HSE

Health and Safety Executive

International Association for Hydrogen Safety 'Research Priorities Workshop', September 2018, Buxton, UK

Prepared by the International Association for Hydrogen Safety and partners

RR1159

Research Report

Prepared 2020
First published 2020

ISBN 9780717667055

DOI: https://doi.org/10.69730/hse.20rr1159.

Hydrogen has the potential to be used by many countries as part of decarbonising the future energy system. Hydrogen can be used as a fuel 'vector' to store and transport energy produced in low-carbon ways. This could be particularly important in applications such as heating and transport where other solutions for low and zero carbon emission are difficult. To enable the safe uptake of hydrogen technologies, it is important to develop the international scientific evidence base on the potential risks to safety and how to control them effectively. The International Association for Hydrogen Safety (known as IA HySAFE) is leading global efforts to ensure this. HSE hosted the 2018 IA HySAFE Biennial Research Priorities Workshop. A panel of international experts presented during nine key topic sessions: (1) Industrial and National Programmes; (2) Applications; (3) Storage; (4) Accident Physics – Gas Phase; (5) Accident Physics – Liquid/ Cryogenic Behaviour; (6) Materials; (7) Mitigation, Sensors, Hazard Prevention and Risk Reduction; (8) Integrated Tools for Hazard and Risk Assessment; (9) General Aspects of Safety.

This report gives an overview of each topic made by the session chairperson. It also gives further analysis of the totality of the evidence presented. The workshop outputs are shaping international activities on hydrogen safety. They are helping key stakeholders to identify gaps in knowledge and expertise, and to understand and plan for potential safety challenges associated with the global expansion of hydrogen in the energy system.

International Association for Hydrogen Safety 'Research Priorities Workshop', September 2018, Buxton, UK

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ACKNOWLEDGMENTS

IA-HySafe thanks the UK Health and Safety Executive for hosting this workshop at its Science and Research Centre in Buxton (formerly the Health and Safety Laboratory) on behalf of the European Commission (EC) and the United States Department of Energy (DOE). Specifically the hard work and essential contributions for meeting organisation and assembly of this report of Simon Coldrick and Kate Jeffrey are acknowledged.

IA-HySafe thanks all Editors and Authors, Other Contributors and Speakers.

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The Contributors produced the bulk of the material used during the different sessions of the Research Priorities Workshop. This material was then summarised and further complemented by the Authors' work. The following chapters have been mainly written by the Authors, but are based on input provided by Contributors.

KEY MESSAGES

1. Globally, there is a strong and diverse interest in and uptake of hydrogen energy technologies. This is expected to lead to:
    - quantitative growth in more traditional and established applications and its impact on existing and existing infrastructure to supply ever increasing quantities of hydrogen in more diverse ways;
    - qualitative change as hydrogen now increasingly attracts interest, studies, attention and projects on the potential of hydrogen for decarbonising heat, energy and transport sectors that are more difficult to be decarbonised by other low and zero emission solutions, creating a clear expectation for hydrogen's use in more diverse environments and in increasing volumes.
2. In September 2018 HSE hosted the International Association for Hydrogen Safety (IA HySAFE) Research Priorities Workshop (RPW). The findings of the workshop reflected the rapid evolution in hydrogen technologies, highlighting a number of important associated priorities in hydrogen safety. IA HySAFE recommends that consideration is given internationally to focus future research on these areas to ensure the continued safe uptake of hydrogen technologies.
3. Identified key priority safety topics included:
    - Accident Physics in the Gas Phase applied to Fuel Cell Vehicle and Railways Applications, and a second-tier priority relating to Heat.
    - Accident Physics in the Liquid Phase relating to Hydrogen Fuelling Stations, Aerospace and Aviation, Trucks, Rail and Maritime applications.
    - Materials Knowledge for Power to Hydrogen and Heat applications, and a second-tier priority relating to storage.
    - Mitigation key priorities relate to Fuel Cells for mobility and transport (also off-road) and Storage, with second tier priorities relating to Hydrogen Fuelling Stations and Heat.
    - Risk Assessment. There is one top tier priority relating to Hydrogen Fuelling Stations and over-conservatism. There are several second tier priorities relating to Fuel Cell Vehicle, Power to Hydrogen, Rail and Trucks.
    - General Safety. Top tier priorities are around Fuel Cell Vehicle (issues around 1st and 2nd responders) and Trucks (a need for crash standards). Second tier priorities include Power to Hydrogen applications, Rail and Heat applications.
4. It is also suggested that this process of critical assessment and rationalisation of priorities is strengthened to more fully evaluate what related work is underway and how all activities could be more effectively be coordinated. To achieve this, modifications to the IA HySafe RPW process are suggested.

EXECUTIVE SUMMARY

Overview

This document describes the outputs of the International Association for Hydrogen Safety (IA HySafe) Research Priorities Workshop (RPW) held at HSE, Buxton, UK, in September 2018. This RPW builds on previous events including the RPW hosted by the European Commission Joint Research Centre (Petten, The Netherlands) and the one hosted by the USA Department of Energy (Washington DC, USA) held in 2016 and 2014 respectively. The RPW, as for the previous events, was attended by invited participants who are experts in the field of hydrogen safety. The objective was to identify the current state-of-the-art research directions and new application fields and to prioritise the knowledge gaps that need addressing to ensure the continued safe deployment of hydrogen technologies. The RPW was divided into sessions addressing the topical areas (1) Industrial and National Programmes; (2) Applications; (3) Storage; (4) Accident Physics – Gas Phase; (5) Accident Physics – Liquid/ cryogenic behaviour; (6) Materials; (7) Mitigation, Sensors, Hazard Prevention and Risk Reduction; (8) Integrated Tools for Hazard and Risk Assessment; and (9) General Aspects of Safety. These areas stem from previous workshops but have been further developed to reflect learnings of the research community and new developments in the technology dimension. The paragraphs below summarise the main priorities in the respective areas, which were determined by initial discussions and final voting by all participants directly at the workshop. The full details are provided in the main body of this document.

(1) Introductory Session: INDUSTRIAL AND NATIONAL PROGRAMMES

Programmes for hydrogen safety and respective standardisation and regulation (RCS) from around the world were presented. This provided a top down view to highlight differences and common areas of interest. For the **USA** the H2@Scale project, which is focused on wide scale production and utilization of hydrogen in the USA, was highlighted along with specific priorities around hydrogen in tunnels and liquid hydrogen (LH2). For **Europe** the status of the FCH2JU programme was described, highlighting the safety relevant projects framework and the setup of the RCS Strategic Coordination Group (SCG) and the European Hydrogen Safety Panel (EHSP). The key projects PRESLHY (LH2 safety), HYSEA (safety of ISO container-based solutions) and HyLAW (addressing the regulatory framework for hydrogen) were explained in slightly larger detail. In **South Australia** the recent push and strategic commitment to export green hydrogen were presented, along with particular priorities around large scale LH2 and LOHC implementation. In the **United Kingdom**, the strong focus on heat and hydrogen networks/grids (H21, HyDeploy, H100 projects) was described to address the high CO2 footprint of heat in the UK. Fuel switching to hydrogen for industry, rail and maritime was also highlighted. In **France**, the recent resurgence in activity was noted, and focus on decarbonising transport and injection into the gas grid were highlighted.

(2) Key Session Topic: APPLICATIONS

This topic was expanded to include rail, trucks, maritime and heat as applications seeing, or likely to see, growth in implementation, adding to HFS, FCV, P2H and Aerospace/Aviation applications addressed previously in 2016. Input from key industry representatives associated with each application contributed to the session, to bring real experience of challenges arising now and foreseen in the coming years. Detailed below are the top three priorities identified across the applications.

For **Hydrogen Fuelling Stations (HFS)** the priorities are:

1st priority: reduction of the over-conservative expensive design, raising safety and

efficiency concerns – still a priority despite some progress on this topic.
2nd priority: cascading effects including effects of various accidental releases of large inventories in complex real geometries, including co-location with conventional fuels.
3rd priority: material and processing (welding) issues for high pressure components. For public supply infrastructure, i.e. HFS scale up and efficiency requirements implies increasing usage of LH2 and associated material issues.

For **Land Transport**, bringing together FCEVs, Rail and Heavy-Duty Trucks, the main progress has been driven through United Nations General Technical Regulations 13 Phase II addressing issues of thermal attack and tests protocols. The priorities are:

1st priority: credible accident scenarios with high pressure hydrogen/ LH2 storage and interaction with infrastructure (i.e. in tunnels and other enclosed spaces).
2nd priority: fire attack and implications of increasing onboard inventories are generic issues, focused particularly for the rail and trucks, and clearly needs attention (suggested on-board storage: 50-100 kg for trucks, 200-500 kg for rail).
3rd priority: Part of same generic picture was operation of Thermally Activated Pressure Relief Devices (TPRDs) across these applications and for rail, hydrogen risks in the presence of high voltage systems is a concern.

The **Maritime** topic is growing quickly for clean propulsion for shipping and energy transport. The priorities are:

1st priority: optimal large scale venting strategies – radiation/blast loads from ignited events.
2nd priority: tolerable blast and impulse loads (how high are pressures that are tolerable for structures and people when duration is only a few ms?).
3rd priority: hazard evaluation of significant releases (5, 10, 20 g/s) into confined spaces.

For obvious reasons the **Aerospace/ Aviation topics shows** strong similarity with the LH2 topic. The priorities are:

1st priority: multi-phase physical processes in heat transfer, mixing with air, and initial thermodynamic status of LH2.
2nd priority: behaviour of liquid hydrogen and liquid/solid oxygen mixtures.
3rd priority: determining the probability of detonation with inhomogeneous gaseous clouds.

The topical areas **Power to Hydrogen** and **Heat** show close synergy. For both topics the priorities are:

1st priority: the behaviour of H2 in H2/NG on plastics pipes, valves, fittings in house gas installations, storage cylinders - effect on component, linked to the control of leaks in buildings and buried pipework.
2nd priority: review of testing procedures such as embrittlement and fatigue life test for H2/NG.
3rd priority: certification of mitigating safety measures (TPRD, Explosion Protection Systems, etc.) for H2/NG.

(3) **Key Session Topic: STORAGE**

Hydrogen storage is now, and will continue to be a key topic for established and developing applications moving forward. The main priorities identified for hydrogen storage are:

1st priority: tank fire resistance (previously identified as a priority in 2016).
2nd priority: non-destructive testing techniques for manufacturing and regular inspection.
3rd priority: understanding the effects of tank overheating on the structural performance and lifetime of the tank (also highlighted as a key priority by session chair to underpin refuelling protocols).

