquid Oxygen and Liquid Nitrogen that will form is unclear.
9. Rapid Phase Transition (RPT)
10. It is unclear in current research whether liquid hydrogen would undergo RPT.

Shell is a leader in a number of projects to demonstrate hydrogen as a marine fuel or cargo. By undertaking this research, Shell can demonstrate to the whole industry that we understand and can safely handle hydrogen as fuel and replicates a similar strategy undertake by Shell at the start of the Liquified Natural Gas (LNG) shipping industry, with Shell leading LNG testing and publishing results to industry.

In the coming years Shell is planning to undertake work on the above priorities through internally funded research and participation in Joint Industry Projects (JIPs). Shell intends to share output directly with key stakeholders (including classification societies, shipping operators, shipyards, government agencies, port authorities). In this way results can be fed directly into code development and help define design requirements for future hydrogen shipping

Within 10 years the marine sector will need to have closed the remaining knowledge gaps to ensure that appropriate codes and standards are in place to ensure that ships can be designed and built within the 2050 timescale. The Hazardous Phenomena identified by Shell at a Knowledge Position level lower than 4, and not immediately prioritised (including: effects on structures, pooling & boil off, pool fire, ignition, 2-phase jet fire, effects of active systems), should be considered for research to generate the data needed for model development and validation.

For the successful development of a decarbonised fleet, it is expected that further research and standardisation will be carried out to take all the identified Causes of LoC from their current knowledge position to that of Level 5. For the simpler development of specific vessels, a Knowledge Level 4 will need to be accepted whilst experience in the new fuels is gained to allow the recommendations, codes and standards to be developed.

Safety Research from ENGIE Crigen

S. Quesnel

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The abstract covers progress in hydrogen safety research activities achieved at ENGIE lab Crigen which is the ENGIE's corporate R&D center focusing on green gases (hydrogen, biogas, and liquefied gases), new energy uses in cities and buildings, industry. It will go through the different activities and funded projects in progress and the priority safety topics to be investigated according to the needs of the industrial projects from our point of view.

To achieve net zero carbon target by 2045, ENGIE targets are a production capacity of 4 GW of renewable hydrogen, 1 TWh of hydrogen storage capacity and more than 100 HRS by 2030. Crigen laboratory contributes to identify, assess, and integrate innovative solutions to answer the needs of the client through green energy for example. To achieve these objectives, Crigen is involved in different collaborative projects funded by FCHJU called now Clean energy partnership for technology and solutions all along the H2 value chain. Moreover, our facilities at Stains in the north of Paris allow us to test innovative technologies of production, storage and applications linked to hydrogen and to Power to X. Finally, Crigen coordinates the hydrogen safety road map of Engie and contribute to related activities to improve ENGIE asset safety for all existing hydrogen facilities and to safely design and operate the new hydrogen projects.

First, regarding the main European funded project by Clean energy partnership where Crigen is involved in hydrogen safety activities we can mention the MultHYfuel project related to HRS, the Hycare project related to Solid storage of hydrogen and the C2fuel project related to the conversion of carbon from steel off gases thanks to hydrogen to fuels. **The pre-normative research (PNR) project MultHYfuel (https://multhyfuel.eu/)** aims to tackle regulatory and technical barriers to safely implement Hydrogen dispenser in a multi fuel context. Crigen is leading the WP3 related to the establishment of best practices to define rules (e.g. separation distances, hazardous area classification, safety barriers) for this safe integration of hydrogen dispenser in conventional gas stations. Through engagement of stakeholders, risk assessment on HRS and experimental test, this project will develop best practice guidelines that can be used as a common approach to risk assessments on HRS (e.g. suggested methods/tools for risk modelling, Atex, safety distances). The main objective is to determine recommendations for the safe implementation of H2 dispensers in multi-fuel stations to be used in standards and regulation relative to HRS. Finally, the experiments from the WP2 on safety barriers and critical scenarios from hydrogen dispenser equipment will allow to confirm risk assessment assumptions by experimentations (severity, likelihood, failure) on dispenser accessories.
The **C2fuel project (https://c2fuel-project.eu/)** is funding from the European Union’s Horizon 2020 research and innovation programme and aims to develop energy-efficient, economically and environmentally viable CO2 conversion technologies for the displacement of fossils fuels emission through a concept of industrial symbiosis between carbon intensive industries, power production, and local economy. It will be achieved through a demonstration pilot for CO2 conversion into carbon-captured energy carriers: carbon captured from blast furnace gas combined to renewable hydrogen for fuel development. Crigen is responsible for the safe integration and operation of this innovative solution: H2 produced by SOEC, innovative capture process of CO2 to produce Diméthylether as fuel

for trucks and maritime. Crigen has achieved detail risk assessment on these innovative technologies in an industrial context with operational and lay out constraint.

The **Hycare project (https://hycare-project.eu/)** is funding from the European Union's Horizon 2020 research and innovation programme and deals with a prototype of hydrogen storage tank with use of a solid-state hydrogen carrier. Up to fifty kilograms of hydrogen are stored at less than 50 barg and less than 100 degrees Celsius in a twenty feet container. The innovative design is based on a maritime container including twelve Ti (Fe, Mn) metal hydride hydrogen storage tanks and thermal energy storage in phase change materials (PCM). Crigen was responsible to ensure the safe design, integration, and operation of this prototype on the Crigen site. It was achieved through preliminary and detailed risk assessment on this innovative technology of storage. CFD modelling of dispersion and explosion were achieved to validate the implementation of the container on the site and the safety barriers to be implemented on this prototype (e.g. ventilation, overpressure protection).