(4) **Key Session Topic: ACCIDENT PHYSICS of GASEOUS HYDROGEN**

For the accident physics of gaseous hydrogen the top three priorities from a list of five are:

1st priority: premixed combustion associated with large scale problems with obstacles, flame acceleration and particularly deflagration-detonation-transition (DDT).
2nd priority: hydrogen venting.
3rd priority: ignition statistical approaches and spontaneous ignition.

These priorities are key to growing application inventories and preventing and understanding the consequences of accidental releases in these new and developing scenarios.

(5) **Key Session Topic: ACCIDENT PHYSICS of LIQUID HYDROGEN**

For the accident physics of liquid hydrogen the top three priorities from an extensive list of 15 are:

1st priority: multi-phase accumulations with explosion potential.
2nd priority: combustion properties of cold gas clouds, especially in congested areas.
3rd priority: knowledge and experience related to releases of large quantities.

Obviously, this is an highly important area with a number of outstanding issues, many of which are beginning to be addressed by international efforts, such as the FCH JU project PRESLHY or the Norwegian project SH2IFT. These efforts are essential, as LH2 is key to a number of applications, as noted with the strong overlap in priorities with aerospace and maritime, and others that will need larger hydrogen inventories and corresponding scaling-up of supply infrastructure.

(6) **Key Session Topic: MATERIALS**

The rapid development and deployment of hydrogen applications leads to an expectation that the materials that enable the novel use of hydrogen today must become the normal, common place and safe materials (or their equivalents) for tomorrow. To meet this expectation, it is essential that the characteristics and long term performance and reliability of materials across all applications is understood, evidenced, catalogued and applied. With this in mind, the materials prioritisation exercise is divided into two sub-chapters, as it was in 2016.

Materials – Part (i): Testing aspects related to the characterization of materials.

Here the top three priorities identified are:

> **1st priority**: international consensus on metrics for qualification of metals for specific applications.
> **2nd priority**: definition of test protocols, selection criteria and relevant standards for polymer materials.
> **3rd priority**: seals, gaskets, hoses, valves and joints. They should receive similar attention to the tank material and their behaviour tested under different and realistic conditions.

Materials – Part (ii): Performance assessment of materials.

Here the top three priorities identified are:

> **1st priority**: is the development of a database providing fatigue data for the most probable materials to be used for hydrogen pressure vessels.
> **2nd priority –** Better understanding on Fatigue Crack Initiation and Propagation is needed. In particular a focus on small cracks and a better understanding of the effect of hydrogen pressure on the threshold of the stress intensity factor range is needed. Special attention to low-temperature / high-pressure conditions.
> **3rd priority –** Definition of appropriate models for lifetime predictions for polymers. In particular, a correlation between the behaviour of polymers under low hydrogen pressures and high hydrogen pressures and effects of temperature peaks (or valleys) and temperature excursions in tanks containing polymers is needed.

(7) Key Session Topic: MITIGATION, SENSORS, HAZARD PREVENTION AND RISK REDUCTION

This session identified the following top priorities:

> **1st priority:** Guidance on sensor placement was clearly identified as the top safety research priority with regards to sensors. Optimal sensor placement will be controlled by proper understanding of hydrogen plume behaviour.
> **2nd priority:** long-term stability, affecting the capital and maintenance cost of the monitoring system (this priority was also identified in the 2016 RPW).
> **3rd priority:** sensor selectivity.

(8) Key Session Topic: INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT

While there has been some progress in this area, the review of the state of the art and progress in this area within 2016-2018, based on panellists' contributions indicated that none of the 2016 priorities (or identified gaps) have been closed. Significant work-in-progress was presented by the contributing panellists Alice B. Muna on HyRAM (Sandia), Donatella Cirrone on e-Laboratory of Hydrogen Safety, NET-Tools project (UU) and Frank Markert on human reliability analysis using Bayesian networks and cause-consequence and barrier diagrams (DTU).
The three top priorities identified are:

> **1st priority:** data/probabilities for hydrogen system component failures (e.g.: leak frequencies, detection effectiveness, etc.) from operative experiences.

2nd priority: development of suitable models for accounting for the effects of different mitigation measures appropriately.
3rd priority: development of a realistic model for high-pressure hydrogen releases inside ventilated enclosures.

(9) Key Session Topic: GENERAL ASPECTS OF SAFETY

Here the priorities identified are:

1st priority: training of First Responders' trainers and Hazmat Officers needs more attention.
2nd priority: safe design concepts and management strategies for tunnels, car parks and complex confined buildings to prevent and mitigate hydrogen accidents.
Priority 3: Best practice for decisions and actions following detection of hydrogen in tunnels and complex buildings.

Discussion

As already noted above and discussed further in the body of this document, there is strong, diverse and increasing uptake of hydrogen technologies. As a result, this is leading to:

- quantitative growth in more traditional and established applications and its impact on existing infrastructure to supply ever increasing quantities of hydrogen; and
- qualitative change as hydrogen is increasingly adopted as a solution to decarbonise a widening range of technologies and applications.

The findings of this RPW reflect these changes, identifying the above listed research priorities. To attempt to rationalise these diverse findings, an analysis has been performed to identify common themes and aspects. Consideration should therefore be given to focus future research on these areas to ensure the continued safe uptake of hydrogen technologies. Identified areas recommended for further international investigation then include:

- Accident Physics in the Gas Phase applied to FCV and Railways Applications, and a second-tier priority relating to Heat.
- Accident Physics in the Liquid Phase relating to HFS, Aerospace and Aviation, Trucks, Railways and Maritime applications
- Materials Knowledge for P2H and Heat applications, and a second-tier priority relating to storage.
- Mitigation key priorities relate to FCV (and Railways, Trucks and Maritime) and Storage, with second tier priorities relating to HFS and Heat.
- Risk Assessment has one key priority relating to HFS and over-conservatism. There are through a number of second tier priorities relating to FCV, P2H, Rail and Trucks.
- In terms of General Safety, key aspects are around FCV (issues around 1st and 2nd responders) and Trucks (a need for a crash standard). Second tier priorities identified include P2H applications, Rail and Heat applications.

In terms of specific priorities which need to be addressed the safe transfer of hydrogen through gas grids of various materials, and the scale of transport applications to use larger inventories would appear to be two key areas for the next five years.

Conclusions and Recommendations

The bigger picture with regard to hydrogen technologies is one of rapid growth and development of applications, which is leading to broadening and rapidly changing safety priorities.

It is suggested that the IA HySAFE Biennial Research Priorities Workshop process, at its next iteration, is further developed to provide a better understanding of research and development that is underway, planned and required in the future. The aim is then to not just identify priorities, but also more effectively coordinate research and development. It is suggested that such a process must include safety projects and in addition to application projects (but not explicitly safety), which could more effectively be contributing to a broader international effort. It is suggested that this international collaborative activity should be considered to ensure maximum progress and impact is achieved from research and development for the international community. It is suggested that this process should be initiated through evolution of the approach to this workshop organised by IA HySafe.

CONTENTS

1 INTRODUCTION

The Research Priorities Workshop on Hydrogen Safety is organized by the International Association for Hydrogen Safety (IA-HySafe) every even year. In 2018 it was held at the HSE's Health and Safety Laboratory in Buxton, UK. This RPW builds on previous events including:

- European Commission Joint Research Centre (Petten, The Netherlands 2016),
- USA Department of Energy (Washington DC 2014),
- Berlin Germany hosted by Bam 2012
- The first workshop was organized by JRC in October 2009

The IA-HySafe organizes this meeting in the framework of its Research Committee activity.

The main objective of the workshop is to identify and prioritize existing knowledge gaps.

The gaps were addressed from two viewpoints, one of scientific knowledge and the other of developing hydrogen applications. In this way, the workshop compares the state-of-the-art, i.e. current knowledge, associated experimental capabilities, analytical and numerical models with the needs for further safe development and operations of innovative hydrogen technologies defined by industry. This approach shall help identifying relevant safety knowledge gaps and associate the right priorities. The outputs from the process are then summarised in a matrix plot displaying primary and secondary priorities in terms of applications (scenarios) and risk controls (H2 behaviour) at Figure 11.1 in the summary (section 11) of this document.

The workshop was structured into sessions, dedicated to the topical areas, which originate in previous workshops but have been further developed to reflect changes in the technology space:

- ***Industrial and National Programs***
- ***Applications***
- ***Storage***
- ***Accident Physics – Gas Phase***
- ***Accident physics – Liquid/ cryogenic behaviour***
- ***Materials***
- ***Mitigation, Sensors, Hazard Prevention and Risk Reduction***
- ***Integrated Tools for Hazard and Risk Assessment***
- ***General Aspects of Safety***

In preparation for the workshop a panel of experts and chairs was selected by the organisers. The selected participants covered their respective areas of competence and their contributions were put together by the different chairs.

During the workshop, the chair of each topical session provided an executive summary, aggregating and coordinating the contributions of the relevant experts. Each panellist, through their contribution, was invited to answer the following questions:

1. What has been done in the last three to four years (progress)?

2. What is planned for near term research direction (working topics)?

3. What are the needs / gaps that need to be filled by future research (new directions)?

After the overview presentation, accessible from the IA-HySafe website[1], and subsequent discussions, the workshop participants were asked to rank the importance of priorities, new and old, within the topical areas through an online survey.

The overarching goal of this exercise is to inform and shape global and local research and innovation programme, specifically on pre-normative research themes. Building on the foundations of previous workshops, it aims at providing an incremental update on the state-of-the-art and knowledge gaps. This process avoids re-addressing already filled gaps, identifies new actual and potential gaps, and helps to demonstrate progress. The workshop aims also at preparing and introducing the relevant topics of the International Conference on Hydrogen Safety which is organized every odd year. The output of this workshop will be presented at the ICHS2019, which will be held in September 2019, in Adelaide, Australia.

In the following, the revised contributions from the chairs and participants and the voting results are presented according to the sessions order held during the workshop. Thus the document is structured in an introduction (Chapter 1), followed by summaries on each topical area provided by the session/topic chairs. Thus, Chapter 2 provides a high level strategic overview of Industrial and National Programmes, followed by Applications (Chapter 3) which contribute to these programmes, followed by a detailed focus into specific topics of interest (Chapters 4 to 10). Chapter 11 then provides a discussion of the findings and some recommendations.