The second pilar of hydrogen safety activities at Crigen is to **ensure the safe tests of our innovative technology pilots for production, storage and applications linked to hydrogen** and to Power to X. To ensure the tests of different hydrogen pilots and technology, a hydrogen network as been built at Crigen site (Stains) with different equipment: a PEM electrolyzer 10Nm3/h, 30 bars bundle storage and Hycare solid state storage to store the hydrogen produced, a compressor to have 200 bar compressed hydrogen. This network will supply and/or receive different innovative pilots such as hydrogen produced by solar energy or by cracking process and innovative fuel cells to be tested. Each of these pilots and equipment mentioned previously go through a detail risk assessment led by Crigen and risk consultant with the providers to ensure that the tests can be achieved at Crigen site in safe conditions.

Finally, the third pilar of the hydrogen safety activities at Crigen is the research around the following topics for the last year: **management of hydrogen production in enclosure** such as 20 feet container, establishment of **hydrogen safety guidelines for the Engie projects conception and operation** based on lessons learned, standards and best practices. The study on the consequences of leaks in typical maritime container electrolyzer was achieved through CFD modelling to help Engie projects during preliminary phase of projects with preliminary separation distances to apply around this kind of equipment. Various hydrogen safety standards and best practices are existing and the aim of these internal ENGIE safety guidelines was to analyze and synthetize by equipment in one document of reference the minimum safety recommendations.

Additionally, to these activities it is worth mentioning the participation of Crigen for the last years to the international hydrogen safety community (e.g. Center of Hydrogen Safety, IEA sub task 43) and the participation in hydrogen standardization activities (e.g. refueling protocol, safe use of hydrogen in built construction).

For the next years, Engie has the ambition to develop large scale hydrogen production by electrolysis and potentially will have the need of large-scale inventories through LH2 handling.
So, according to our industrial projects and needs, it appears that for ENGIE the research topics of interest for the next years are the followings:

- H2 safety in **confined space such as Electrolyzer in building** (ventilation design, safety barriers...)
- **LH2 consequence modelling tools** for a better assessment of consequences for LH2 leaks
- **Hazardous classification area** for H2 facilities taking in consideration the specificities of H2 technology and equipment (e.g. double ferrule fittings)
- **Likelihood for H2 facilities** (failure of equipment, ignition…)

CNL's Recent Progress on Hydrogen Safety Research and Experience with Safety Assessments for Select End-use Sectors in Canada

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ABSTRACT

Canada's 2050 greenhouse gas emissions reduction plan includes hydrogen as a promising replacement for fossil fuel-based heavy industries. It is critical to fully understand the long term safety, performance, and reliability of equipment handling hydrogen, and the hydrogen behavior in the event of a significant release. Managing the risk is an essential requirement for the success of the hydrogen economy.

CNL performs research to address select hydrogen safety issues and aspects with the following objectives and progress:

- To improve understanding of hydrogen impacts on materials and the effectiveness of surface coatings, a test rig is being constructed to study hydrogen permeation through thin membranes. In addition, experimental set-ups are being developed to expose samples to hydrogen gas and hydrogen containing liquids to study the effect of hydrogen embrittlement on pipeline steels. In parallel, a multiscale modelling approach is being developed to elucidate the underlying mechanisms by which hydrogen influences the mechanical properties.
- To help validate the engineering and computational fluid dynamics models that are useful to assess the consequences of an accidental hydrogen release, experiments were conducted to measure the helium profile in the vicinity of the jets and examine far field dispersion behavior inside semi-confined enclosures. The enclosures are representative of residential or parking garages. The effects of geometry, natural ventilation driven by buoyancy or wind and forced ventilation were examined and their implication for safety sensor placement was studied.
- To study the effect of hydrogen explosions on solid structures and advance the understanding and predictability of such events, work has been done in collaboration with CEA (France) and University of Ottawa. Experiments were conducted to understand the pressure dynamics from head-on reflections of hydrogen detonations and high speed deflagrations, and to measure the resulting material deformations.
- To examine the potential use of hydrogen recombiner technology for mitigation of hydrogen risk in confined spaces (i.e., parking garages, underground mining), tests were conducted to examine the catalyst performance at low temperatures (down to -10 C). New catalysts are being developed, characterized and tested to enhance the catalyst performance in the presence of air impurities with potential to poison the

catalysts (i.e., carbon monoxide).

- To support quantitative risk assessment of accidental hydrogen releases, engineering and risk calculation models were constructed using MATLAB. Benchmark studies were conducted to compare with the HYRAM code developed by the Sandia National Laboratories, and the toolkit developed by Université du Québec à Trois-Rivières and AVT Research Inc.
- To perform safety risk assessments and regulations, codes, and standards (RCS) applicability analysis, CNL performed a high-level quantitative risk assessment and assessment of hydrogen RCS for the entire hydrogen infrastructure and rail vehicle components for GO Trains in Toronto in 2018. A similar analysis was also performed for the fleet of vessels within the Canadian Coast Guard in 2021. Currently, CNL is involved in safety risks assessment (both qualitative and quantitative) for a hydrogen-powered locomotive funded by Transport Canada.
- To provide support and data development relating to RCS development, CNL has started working with several partners, including Canmet MINING of Natural Resources Canada for hydrogen infrastructure in underground mines, geology experts at Geologic Survey of Canada, Canmet Energy-Devon, and Ontario Geologic Survey to expand the scope of CSA Z341 standard to include hydrogen storage in underground salt caverns and reservoirs.
- More details from the above mentioned projects will be presented and discussed at the workshop.

Self-Ignition of Hydrogen Releases

Stuart Hawksworth, Health Safety Executive
Professor Jennifer Wen,
Centre for Energy Resilience University of Surrey

In recent incidents hydrogen continues to ignite with high probability and without an obvious ignition source. This behaviour, often referred to as the spontaneous ignition of hydrogen has been investigated experimentally and numerically and the phenomena involved are starting to be well understood. With this in mind, now seems a good time to:

i. Review what we now about recent spontaneous hydrogen ignitions
ii. Consider standard approaches to industrial safety and consider if we should be doing things differently?
iii. Think about possible next steps for work to improve this understanding.

Some numerical studies have predicted spontaneous ignition during direct release into the atmosphere under certain pressures, such scenario has not been captured in any experiments and suggested by numerical simulations to be only possible if the release was infinitely fast, which was not possible in practical/laboratory scenarios. Most literature has focused on the release through a section of a tube. Generally, the propensity to spontaneous ignition increases with the increase of the initial pressure and tube length and decrease of the tube diameter, while it decreases with hydrogen dilution by other gases. Early experimental studies were mostly based on qualitative studies with limited global measurements. Numerical studies, some with high order numerical schemes and ultra-fine grid resolutions, were conducted to capture the fast evolution and complex shock laden flow structures leading to the autoignition, there were largely conducted prior to the availability of some recent experiments which contained more detailed images of the shock and flame structures, which can aid model validation. As such, the reported numerical simulations have only been subjected to limited qualitative comparison with experimental observations. Direct quantitative comparison between the earlier numerical studies with the few recent more detailed experiments is also not possible due to the differences in initial pressure and tube geometry. Fresh numerical studies with the same conditions as the newly available detailed measurement will be desirable.

What did you get out of attending the RPW 2022?

- Face to Face Networking
- I am making LH2 regulations in Korea. I am interested in safety distances, inspection method for the products such as storage tank, cylinder, emergency shutdown valve, safety valve. etc. Actually we made regulations for the demonstration facilities and related products. Our department are making the inspection facilities to test and approval of LH2 products. So I get the information's and related stories about LH2 out of RPW2022. Thank you HySafe for inviting us to this worship.
- Through RPW2022, I understood the research trends related to hydrogen in the world. And there were many interesting topics.
- Been an interesting couple of days with some really good topics generating discussion. I think there remains a lot of opportunity for HySafe to pull together a database on research which can prevent overlap of research and can create further value. Also gained a couple of extra kilos and a reasonable sleep debt. Good to see everyone again.
- RPW 2022 was an excellent collection of relevant state of the art in research with active relevant discussion. Far and away the most productive RPW I have attended.
- Intelligence on applications, work of others through contact with group of experts with diverse backgrounds in in key areas of interest.
- The overall vision of HySafe is to introduce Hydrogen as a safe and suitable energy carrier - to reach this goal all promising new applications enabling massive CO2 reduction like e.g. steel and concrete production and the therefore related hydrogen technologies with safety questions should be treated as high priority topic.

  Efficient safety training methodology's for a predicable large amount of people getting in contact with hydrogen should be an upcoming topic for the safety community.
- Incredible amount of research activities on hydrogen safety going on worldwide. Many new national initiatives. HySafe RPWs provide unique platform for international exchange.
- Increased awareness of activity within the community that synergizes/complements with my program which can be (possibly to) utilized to increase mutual impact of the respective programs (and in some cases, maybe "competitive activities"....). I'll have several follow-up calls.
- Great Event. Exchange with experts from all over the world. Many new insights from people with different background. Helps to set research priorities and to verify the importance of the work. Many thanks to the organizers.
- Understanding of ongoing research, chance to talk face to face with others doing this research, building relationships, chance to argue and debate on hydrogen phenomena, yummy food.
- Criticism:
  - More time for discussion
  - Potentially, project development exercise --> derive a set of project to be driven commonly
  - No industry involved...so possibly a fundamental research bias
  - Make sure that presentations are available for participants and rules for sharing are

established.
    - Make sure a summary report is written before end of the year.

- Opportunity to meet experts in the field. Useful discussions on future directions.
- Belated suggestion: to consider "Release from CHSS not protected by μLNB technology" as actually "Safety of CHSS not protected by μLNB technology" - we know how to model releases and predict their hazards, what is unclear - what would be safety strategy for such storage design?
- Connections and ideas for future research projects
- Protective coating against accidental LH release to protect critical equipment, components and facilities.

Prioritization

At the end of the presentations a prioritization survey was taken. In the next 4 pages we present the results of this survey. The voting results across the categories presented in the meeting are given below. The following pages display the voting results in each category.

- Accident physics – Liquid / Cryogenic Behavior
- Mitigation, Sensors, Hazard Prevention and Risk Reduction
- Integrated Tools for Hazard and Risk Assessment
- Materials
- Accident Physics – Gas Phase
- Applications
- Storage
- General Aspects of Safety

Following that are the rankings within each category starting with Accident Physics relating to liquid / Cryogenic behavior to General Aspects of Safety.
These were calculated by taking the score given to each category by the participant and added them together dividing out the number of participants in each category (industry, research , .. etc.) to remove the number of votes biasing the data. The figure shown below was shifted and normalized so the plot goes between 0 and 1 representing a relative score between the categories. The number of representatives from each category was: 1 for industry, 5 for Regulatory / Government, 10 for Research, and 5 for University. The bias resulting from this uneven number of participants in each category has been normalized out of these results.