[1] https://www.hysafe.info/activities/research-priorities-workshops/
(Registration might be required).

2 INDUSTRIAL AND NATIONAL PROGRAMS

Chairpersons: T. Jordan (KIT) and J. Keller (Zero Carbon Energy Solutions) - Participants and contributors (in same sequence as presented): Chris LaFleur and Jay Keller representing Laura Hill (USA) and informing about Japan, Pietro Moretto (EU), Thomas Jordan was representing Nick Smith (South Australia), Philip Cohen (UK), Benno Weinberger (France).

2.1 Introduction and Stage Setting

The former title "Industry Programs" of this introductory session has been changed to reflect better the actual content, which is composed by contributions describing national and partly international public frameworks or programs about hydrogen safety, standards and regulations. The presentations are relevant indications for new developments, locally prioritised topics and potential new business cases around hydrogen in the different, highly committed communities worldwide.

This session highlighted the activities and developments in USA, EU, South Australia, UK and France.

2.2 National programs

United States of America

Chris LaFleur described the status of the US H2@scale program. She reported also on recent communications with Japanese coordination groups and highlighted the commonly adopted topics "Hydrogen in Tunnels" and "Liquid Hydrogen". Both topics were realised as priorities already in the previous workshop and therefore two special workshops - the IPHE Tunnel Workshop organised by HySafe and the US DoE and the Liquid Hydrogen Research Priorities of the project PRESLHY - were organised in combination with the general Research Priorities Workshop.

Europe

Pietro Moretto presented the Fuel Cell and Hydrogen 2 Joint Undertaking (FCH 2 JU) program status with a focus on the safety and regulation codes and standards (RCS) related activities in the cross-cutting pillar. Research is conducted in pre-normative research projects like HYSEA for the safety of container based solutions, or PRESLHY for the safe use of liquid hydrogen. The regulatory framework is investigated in the HYLAW project. Besides, the JU has started two related initiatives: the Regulations Codes and Standards Strategy Coordination Group (RCS SCG started in 2015) and the European Hydrogen Safety Panel (EHSP started in 2017). The RCS SCG mission is to enable coordinated implementation of science-based fit-for-purpose European and international standards to promote the safe deployment of hydrogen technologies. The EHSP seeks to assist the FCH JU at the programme and the project level to assure that hydrogen safety is adequately managed, it is also to promote and disseminate H_2 safety culture within and outside the FCH 2 JU programme. Both initiatives were represented at the workshop by the respective chairpersons, Nick Hart for the RCS SCG and Inaki Azkarate for the EHSP.

South Australia

Australia's recent push on hydrogen and in particular South Australia's commitment and strategy with respect to exporting "green" hydrogen have generated a strong need for setting up suitable standards and regulatory frameworks. The corresponding measures were underlined by the presentation of South Australia, given by Thomas Jordan. Obviously, for exporting hydrogen on large, international scale liquid hydrogen and LOHCs receive special interest. Hosting the ICHS2019 in Adelaide just underpins the highly active and strategic attitude of South Australia.

United Kingdom

The situation and prospects were presented by Philip Cohen of the UK Department for Business, Energy & Industrial Strategy. Because of the relatively high CO2 footprint of heat in UK a strong focus on hydrogen for heat application has emerged. The associated projects (h21, Hy4Heat, HyDeploy,…)

address the relevant open issues from scientific to regulatory aspects and also include acceptance issues. Besides, industrial fuel switching and transport including railway applications and corresponding supply infrastructures play an important role in UK.

France

Benno Weinberger presented an overview on the French activities, which recently gained considerable momentum. The targeted applications include transport (bus and taxi fleets, as well as new concepts for aircrafts) and also hydrogen injection into the gas grid.

3 APPLICATIONS

Chair: Thomas Jordan (KIT) - Participants and contributors: Jens Franzen (Daimler) mainly to the Trucks application, Andy Griffith (Alstom) to the Railway application), Olav Hansen (Lloyds) to the Maritime application, Andreas Haberzettl (DLR) to the Aerospace application, Stuart Hawksworth (HSL) to the Heat application, Benno Weinberger (INERIS) to the P2H application, Pratap Satiah (Shell) to the HFS application, and Peter Wilde (BMW) to the Hydrogen vehicles application.

3.1 Introduction and Stage Setting

The Application session of the Research Priorities Workshop 2018 provided updates for the four applications fields in the previous RPW (see below), and the first time priorities for four new application fields Railways, Trucks, Maritime and Heat.

The Application session is different from the phenomena oriented sessions. Here the market potential identified by contributors from industry is used to add specific "weight" to the ranking done in the other sessions. The obvious way how applications connect risk and safety assessments of concerned technologies with the more fundamental properties and behaviour of hydrogen has been described in the previous report[2].

Despite the fact that this report is, in general, a simple update of the previous ones, the scope of this session on applications has been broadened to take into account the development of new potential markets. Moreover, the list of the sub-topics to be ranked has also expanded.

3.2 The ranking results of the workshop 2016.

The previous workshop included the following sub-topics: 1) Hydrogen Fuelling Stations HFS, 2) Fuel Cell Electric Vehicle FCEV, 3) Power-to-Hydrogen and 4) Aeronautics / Aerospace.

The voting for HFS related issues, at the 2016 workshop, gave first priority to cascading effects (priority 7.1.6) including effects of various accidental releases of large inventories in complex real geometries, implying also co-location with conventional fuels. Second rank was given to the reduction of the over conservative expensive design, raising safety and efficiency concerns (7.1.2). Material and processing (welding) issues for high pressure components (7.1.3) received third rank. For public supply infrastructure, i.e. hydrogen fuelling stations the expected scaling up and efficiency requirements of the fuelling services implies increasing usage of LH2. Therefore most relevant scenarios include LH2 related phenomena.

For the hydrogen vehicles in particular accident scenarios in confined or partially confined environments, like tunnels, garages, and repair shops or at fuelling stations, have been given highest priority. These scenarios include the critical issue of safe strategies for first and second responders and concepts for mitigating catastrophic pressure vessel ruptures. The latter comprises second and third rank, which is thermal attack of the on board storage and Temperature/ Pressure Relieve Device (TPRD) venting.

For the Power-to-Hydrogen application collection of available field data (7.3.10) received first, the effect of larger concentration of H2 in H2/NG on flame stability in standard burners (7.3.7) second, and training on the safety aspects of H2/NG (7.3.11) third rank.

[2] https://www.hysafe.info/activities/research-priorities-workshops/rpw2016-agenda-and-presentations/

Hydrogen aerospace and aviation applications are mainly applying LH2 for its high gravitational energy density. Therefore, these applications refer to the same gaps in the basic understanding and in the modelling capabilities related to the accident physics of LH2.

3.3 Application - Hydrogen Fueling Stations (HFS)

To summarise recent progress, there have been only a few contributions to the cascade/co-location topic by the Japanese group of authors Sakamoto and Nakayama mainly for co-location of gasoline/LH2 and H2/LOHC (Liquid Organic Hydrogen Carrier). Concerning the reduction of over-conservatisms, again only a few publications have been released within the last two years (e.g. Risk based safety distances for hydrogen fuelling stations by Piet Timmers and Gea Stam at ICHS2017[3]).

A new sub-topic addressing "Vent stack design, accounting also for cold releases from LH2 transfer and cryostat purging" has been added to the six previous topics. This was an outcome of previous discussions.

1. Adverse effects on material and systems in 'below-design', idling conditions (corrosion, T cycles, etc.)
2. Reduction of the over conservative expensive design raising safety and efficiency concerns (e.g. alarm limits, electrical grounding of busses and cooling requirements)
3. Material and processing (welding) issues for high pressure components
4. Compressor: ventilation requirements for compressor containers
5. Compressor: effect of compressor vibrations on material
6. Cascade effects: effect of various accidental releases in case of scale-up, complex real geometry (large bus fleets, trains, etc.)
7. ***Vent stack design, accounting also for cold releases from LH2 transfer and cryostat purging***

The voting on the above 7 issues delivered the ranking, as depicted in Fig. 3.1:[4]

1. Reduction of the over conservative expensive design raising safety and efficiency concerns
2. **Cascade effects**: effect of various accidental releases in case of scale-up, complex real geometry including co-location with conventional fuels
3. **Vent stack design**, accounting also for cold releases from LH2 transfer and cryostat purging

Figure 3.1 2018 voting results for the HFS application issues

Application - refuelling stations

Q	TOT	%	RANK
1	62	13.78	4
2	97	21.56	1
3	61	13.56	5
4	44	9.78	6
5	38	8.44	7
6	78	17.33	2
7	70	15.56	3

[3] https://www.hysafe.info/ichs2017/conference-presentations/

[4] Voting was done during the workshop by the participants at the end of each session to capture ranking of topics in that session. We did not rank between sessions.

This result is largely consistent with the previous ranking, as may be derived from Fig 3.2 . However, there is a swap of rank 1 and 2 and obviously the new “vent stack design” issue, rooted in LH2 based fuelling station operations, was introduced for good reason as it received rank 3.

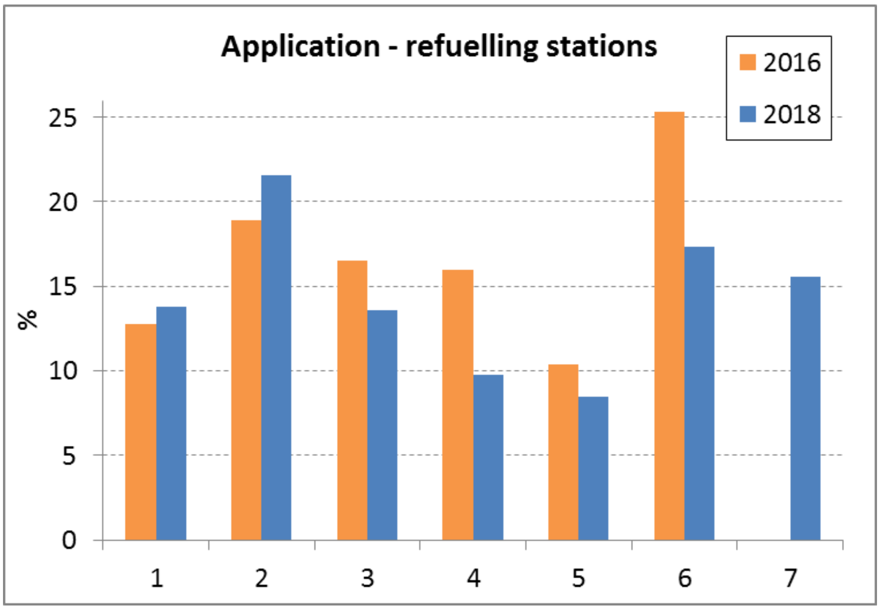

Figure 3.2 Comparison of current and previous ranking of HFS related issues

3.4 Application - Fuel Cell Electric Vehicles (FCEV)

The chairperson listed a couple of recent publications in the field of structural strength/health monitoring of onboard pressure vessels of Type III or IV. Optical, ultrasonic and acoustic emissions test strategies are currently investigated.