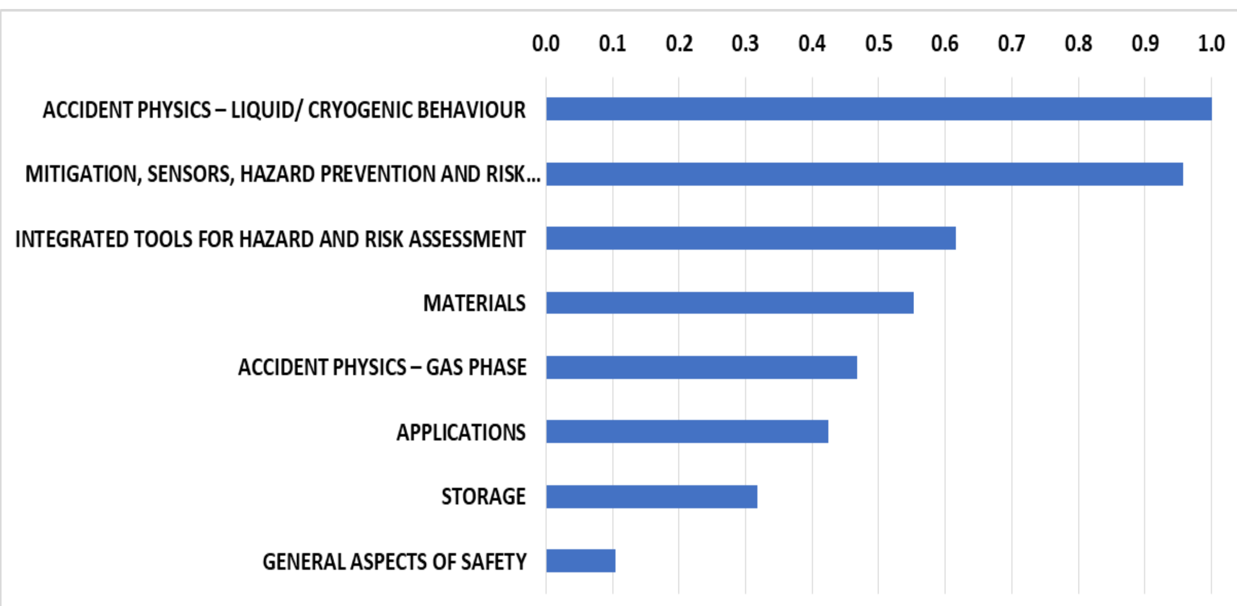
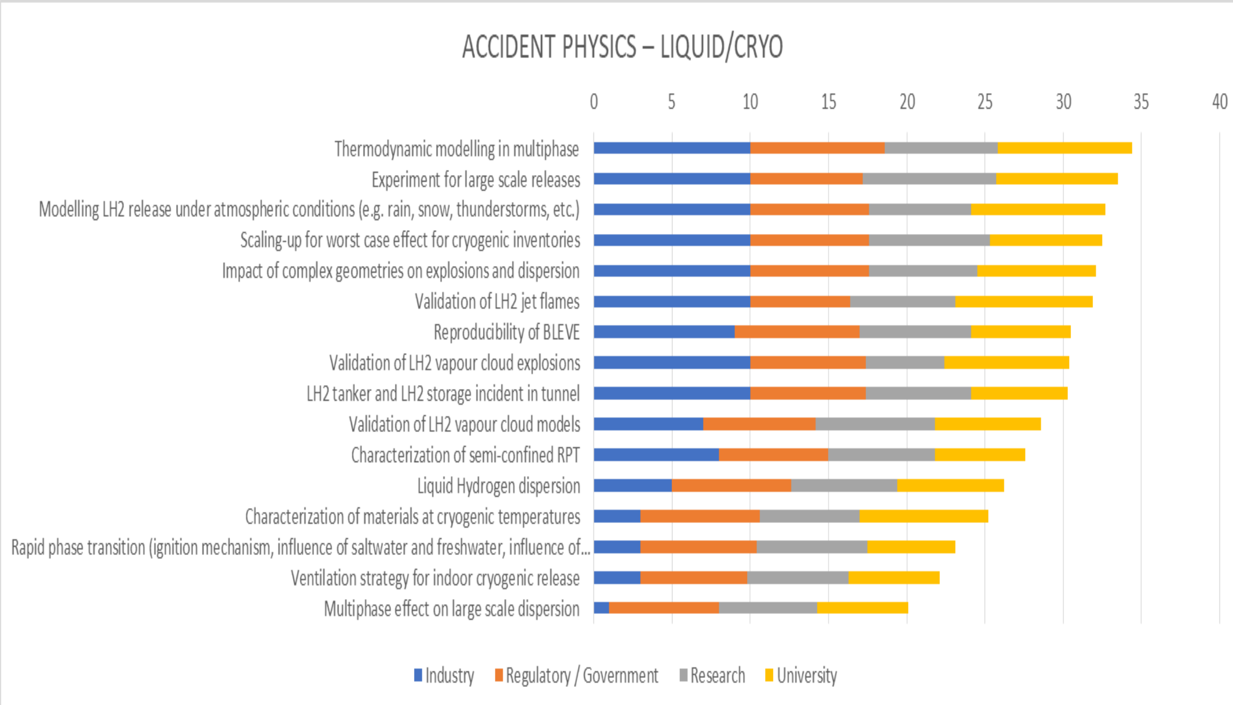


Figure 1. Prioritization Categories.

Categories presented in the order of prioritization given in Figure 1.