The ongoing work at the UN-ECE Global Technical Regulation (GTR) 13 Phase II is addressing thermal resistance and its appropriate test protocol. This progress is based on pre-normative research performed by various groups in US, Japan and Europe (e.g. FCH JU project FIRECOMP).

Moreover, some prenormative work towards an explosion-free tank is at University of Ulster. The European project FIRECOMP has produced results presented ad worked out at the GTR13. Still lacking is data on real life degradation, which is in the hands of OEM and tank manufacturers. The lack of these data hinder further refinement of the type-approval tests.

With this in mind the two new voting items 8 and 9 have been introduced.

The workshop participants therefore voted on the following items:

1. State of health/monitoring
2. Hydrogen venting via TPRD in garages (especially a single car garage)
3. Complex accident situation in tunnels
4. Pressure vessel rupture mitigation
5. Understanding vehicle fires and the response of storage components to thermal excursion
6. Improved protection of vehicle hydrogen systems against fire, thermal excursions and other extreme events
7. Remotely initiated venting
8. Objectives and roles in safety assessments, in particular accounting for extreme events
9. Data base for extreme events

The results of the voting are shown in Figure 3.3.

Application - FC vehicles			
Q	TOT	%	RANK
1	36	8.00	8
2	66	14.67	3
3	69	15.33	1
4	60	13.33	4
5	68	15.11	2
6	53	11.78	5
7	12	2.67	9
8	40	8.89	7
9	46	10.22	6

Figure 3.3 2018 voting results for the HFS application items

So the 3 highest ranks are given to:

1. Complex accident situation in tunnels (issue 3)
2. Understanding vehicle fires and the response of storage components to thermal excursion (issue 5)
3. Hydrogen **venting via TPRD** in garages (issue 2)

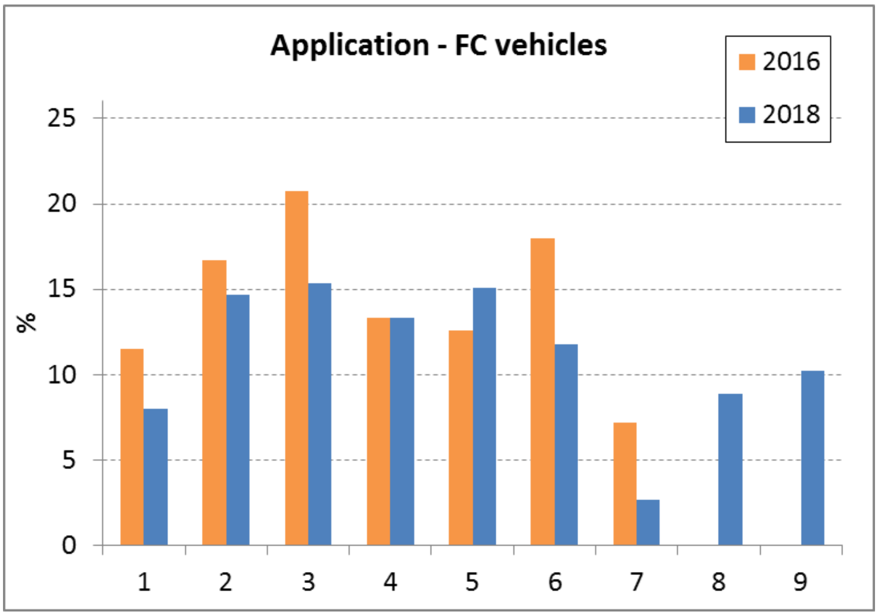

Figure 3.4 Comparison of current and previous ranking of FCV related issues

The comparison of the current and previous ranking shows that it stays almost unchanged. The replacement of issue 6 by issue 5 on 2nd rank is only a formality as both issues actually address the same problem. For the next workshop it is suggested to merge issue 5 and 6. Although issue 7 "Remotely initiated venting" has received lowest rank by far, the chairperson suggests to maintain this for the next phase. For future RPW it sis suggested that this Application is referred to as "Light Duty Fuel Cell Electric Vehicles" "LD FCEV .

3.5 Application - Power to Hydrogen (P2H)

In this application field progress related to the following issues has been achieved:

- Diffusion rates of hydrogen in several applied materials in the NG distribution/transportation network have been evaluated
- Embrittlement mechanisms with hydrogen in some applied materials in the NG distribution/transportation network have been further developed
- Confirmation of absence of stratification effects for NG/H2 mixtures
- LEL & UEL, Minimum Ignition Current, Maximum experimental safe gap, Minimum Ignition Energy in the range up to 20% H2 admixture in CH4 have been determined.

There is some work ongoing at KIT addressing the detonation sensitivity of H2/NG mixtures by determining the ignition delay times in a shock tube. . In the UK the project HyDeploy (www.HyDeploy.com) is addressing and demonstrating the injection of up to 20% hydrogen into real gas networks.

The CEN/CENELEC SFEM WG hydrogen has produced a report with an analysis of the existing standardisation gaps and a roadmap for the required pre-normative research and standardisation efforts. . The experts contributing to the SFEM report have dedicated special attention to hydrogen admixtures to natural gas.

On this background voting took place on an unchanged set of issues:

1. List of materials compatible with H2/NG systems, taking into account already collected data and available standardization deliverables such as the technical report ISO/TR 15916:2004 7
2. Behaviour of H2 in H2/NG on plastics pipes, valves, fittings in house gas installations, storage cylinders - effect on components
3. Metering and mixture concentration and homogeneity control
4. Influence of hydrogen on integrity of underground storages
5. Review of testing procedures such as embrittlement and the fatigue life test for H2/NG
6. Correlation between laboratory specimen and component tests for the characterization of susceptibility to hydrogen embrittlement and enhanced fatigue
7. Effect of larger concentration of H2 in H2/NG on flame stability in standard burners
8. All kinds of mitigating safety measures (TPRD, Explosion[5] Protection Systems, etc.) have to be certified for H2/NG
9. Re-assessment of the ATEX Zoning should be standardized for H2/NG
10. Collection of available field data from Power-to-H2 installations
11. Training on the safety aspects of H2/NG

The results of the voting (see Fig. 3.5) highlighted the following 4 issues:

1. Behaviour of H2 in H2/NG on plastics pipes, valves, fittings in house gas installations, storage cylinders - effect on component (issue 2)

[5] For the purposes of this work an explosion is defined as any combustion process that results in an over pressure. (such as a chemical reaction where a fuel reacts with an oxidant releasing heat)

2. Review of testing procedures such as embrittlement & fatigue life test for H2/NG (issue 5)
3. Certification of mitigating safety measures (TPRD, Explosion Protection Systems, etc.) for H2/NG
4. Re-assessment of the ATEX Zoning should be standardized for H2/NG

Application - P2H

Q	TOT	%	RANK
1	40	9.20	5
2	86	19.77	1
3	27	6.21	10
4	35	8.05	8
5	43	9.89	2
6	12	2.76	11
7	39	8.97	6
8	42	9.66	3
9	42	9.66	3
10	36	8.28	7
11	33	7.59	9

Figure 3.5 2018 voting results for the P2H application issues

There is a clear vote for the clarification of plastic materials' compliance in home gas installations and pressure vessel and piping components. Compared to the previous voting the data collection and training issues lost their high ranks and were replaced by identifying appropriate material and structural test methods. This further supports the focus on material issues highlighted by the new first rank.

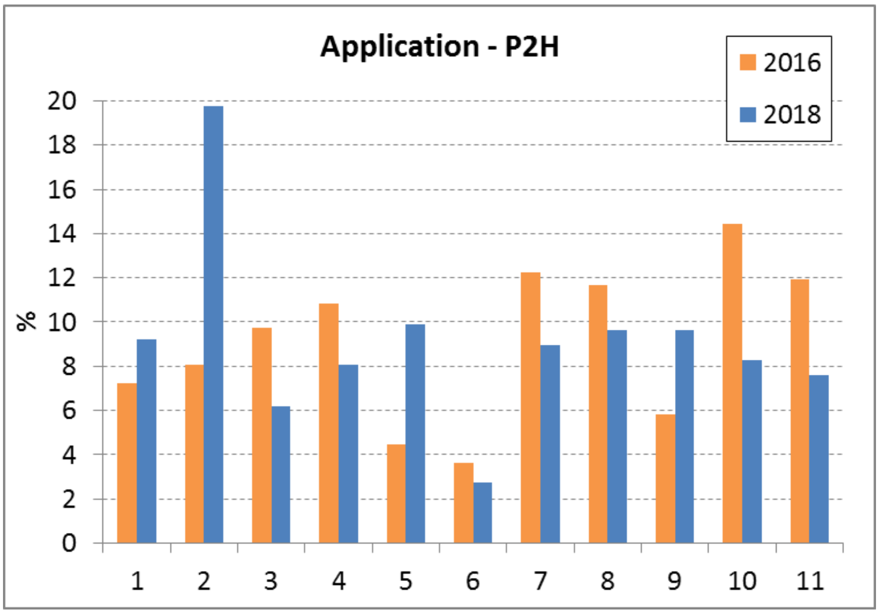

Figure 3.6 Comparison of current and previous ranking of P2H related issues

3.6 Application - Aerospace/Aviation

In general this application field is dominated by issues treated in the LH2 session, the PRESLHY workshop. However, a dedicated voting was done on this application field, because only recently concepts for hydrogen driven aircrafts have been circulated.

The voting on:

1. Multi-phase physical processes (heat transfer, mixing with air, and initial thermodynamic status of the liquid) are largely unknown for large liquid hydrogen releases
2. Determining the probability of detonation with inhomogeneous gaseous clouds
3. Behaviour of liquid hydrogen and liquid oxygen mixtures
4. Appropriate design of test cells including suitable mitigation concept
5. Physics of hydrogen ignition and flame propagation for low external pressure and temperature (aircraft conditions)

This delivered the ranking shown in Fig. 3.7.

Application - aerospace/aviation			
Q	TOT	%	RANK
1	107	25.48	1
2	88	20.95	3
3	100	23.81	2
4	51	12.14	5
5	74	17.62	4

Figure 3.7 2018 voting results for the Aerospace/Aviation application field

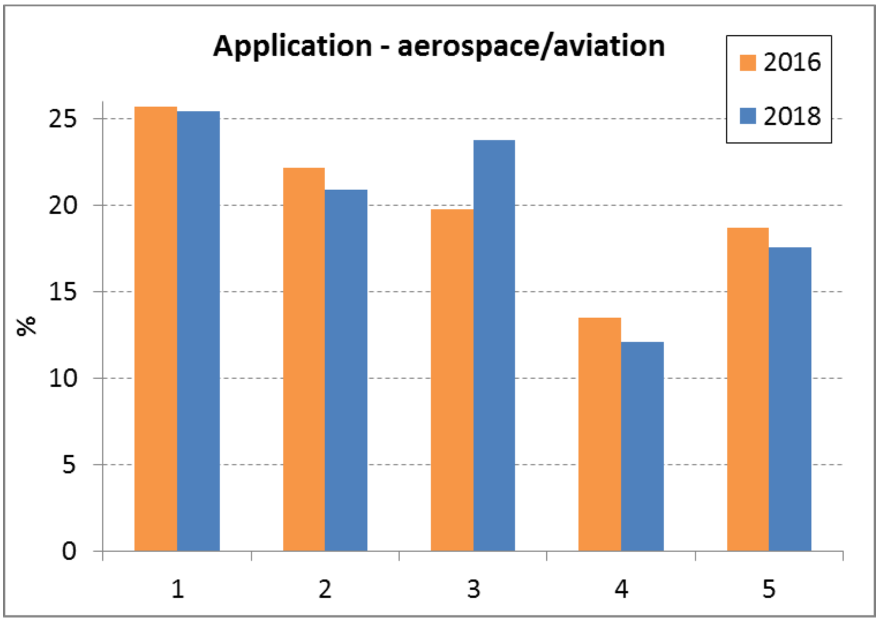

Figure 3.8 Comparison of current and previous ranking of Aerospace/Aviation related issues

As shown in Fig. 3.8 the ranking did not change seriously since 2016 and still highlights:

1. Multi-phase physical processes in heat transfer, mixing with air, and initial thermodynamic status of LH2
2. Behaviour of liquid hydrogen and liquid oxygen mixtures

3. Determining the probability of detonation with inhomogeneous gaseous clouds

In fact, these are the key working topics of the pre-normative research project PRESLHY, and so confirms the orientation and the relevance of the project.

3.7 Application - Rail

As hydrogen driven trains recently proved to be a real business case - at least in Germany - and interest in other countries, e.g. UK, interest in these applications has grown, it was decided that this application field should be included in the research priorities workshop.

Obviously this application field implies a scaling up in the supply infrastructure, increased inventories on the vehicles and possible use of LH2, both requiring special RCS environment.

For the beginning only two special items had been listed for voting, which are directly presented in their ranking sequence:

1. H2 in railway tunnels and other enclosed rooms (station halls, repair workshop, etc.)
2. H2 safety in the presence of high voltage systems

Figure 3.9 LH_2 rail application (photo source: Alstom)

Here the ranking of the topics is almost meaningless as it is overly constraint with only 2 issues to be voted on. So both issues deserve special attention and should be pursued by dedicated research. The railway tunnel issues, for instance, will be addressed, at least partially, in the FCH 2 JU HyTunnel project, which will start 2019.

Application - rail			
Q	TOT	%	RANK
1	125	46.30	2
2	145	34.52	1

Fig 3.10 Ranking of issues in the new rail application field

3.8 Application - Heavy Duty Trucks

Similar as for the trains also hydrogen driven heavy duty trucks are attracting attention and some first projects in US and Switzerland will roll-out first small fleets in the coming years. Therefore, it was decided to include this application field in the research priorities workshop.

Figure 3.11 LH_2 heavy duty truck application (photo source: Nikola)

Again, as for the railway application field, truck applications imply a scaling up in the supply infrastructure and increased inventories on the vehicles. Again this suggests potential use of LH2, eventually even cryo-compressed hydrogen CCH2, and therefore a strong link to LH2 related issues.

The following special items had been listed for voting:

1. Crash norms and implications of vehicle high pressure CGH2 or LH2 tanks
2. Safety aspects of large inventory (~100kg and more) fillings/refuellings including LH2 and CCH2
3. Credible accident/incident scenarios
4. Safety in workshops
5. Mass flow measurement and efficiency standards

Application - heavy vehicles

Q	TOT	%	RANK
1	125	27.78	1
2	100	22.22	3
3	106	23.56	2
4	80	17.78	4
5	39	8.67	5

Figure 3.12 Ranking of issues in the new heavy duty trucks application field

As shown in Figure 3.12 is the initial focus in the Truck application:

1. Crash norms and implications of vehicle high pressure CGH2 or LH2 tanks
2. Credible accident/incident scenarios
3. Safety aspects of large inventory (~100kg and more) fillings including LH2 and CCH2

3.9 Application - Maritime

Figure 3.13 Maritime application - artists impression of LH2 transport ship (photo source: Kawasaki Heavy Industries)

Recently the application field “Maritime” has attracted attention. Hydrogen, in particular LH2, is envisaged as an alternative fuel for ship propulsion. In addition, shipping of LH2 seems to be a viable solution for international transportation of stored renewable energy over long distances. For the latter case first demonstration projects are fairly well developed with a signed agreement between

Australia as an exporter and Japan as importer. Further drivers of the topic are found in Norway, US, UK and Germany.

A broad list of safety issues has been suggested and discussed at the workshop:

1. Blast and impulse understanding (understanding of the effects on people and structures of high pressure short duration (few ms) pulses),
2. Optimal (large scale) venting – radiation/blast from ignited events (how quickly can tanks be emptied safely, without leading to non-tolerable consequences for people/structures)
3. Material fire tolerance (fast ferries require light tanks, how well is integrity maintained)
4. Likelihood for ignition? (How likely will a tank rupture lead to ignition, will this give 3-4 times higher blast loads?)
5. 8% acceptable "LFL"-limit or fraction of 4%?
6. Fuel cell spaces < LFL? (Use of ventilation to ensure fuel cells atmosphere shall never become flammable during full bore rupture of fuel pipe, very challenging)
7. Release and dispersion behaviour in maritime conditions
8. Spray vs "pool" – better understanding of expected releases
9. Cryogenic loads, materials (will we handle major LH2 releases inside a ship without damaging structure?)
10. Significant releases (5, 10, 20 g/s) into confinement acceptable?
11. Can water sprays be useful to remove LH2? Can sprays lead to Ignition?
12. Bunkering – should 8% or 4% H2 concentration be threshold for flashfire fatality-risk
13. Is LH2 sloshing in tank a problem?
14. BLEVE
15. Trapped LH2 pressure build-up
16. Pressure build-up vs. venting during transfer to outer tank

The voting on priorities provided a first ranking (see Figure. 3.14). Only the first 3 ranks are highlighted here:

1. **Optimal large scale venting strategies**– radiation/blast loads from ignited events
2. **Tolerable blast and impulse loads** (how high pressures are tolerable for structures and people when duration is only a few ms?),
3. Significant releases (5, 10, 20 g/s) into confinement acceptable?

The 2nd and 3rd rank have same number of votes. In principle the highly ranked issues similarly address new/different **acceptance thresholds for maritime applications** with their typically huge inventories and special boundary conditions. The issue which has been ranked lowest Sloshing (issue 13) possibly will be treated in a Norwegian project. Depending on its outcome and on the next ranking exercise, this issue might be removed from the list.

Application - maritime			
Q	TOT	%	RANK
1	44	9.78	2
2	65	14.44	1
3	22	4.89	10
4	31	6.89	7
5	36	8.00	5
6	23	5.11	9
7	43	9.56	4
8	36	8.00	5
9	17	3.78	13
10	44	9.78	2
11	20	4.44	11
12	19	4.22	12
13	7	1.56	16
14	26	5.78	8
15	8	1.78	15
16	9	2.00	14

Figure 3.14 Ranking of issues in the new Maritime application field

As for trucks and trains, the large inventories imply the use of LH2 with its own set of priorities. Consequently, more generic issues like BLEVE (issue 14) might be transferred to the phenomena oriented topic LH2. However, for the time being it is suggested to keep the long list of issues of this new topic.

3.10 Application - Heat

Decarbonisation of heat (space heating, water and industrial heating) using hydrogen is a key area of growth and addressed by a number of projects. In the last couple of years it has received particular interest in the UK and there a number of projects underway, and these are briefly summarised below:

The safety of hydrogen in appliances and within the home is being considered in the UK Hy4Heat Programme. This is a large £25M programme that started in 2018 and some of its findings are now published. See https://www.hy4heat.info/ . One of the leading projects in this area is the HyDeploy project, which aims to demonstrate that blending up to 20% by volume of hydrogen with natural gas is a safe and greener alternative to the gas we use now. The project is using a real gas network at Keele University today, and is providing evidence on how customers can safely use their current cooking and heating appliances to take the blend. See https://hydeploy.co.uk/ . Addressing gas grids transporting 100% hydrogen to people's homes, the first UK project to demonstrate this will be the H100 project, led by SGN, which is working to construct and demonstrate the UK's first network (supplying a few hundred houses) to carry 100% hydrogen. See https://sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100 . The next milestone is then to repurpose the UK gas grid (distribution & transmission) to operate with 100% hydrogen. The H21 suite of gas industry projects, led by Northern Gas Networks, is designed to support conversion of the UK gas networks to carry 100% hydrogen. See https://www.h21.green/. In terms of the UK gas transmission grid, HyNTS is a National Grid initiative which comprising a number of hydrogen projects, predominantly feasibility studies, relating to the conversion of the NTS to carry hydrogen.

All of these projects and demonstrations are providing critical evidence to inform strategic decisions on the future of the natural gas grid in the UK and the future balance between hydrogen and electrification for heating which need to happen soon if we are to meet Net Zero by 2050.

The initial set of issues raised for consideration in terms of heating included for the ranking are:

1. Gas Distribution Networks (New & Re-purposed)
2. Materials Issues (Steel, PE etc. including effects of long exposure and jointing)
3. Hydrogen/ NG mixes (Detection, mixing local and downstream in large grids with multipoint injection, appliance testing)
4. Pure hydrogen systems (production, purity, odorants, colourant)
5. Leaks in buildings and buried pipework including tracking effects etc.