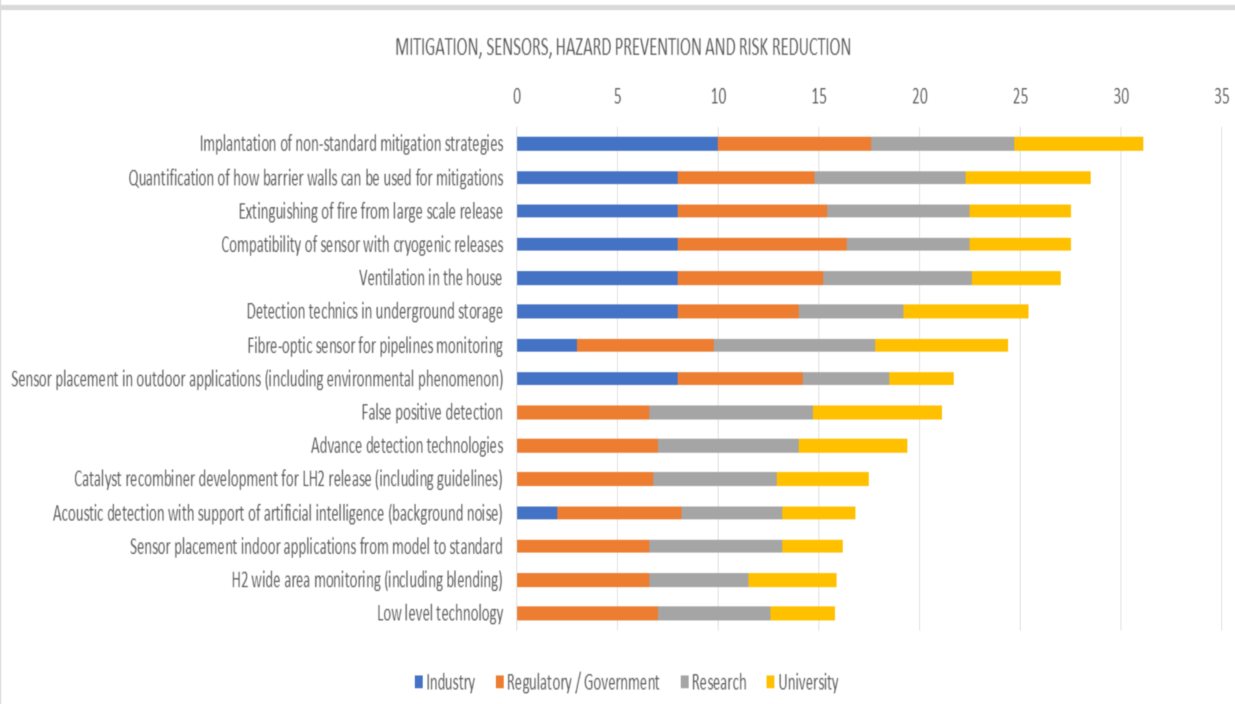
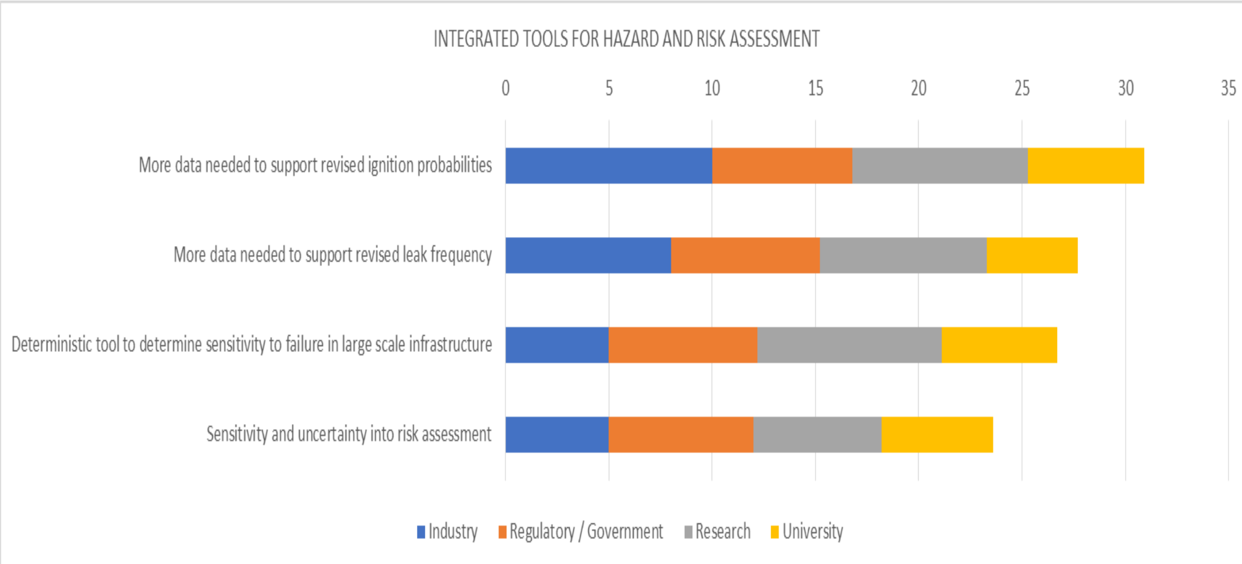


Figure 2 (Top Figure) Shows the prioritization scores for the subcategories for Accidental Physics for Liquid / Cryo.

Figure 3 (Bottom Figure) Shows the prioritization scores for the subcategories for Mitigation Sensors, Hazard Prevention and Risk Reduction.