The results of the voting provided an almost equal distribution, see Figure 3.15. Furthermore, the issues including those ranked high are quite similar to Power to Hydrogen priorities, in particular 2nd rank addressing the suitability of existing gas distribution networks. This implies the compatibility of materials, in particular plastic materials and components.

Application - heat

Q	TOT	%	RANK
1	93	20.67	2
2	88	19.56	4
3	92	20.44	3
4	72	16.00	5
5	105	23.33	1

Figure 3.15 Ranking of issues in the new Heat application field

For this reason only the issue on 1st rank shall be highlighted here. The **control of leaks in buildings and buried pipework** deserves special attention.

Editors' note: this section on safety priorities related to the utilisation of hydrogen for (domestic) heat will have to be redesigned to reduce topics' overlap with the section on power-to-gas. Also end-users aspects such as hydrogen burners' behaviour should receive more attention.

4 STORAGE

Chair: Dr. Hervé Barthélémy (Air Liquide) - Participants and contributors: Alberto Agnoletti (Faber), Paolo Bortot (Tenaris Dalmine), Dr. Georg W. Mair (BAM), Prof. Jinyang Zheng (Zheijiang University)

4.1 Introduction and stage setting

Efficient storage of hydrogen is crucial for the success of hydrogen markets for both stationary and on-board storage applications'. Hydrogen can be stored as a compressed gas, a refrigerated liquefied gas, a cryo-compressed gas or in solids such as hydrides. Each technology brings common and specific challenges.

At the time of this workshop (September 2018), compressed and liquefied technologies are preferred and offer the most effective solutions for commercialisation.

4.2 Identified R&D gaps FROM The Previous RPW 2016:

The priorities that were identified at the 2016 workshop were:

- Fire safety
    - Need for modelling tools of fire scenarios (fire, temperature and radiative effect levels, temperature of the cylinder, etc.). Predictive tools of burst time in fire were recently developed in FCH JU project FIRECOMP[6].
    - Need for new cylinder and fire solutions and the design of smart and reliable fire detection and protection (TPRD, protections, fire detections, heat conduction to promote liner melting, etc.)

See progress in Session 7 “Materials”.

- Damage & inspection
    - Modelling damage induced by impacts and lifetime assessment (including metal liner) and structural health monitoring

  See progress in Session 7 “Materials”.

- Cryo-compressed storage
    - Improvement of the insulation function of cryo-compressed storage was identified as priority.

Progress/Closed gaps since RPW 2016:

- Design standards
    - The progress achieved has been input in the development of the standard ISO/DIS 19884 on Cylinders and tubes for stationary vessels:
        - Introduction of ASME KD-10.
        - Dedicated Annex for existing transportable vessels used as stationary vessels

      Introduction of Accelerating Factor (5) for fatigue life in hydrogen service (from FC JU project MATHRYCE results[7])Editors' note: unfortunately the Draft Standard has not

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[6] FCH JU FIRECOMP project, *Modelling the thermo-mechanical behaviour of high pressure vessel in composite materials when exposed to fire conditions*, 2013-2016, project factsheet available at https://cordis.europa.eu/project/id/325329 , results available at http://www.firecomp.info/

[7] FCH JU MATHRYCE project, *Material Testing and Recommendations for Hydrogen Components under fatigue*, 2012-2015, summary available at https://cordis.europa.eu/project/id/303422

been approved and is now cancelled. Nevertheless, the scientific achievement will be used for drafting a new standard.

  - Development of a new European standard (prEN 17339) for fully wrapped transportable composite cylinders and tubes for hydrogen service that are permanently mounted in a frame such as trailer or bundle with reduced safety factor (from FCH JU HHYCOMP project results[8]).
- Hydrogen compatibility standards
  - Publication of ISO 11114-4:2017 (testing methods for determining hydrogen compatibility of steels)
  - New work at ISO level is being initiated for checking the compatibility of plastic liner materials
- Non Destructive Examination
  - Progress on the development and publication of ISO/TS 19016 on Modal Acoustic Emission for periodic inspection and testing of composite cylinders[9]
  - New work at ISO level to have a separate standard for Acoustic Emission
- Recycling
  - On-going developments of composite cylinders with thermoplastic resins

4.3 RPW 2018

Working topics on Hydrogen Storage Technologies

- Types 1 and 2 vessels from 850 to 1100 bar (since weight is not the most important issue)
  - Hydrogen fatigue tests
  - Development of multi-layered high pressure storage to eliminate the risk of hydrogen embrittlement
- Types 3 and 4 vessels
  - Creep rupture strength of carbon fibre strands

  Currently, burst ratio considers exclusively static fatigue (creep strength). Cyclic fatigue is tested under the focus of functionality not of degradation that is detectable in statistics. The worst case degradation in service has to be based on residual strength tests of storage units in service. If the sketched approach for the worst case degradation is globally successful, the life time issue could be solved easily. If it is partly successful, it will become necessary to look in detail on the issue of artificial ageing processes: causing level and kind of degradation adequate to in-service degradation? This has to be done on the basis of statistical assessment of test results.

Identified new gaps or directions

- Metal liner
  - A need Improve database of tests including other steel grades
  - Harmonized test method to characterize metal components in hydrogen
  - Harmonized analysis method to evaluate fatigue life
  - Degrading mechanism of material/component/system in contact with high pressure hydrogen
- Plastic liner

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[8] FCH JU project HYCOMP, *Enhanced Design Requirements and Testing Procedures for Composite Cylinders intended for the Safe Storage of Hydrogen*, summary available at https://cordis.europa.eu/project/id/256671

[9] ISO/TS 19016:2019 Gas cylinders — Cylinders and tubes of composite construction — Modal acoustic emission (MAE) testing for periodic inspection and testing

  - Temperature limits (especially during filling and emptying cycles)
  - Behaviour in hydrogen: solubility in hydrogen, decompression, blistering and collapse
  - Need for a standard for hydrogen compatibility of polymers with harmonized material test method at sample level to select liner materials compatible with service condition
- Composite structure
  - Lack of an effective NDT technique for composites applicable at the manufacturing stage and in service
  - Trials with Acoustic Emission and Modal acoustic emission techniques need additional development for the calibration phase, standardisation
- General
  - Need for an agreement on periodic requalification procedures
  - Desire for development of effective in-service continuous monitoring of the composite structure
  - Degradation mechanisms of high pressure gaseous hydrogen storage vessels under extreme conditions (fire, blast, etc)

Results of the RPW 2018 survey

Priorities:

1. Ageing models considering mechanical loads and all influencing operating parameters, including liner collapse (this will also assist improvement of test protocols defining material selection criteria to qualify H2 cylinder design)
2. Modelling the damage induced by impacts on high-pressure tanks
3. Fires: new solutions for smart and reliable fire detection and protection systems (TPRD, protections, fire detections, heat conduction to promote liner melting, etc.)
4. Understanding effect of overheating on the structural performance and lifetime of the whole storage systems in case of extreme hot filling scenarios, and other temperature excursions.
5. Structural health monitoring of pressure vessels for operative conditions (fatigue, creep, etc.) and accidental conditions (after crash, thermal events and misuse).
6. Non-destructive-techniques for ensuring constant manufacturing quality and required performance (number of cycles, tightness, etc.).
7. Testing of and advanced testing methodology for TPRD, to identify failure modes and frequencies.
8. Hydrogen conversion system (for blow off hydrogen), improve availability and operating range in cryo-compressed storage systems
9. Burst impact mitigation
10. Extreme impact loads: event statistics, protection on vehicle side, pressure vessel robustness
11. Improvement of insulation function in cryo-compressed storage systems
12. Tank fire resistance protocol (more realistic bonfire test)

Storage			
Q	TOT	%	RANK
1	44	8.63	6
2	32	6.27	9
3	43	8.43	7
4	56	10.98	3
5	53	10.39	4
6	63	12.35	2
7	53	10.39	4
8	19	3.73	11
9	37	7.25	8
10	29	5.69	10
11	14	2.75	12
12	67	13.14	1

Figure 4.1 Result of the RPW 2018 survey

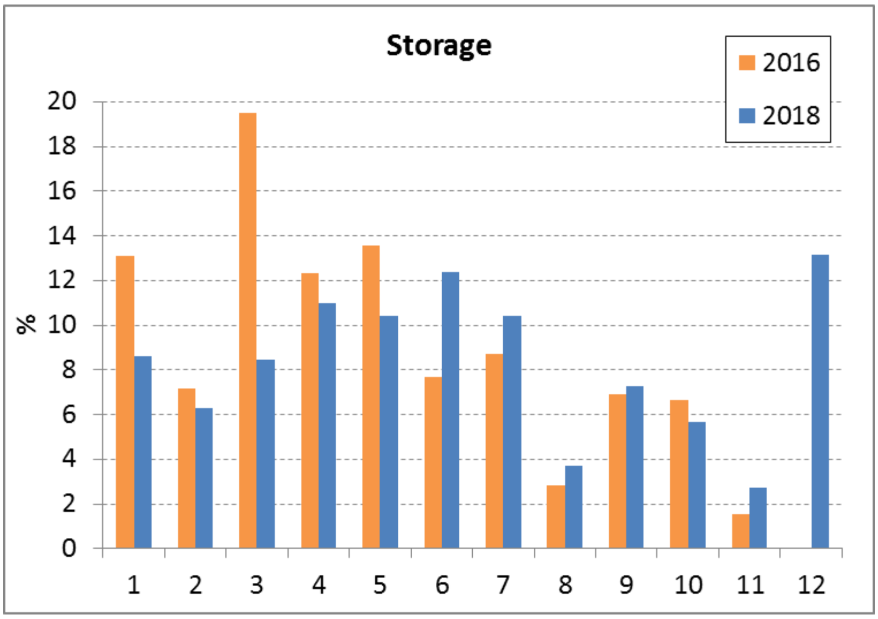

Figure 4.2 Comparison of the results of the surveys (2016 vs. 2018)

4.4 Conclusion:

The top 3 priorities identified during the RPW 2018 are:

- Tank fire resistance protocol (more realistic bonfire test)
- Non-destructive-techniques for ensuring constant manufacturing quality and required performance (number of cycles, tightness, etc.).
- Understanding effect of overheating on the structural performance and lifetime of the whole storage systems in case of extreme hot filling scenarios, and other temperature excursions.