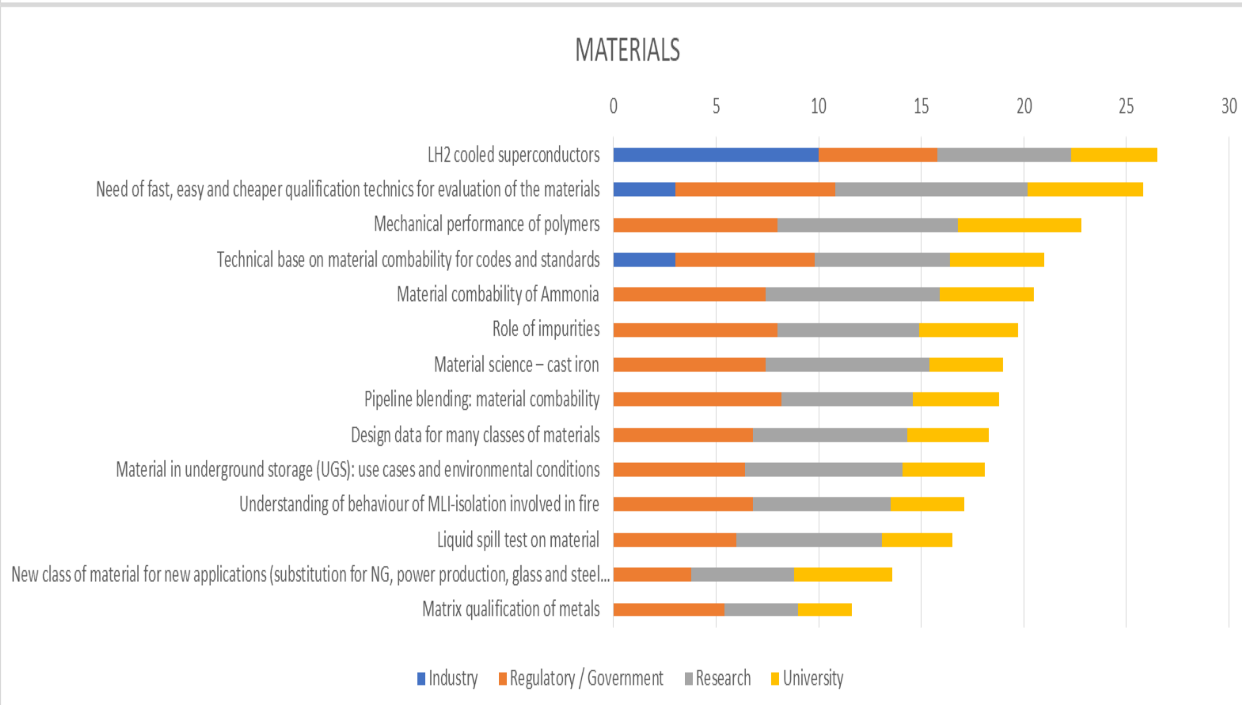
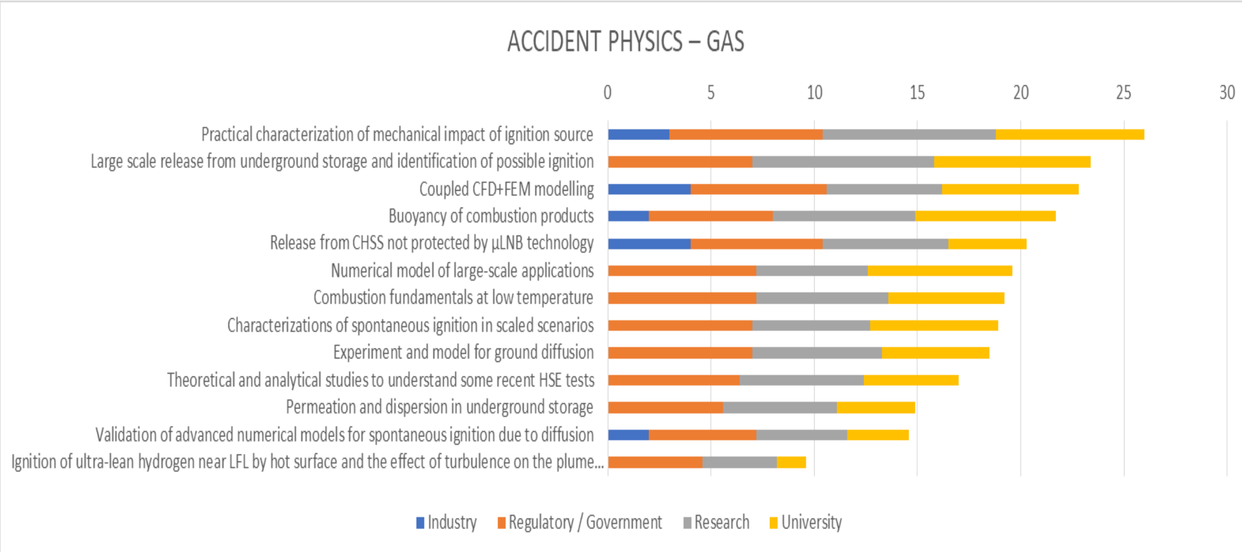


Figure 4 (Top Figure) Shows the prioritization for Integrated Tools Hazard and Risk Assessment. Figure 5 (Bottom Figure) Shows the prioritization for Materials.



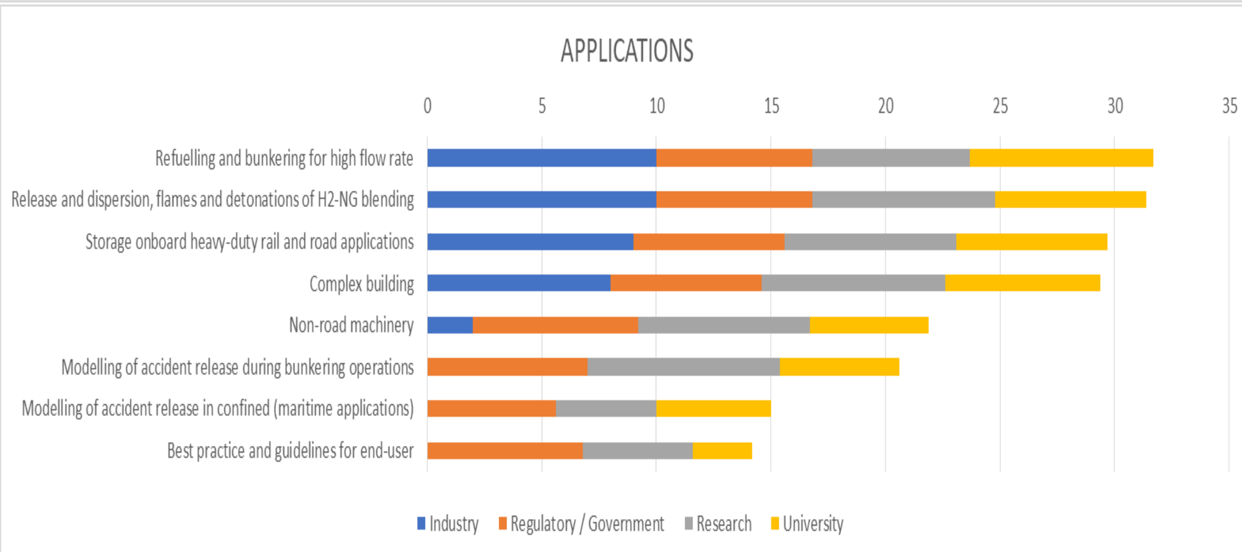
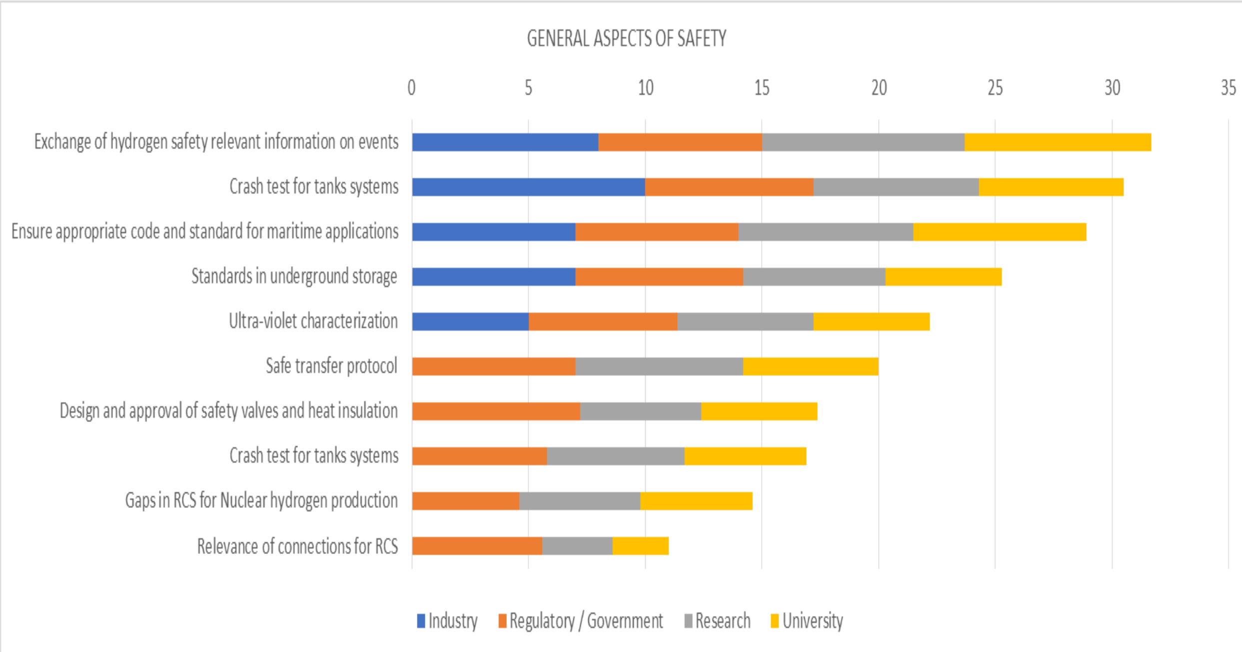


Figure 6 (Top Figure) Shows the prioritization for Accidental Physics Gas Phase.
Figure 7 (Bottom Figure) Shows the prioritization for Application.



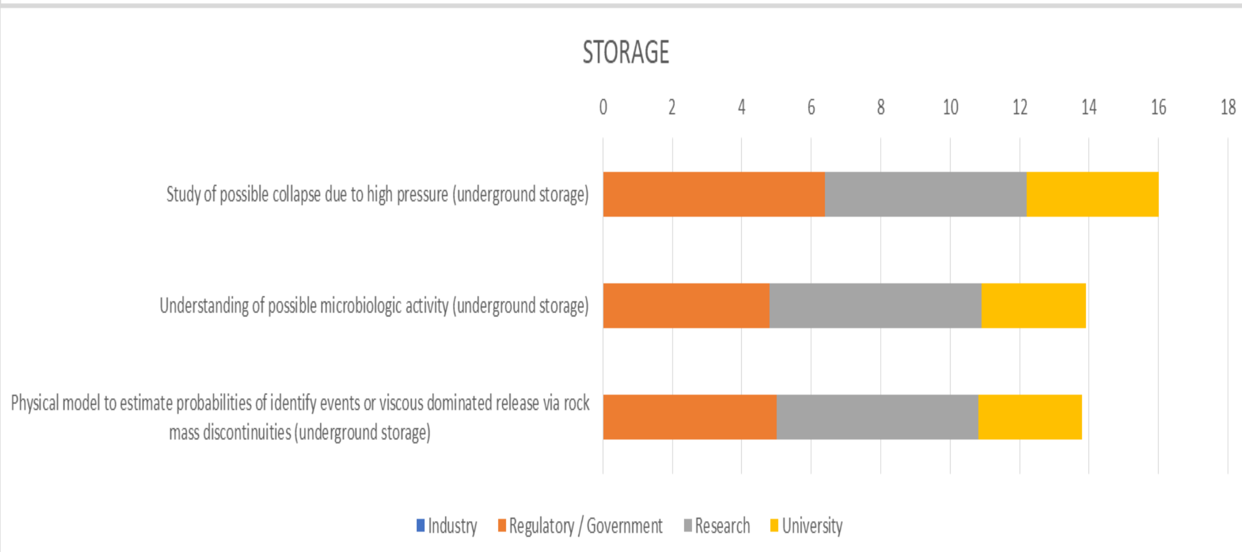


Figure 7 (Top Figure) Shows the prioritization for General Aspects of Safety.
Figure 8 (Bottom Figure) Shows the prioritization for Storage