4.5 Comment of the Chair of Storage Session:

The understanding of the effect of overheating is particularly important. This issue needs resolution as there are serious concerns that during fuelling the application of the protocols ensures that the maximum operating temperature of the tank is not exceeded.

Editors' note: more realistic bonfire test is now discussed in the frame of the Phase 2 of the UN-ECE working group on the Global Technical Regulation 13 on FCEV safety.

5 ACCIDENT PHYSICS – GAS PHASE

Chair: Jay Keller (ZCES) - Participants and contributors: Cirrone, Donatella (University of Ulster, UK)

5.1 Introduction and Stage Setting

This Chapter addresses issues involving gas phase unintended releases; topics include Venting, Pressure Peaking, Blast Waves, Jet Fires, and reduced order modelling for use in integrated software tools. Understanding unintended gas phase releases under realistic scenarios has been central to ensuring the safe deployment of hydrogen technologies.

5.2 Results from 2016 workshop

This workshop builds on results from the 2016 workshop. Topics for this session in 2016 were:

1. Venting
2. Pressure Peaking
3. Blast Waves
4. Non-Premixed Combustion (Jet flames)
5. Ignition
6. Premixed Combustion

5.3 Topics for 2018 workshop - Working topics on Accident Physics – Gas Phase

- Venting – 2018 ranking **3**
- Ignition – 2018 ranking 4 and 5
    a. statistical approaches to ignition
    b. spontaneous Ignition
- Premixed Combustion – 2018 ranking **1**
    a. Premixed combustion - further modelling studies are needed for large scale applied problems with obstacles, particularly for DDT, Flame acceleration in confined and obstructed spaces and Blast Waves
- Jet Flames – non-zero ignition delay 2018 ranking **2**
    a. Jet Flames with 0 ignition delay were considered well enough understood to be removed from further consideration in the 2016 ranking and hence this topic is closed out

Issues that came up in the open discussion, not voted on but were considered important were:

- Validated Turbulence Models (not addressed)
- Behavior and dispersion of cryogenic jets – addressed in PRESLHy (liquid behavior)
- Non-credible scenarios that are only of academic valueIt should be noted that the ranking across these topics is fairly close, indicating that all these topics are equally important both from a physical consequence perspective and hence motivates continued research in these research areas.

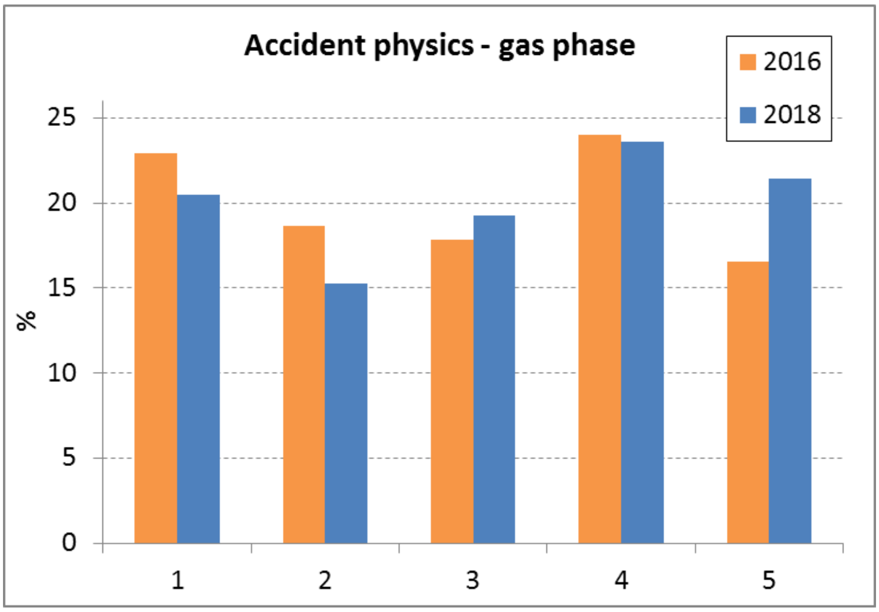

Figure 5.1 Comparison of voting results: 2016 and 2018

6 ACCIDENT PHYSICS – LIQUID/ CRYOGENIC BEHAVIOUR

Chair: Phil Hooker (HSL) - Participants and contributors: Simon Jallais (Air Liquide), Lee Phillips (Shell), Alexandros Venetsanos (NCSRD), Jennifer Wen (University of Warwick), Marco Carcassi (Università di Pisa), Donatella Maria Chiara Cirrone (Ulster University), Andreas Friedrich (Pro Science), Andreas Haberzettl (DLR), Ethan Hecht (Sandia)

6.1 Introduction and Stage Setting

There are a number of properties that distinguish the behaviour of LH2 and cryogenic hydrogen from that of other cryogenic materials such as liquefied natural gas (LNG). For example, the boiling temperature of hydrogen is lower than that of the main constituents of air, nitrogen and oxygen, which is not the case with methane.. In particular, there are also issues related to the complexity of behaviour during and after release, i.e. heat transfer and the physical phases of the hydrogen itself, and the condensation of components of the air into which it is released.

6.2 Results from 2016 workshop

The issues perceived to be key at the time of the HySafe RPW in 2016 are given below.

RPW 2016 recognised that the modelling of liquid hydrogen releases was impeded by lack of good quality experimental validation data. Source term data from reported experiments lacked detail for the release mass flow rate, knowledge of the proportions of liquid and gaseous hydrogen exiting the release point, the pressure at the storage vessel and at the release point.

Also for the modelling of liquid and cryogenic releases the weaknesses were identified:

- the influence of different Equations of State,
- the calculated heat capacity of hydrogen at low temperatures,
- the need for development of pool spreading and evaporation models, coupled with vapour dispersion,
- comparison between liquid pool models, and the models that solve the pool and cloud combined,
- modelling of ground heat flux where a liquid/solid pool/slush is formed,
- the radiative heat transfer contribution from the air and ground to the cold
- the turbulence intensity at the source and the effect of non-ideal behaviour of hydrogen on CFD predictions in liquid releases

On top of the partial lack of knowledge and validated modelling, application developments were foreseen to potentially lead to:

- large inventories of LH2 in public spaces, congested areas such as railway tunnels, and harbours, ports etc.
- An understanding of LH2 large pool fire behaviour compared to that of LNG is also seen as important to aid potential technology transfer and development between the two fuels.
- The potential for, and consequences of, BLEVEs of LH2 storages in fire engulfment scenarios was also highlighted.LH2 dispersion indoors and outdoors, jet and pool fires, solids (oxygen)/liquid hydrogen explosions, general ignition and BLEVE/fire resistance.

The output from the prioritisation of research requirements resulted in the priorities identified in ref: report
http://publications.jrc.ec.europa.eu/repository/bitstream/JRC111028/kjna29146enn.pdf):

It is against this background that the RPW of 2018 have been considered.

6.3 2018 RPW summary

The following Chapters report progress made since the 2016 RPW, planned programmes to investigate these further and any new areas of interest.

Progress since last RPW

Progress on the understanding of cryo hydrogen accident physics since the last workshop includes improvements in the measurement techniques for determining the concentration and temperature of gaseous components in the jets resulting from cryogenic releases in air (Hecht and Panda, 2018), modelling of LH2 pool formation (Nazarpour et al., 2017; Jäkel et al, 2017), empirical work on the behaviour of cold plumes (Buttner et al., 2018), the development of CFD predictions of thermal radiation from cryogenic jet fires (Cirrone et al., 2017). In addition, the European Commission funded PRESLHY (FCHJU, (2018) project has started and has recently conducted a state of the art review (Jallais et al., 2018).

Composition measurement and modelling of cryogenic jets

Extensive work has been carried out by Hecht and Panda, (2018) on establishing optical methods of determining the composition of gas phases during cryogenic releases. The work has included the use of Raman spectroscopy and Particle Image Velocimetry (PIV) to generate accurate data for model validation.

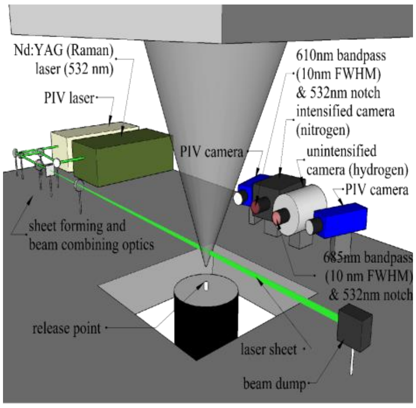

Figure 6.1 Experimental arrangement used by Hecht and Panda, (2018)

Jet fires

Extensive experimental and modelling work carried out in recent years has enabled a good understanding of cryogenic hydrogen jet fires (e.g. Panda and Hecht, 2017), with classical flame length models appearing to be valid.

Planned programmes

Further work is planned in a number of projects:

- The work of Hecht and Panda, (2018) is to continue, with the aim of trialling the techniques on a larger scale.

- The European project PRESLHY[10] will be carrying out work in three main work areas relating to accidental LH2 releases; dispersion and rain-out / pool formation, ignition phenomena (including condensed LH2/air, and an assessment of electrostatic charging), and combustion of cryogenic gas / air mixtures.
- The Norwegian SH2IFT[11] project will address knowledge gaps regarding safe handling of liquid H2, theoretical approaches will be complemented by fire and explosion experiments, with emphasis on topics of strategic importance to Norway, such as tunnel safety, maritime applications, etc.

New areas of interest

There is increasing interest in the behaviour of high pressure liquid hydrogen (i.e. hundreds of bar) relating to the development of novel approaches to the vehicle refuelling. No experimental data is available under these conditions to enable the development and validation of models.

The potential for LH2 accident scenarios where cold clouds of hydrogen could occur in congested environment. Therefore there is a need to develop an improved understanding of the combustion behaviour of cold clouds of hydrogen, including fundamental behaviour (such as burning velocity) and the propensity for flame acceleration (FA) and deflagration to detonation transition (DDT).

It is also important to improve understanding of rapid phase transition phenomena in congested environments, with respect to the consequences of the use of water deluge to LH2 spillage, etc.

6.4 Results of voting on 2018 RPW

The list of topics at the 2018 workshop is given below. This comprises those topics identified in the previous workshop and also new topics shown in **bold**.