These data clearly show the level of importance for the different categories addressed here in this workshop. Accident physics of liquid / cryogenic behavior is on top followed closely by Mitigation Sensors, Hazards prevention and Risk. A sharp drop in the priority for Integrated Tools probably represents the fact that many such tools currently exist for use by the industry. While there is still much to be understood about hydrogen effects on materials, the group ranked that about in the middle with a score of 5.5. Accident physics for the Gas Phase ranked pretty low. This is a topic that the pre-normative effort has been spending significant effort on over the past many years. This ranking clearly shows that the topic is reasonably well understood. Applications followed by storage and General Aspects of Safety make up the bottom three levels.

Appendix A

Meeting agenda.

Time	Presentation	Presenter	Topic		
Monday 21st November 2022					
8:00	Welcome and introduction to research priorities workshop	Stuart Hawksworth IAHySafe President and Jay Keller, RPW Chair			
8:30	Hydrogen research for regulating safety in UK	Kate Jeffery, Health and Safety Executive (HSE), United Kingdom	INDUSTRIAL AND NATIONAL PROGRAMS	GENERAL ASPECTS OF SAFETY	
9:15	Hydrogen sensors - safety research and development advances in NREL sensor laboratory	Bill Buttner, National Renewable Laboratory (NREL), United States	MITIGATION, SENSORS, HAZARD PREVENTION AND RISK REDUCTION		
10:00	Break				
10:30	Hydrogen behaviour in semi-confined spaces – HyTunnel-CS	Dmitriy Makarov, Ulster University, U.K.	ACCIDENT PHYSICS – GAS PHASE	APPLICATIONS	
11:15	Current status of hydrogen materials compatibility research	Chris LaFluer, Sandia National Laboratories, United States	MATERIALS		
12:00-13:30	Lunch				
13:30	Cryogenic hydrogen storage research	Ernst-Arndt Reinecke, Institute of Energy and Climate Research (IEK-14), Germany	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR	STORAGE	
14:15	Risk and environmental impact assessment for a salt cavern hydrogen storage	Benno Weinberger, INERIS, France	INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT	STORAGE	
15:00	Break				
15:30	Industrial offshore wind farm hydrogen technology implementation	Armin Kessler, Fraunhofer-Institut Chemische Technologie, ICT, Germany	APPLICATIONS		Not presented
16:15	Status of hydrogen release behaviour and quantitative risk research	Brian Ehrhart, Sandia National Laboratories, United States	ACCIDENT PHYSICS – GAS PHASE	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR	INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT
17:00	Liquid behaviour (PRESLY)	Thomas Jordan, KIT, Germany	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR		
17:45	Prioritisation, ranking and discussion	Daniele Melideo, University of Pisa, Italy, and Jay Keller, RPW Chair, United States			
18:45	Close of the day				
Tuesday 22nd November 2022					
Time	**Presentation**	**Presenter**	**Topic**		
8:30	H2Safety@BAM – overview of hydrogen research activities	Enis Askar, Bundesanstalt für Materialforschung und -prüfung (BAM), Germany	INDUSTRIAL AND NATIONAL PROGRAMS	ACCIDENT PHYSICS – GAS PHASE	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR
9:15	Predictive tools for liquid hydrogen	Jennifer Wen, The University of Warwick, United Kingdom	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR	INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT	
10:00	Break				
10:30	Safety distance methodologies	Marcus Runefors, Lund University, Sweden	MITIGATION, SENSORS, HAZARD PREVENTION AND RISK REDUCTION	ACCIDENT PHYSICS – GAS PHASE	
11:15	Active Hydrogen-related projects at the University of Bergen	Matthijs Van Wingerden, University of Bergen	INDUSTRIAL AND NATIONAL PROGRAMS	ACCIDENT PHYSICS – GAS PHASE	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR
12:00 – 13:30	Lunch				
13:30	Hazards associated with maritime	Lee Phillips, Shell Hydrogen, United Kingdom	APPLICATIONS	INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT	
14:15	Safety research from Lab Crigen **(not presented)**	Sebastien Quesnel, Engie, France	INDUSTRIAL AND NATIONAL PROGRAMS	ACCIDENT PHYSICS – GAS PHASE	ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR
15:00	Break				
15:30	CNL's Recent Progress on Hydrogen Safety Research and Experience with Safety Assessments for Select End-use Sectors in Canada	Zhe Liang, Nirmal Gnanapragasam, Lee Gardner, Canadian Nuclear Laboratory, Canada	ACCIDENT PHYSICS – GAS PHASE	MITIGATION, SENSORS, HAZARD PREVENTION AND RISK REDUCTION	APPLICATIONS
16:15	Self-ignition of hydrogen releases	Stuart Hawksworth HSE, Jenifer Wen, The University of Warwick, United Kingdom	ACCIDENT PHYSICS – GAS PHASE		
17:15	Prioritisation, ranking and discussion	Daniele Melideo, University of Pisa, Italy, and Jay Keller, RPW Chair, United States			
18:45	Close of the day				
Wednesday 23rd November 2022					
8:30	Wrap up of topic prioritisation	Daniele Melideo, University of Pisa, Italy, and Jay Keller, RPW Chair, United States			
9:45	Break				
10:00	IAHySafe AGM start	All members			
12:00	IAHySafe AGM close	All members			