1. Knowledge and experience related to indoor releases and dispersion
2. Knowledge and experience related releases involving large quantities
3. Knowledge and experience related releases in congested areas
4. Multi-phase accumulations with explosion potential (LH2 can condense and freeze oxygen. The resultant mixture can be made to detonate): conditions for occurrence and the consequences are not understood
5. BLEVE (Boiling Liquid Expanding Vapour Explosion or Fireball): knowledge on fire resistance and prediction of consequences are needed.
6. Studies on humidity / air phase change during LH2 and cryogenic compressed hydrogen releases should be undertaken to inform modelling of these phenomena
7. Correlations for accurately calculating the specific heat capacity of hydrogen at low temperatures and high pressures should be further investigated and incorporated into CFD codes.
8. CFD validation especially for complex obstructed industrial environments and various weather conditions (wind speed atmospheric stability class)
9. Modelling of the two-phase chocked releases, in particular for achieving a reasonable estimation of the mass flow rate
10. Further development of pool spreading and evaporation models, coupled with vapour dispersion. Research should be directed at improving the modelling of ground heat flux in cases

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[10] FCH JU PRESLHY project Pre-normative Research for Safe use of Liquid Hydrogen, 2018-2020, summary available at https://cordis.europa.eu/project/id/779613

[11] Project SH2IFT - Safe and efficient hydrogen fuel handling and technology, funded by the Research Council of Norway, summary available at https://www.sintef.no/projectweb/sh2ift/

where a liquid pool is formed- for both solid and liquid (usually water) substrates. The radiative heat transfer and its contribution to the total heat transfer from the air and ground to the cold cloud should also be studied. Liquid hydrogen pool fire not well characterised

11. Evaluation and comparison of the performance of the different Equation of States (EOS) in the two-phase chocked flow approaches should be attempted
12. Ignition sensitivity & electrostatic hazards during venting / accident scenarios
13. Combustion properties of cold gas clouds, especially in congested areas
14. Rapid phase transition / response to water deluge etc
15. High Pressure LH2 releases

The results from the voting on the priorities are shown in Figure 6.2, and compared to the results from 2016 in Figure 6.3. The top three priorities are: topic 2 (Knowledge and experience related releases involving large quantities), topic 4 (Multi-phase accumulations with explosion potential) and topic 13 (Combustion properties of cold gas clouds, especially in congested areas). Of these, only topic 13 is new.

It is evident from Figure 6.2 that there are five topics that are very close in terms of voting results, 2,3,4,12 and 13, all obtaining more than 9% of the votes each.

Accident physics - liquid phase

Q	TOT	%	RANK
1	21	5.19	11
2	40	9.88	3
3	39	9.63	4
4	45	11.11	1
5	31	7.65	7
6	24	5.93	9
7	2	0.49	15
8	17	4.20	13
9	24	5.93	9
10	25	6.17	8
11	3	0.74	14
12	37	9.14	5
13	44	10.86	2
14	21	5.19	11
15	32	7.90	6

Figure 6.2 Results of voting

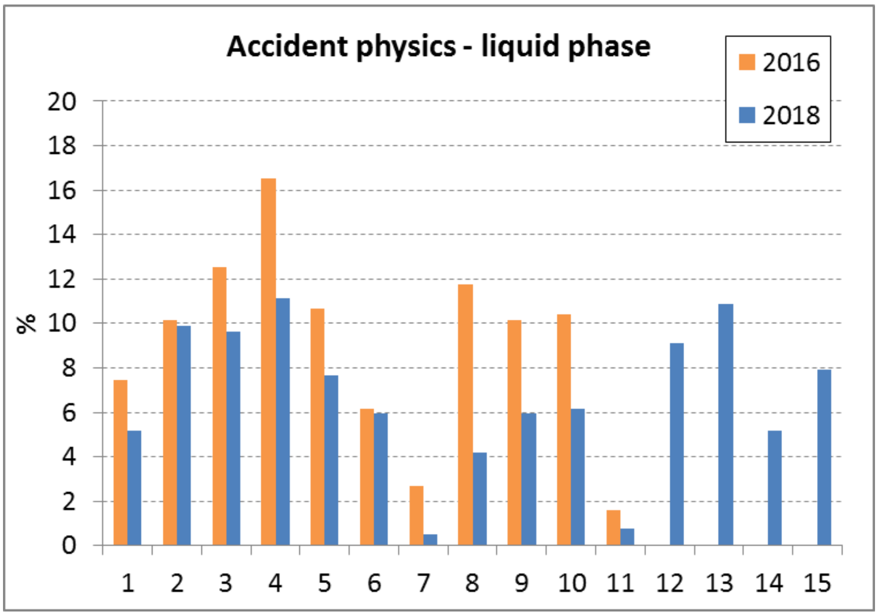

Figure 6.3 Comparison of voting results: 2016 and 2018

The most pronounced changes from the last RPW are:

- the reduction in the number of votes relating to condensed phase explosion phenomena (No.4) though it was still voted as number 1 priority,
- A significant reduction in the number of votes related to CFD modelling and validation (Nos.8, 9 and 10) , and
- Significant voting on three new topics relating to ignition sensitivity (No 12), combustion in cold clouds (No 13)_, and high pressure releases (No, 15),.

6.5 Comment of the Chair of Accident Physics – LIQUID/ CRYOGENIC BEHAVIOUR

As the rationale for their rankings, the experts attending the RPW 2018 submitted the following comments summarised in Table 6.1 below.

Table 6.1 Rationale comments submitted by RPW 2018 experts.

Topic area number	Expert Comments
2,3,4,12, 15	For large scale maritime applications
5, 6, 12, 13, 14	According with my experience
1, 4, 10, 11, 13	Many of these are interesting topics
1, 3, 13, 14, 15	Taking into account current work addressed by PRESLHY
2, 4, 6, 10, 14	The fundamental physics need to be studied and understood if we are to make safe LH2 systems and applications.
5, 9, 12, 14, 15	I tried to account for the PRESLHY project plan and ranked those topics addressed therein lower
1, 2, 3, 4, 14	We need early stage research on this problem. After foundational research we can move to the second order work.
4, 9, 12, 13, 15	BLANK
1, 7, 8, 9, 10	Important for consequence scenarios

6,8,9,10, 15	It is important to study the basic behaviour of release of liquid hydrogen to understand how to predict its behaviour
3, 4, 12, 13, 15	No special comments on this topic
4, 5, 10, 12, 13	For me many open issues to be clarified.
1, 3, 10, 12, 13	Combustion and ignition properties of gas clouds seems to be a fundamental need. Pool spreading/fire is also somewhat fundamental so was ranked 3rd. Finally, congested and indoor areas may have different dispersion characteristics so is of interest.
2, 3, 12, 13, 15	Accurate measurements/investigations prior to simulations
2, 3, 5, 10, 13	Mixing/combustion behaviour of large-scale release of liquid hydrogen is of lot of importance.
2, 3, 4, 9, 14	The main reasoning behind the use of liquid hydrogen is the large capacity offered by the storage systems using it. Therefore, more realistic scenarios are the one involving releases of large quantities of hydrogen and these should be the one needing prioritisation.
2, 3, 5, 13, 14	RPT important for ship to shore transfer operations BLEVE will be issue with regulator, even if we don't believe it to be credible they will assume it is and ask for demonstration that we understand risk (based on direct experience during safety case submission)
2, 4, 5, 10, 11	Consequences of large releases from spillage, BLEVE will drive the maximum cost of mitigation, smaller releases need to be considered with knowledge of the acceptable operating conditions / volumes of stores.
4, 6, 12, 13, 14	Ignition sensitivity and effect of frozen / liquid O2 appears to be most important for practical applications.
3, 6, 8, 9, 13	There is a need for both fundamental understanding and some more real-world situations
1, 4, 9, 12, 15	High pressure LH2 release is the main issue
1, 2, ,3, 4, 15	Behaviour understanding is critical
6, 9, 10, 13, 15	Basic phenomena and source term first
2, 3, 5, 6, 14	There seems to be very limited knowledge on BLEVEs and RPTs.
1, 4, 6, 12, 15	Electrostatic hazards have to be understood in order to address this topic by standardization regarding the mitigation measurements
3, 4, 6, 8, 10	There are a lot of physics that aren't very well understood, but one must start with credible scenarios of small leaks that rapidly vaporize before considering large leaks that might pool and/or condense air.
1, 2, 5, 8, 13	Knowledge of state of the art

It is interesting to note that the research needs prioritised in this 2018 workshop appear to follow the theme of investigating large scale releases, and consequences, in obstructed environments. However, it is important to remember that understanding the large-scale phenomena relies also on the detailed understanding of fundamental behaviour to facilitate the development of accurate models.

The list of research topics has extended and become somewhat unwieldy. A rationalisation of these before the next RPW is required.

7 SESSION 7: MATERIALS

Chair: Iñaki Azkarate (TECNALIA) - Participants and contributes were: Beatriz Acosta-Iborra (JRC), Olivier Bardoux (Air Liquide), Laurent Briottet (CEA), Chris San Marchi (SNNL).

7.1 Introduction and Stage Setting

Materials for industrial applications are selected according to several factors, and service conditions have great impact on this choice. Hydrogen mainly affects materials in their mechanical properties. Depending of the material's nature, metal or polymer, hydrogen can impact it in different ways. Understanding the effects of hydrogen in material's properties is clearly very important, and with this in mind, the RPW process is divided into:

Materials – 1: Testing aspects related to the characterization of materials

Materials – 2: Performance assessment of materials

7.2 Identified gaps FROM The Previous RPW 2016

The RPW 2016 identified the following topics as research priorities in the Materials Compatibility Session:

Materials – 1: Testing aspects related to the characterization of materials

1.1. Methodology validation on several metals and components between different laboratories. (priority also relevant for future international standardization efforts)

1.2. International consensus on metrics for qualification of metals for specific applications

1.3. Definition of test protocols, selection criteria and relevant standards for polymer materials

1.4. Development of non-destructive test methods for liner evaluation

1.5. Activities on seals, gaskets, hoses, valves and joints. They should receive similar attention to the tank material and their behaviour tested under different and realistic conditions.

Materials – 2: Performance assessment of materials

2.1. Better understanding on Fatigue Crack Initiation and Propagation. In particular, focusing on small cracks and better understanding of the effect of hydrogen pressure on the threshold of the stress intensity factor range. Special attention to low-temperature / high-pressure conditions. From a general point of view a better understanding of materials behaviour under mechanical stresses is needed

2.2. Database providing fatigue data for the most probable materials to be used for hydrogen pressure vessels

2.3. Scalability of fatigue testing: effect of deep vs shallow cycles, hydrogen accelerating effect for lab (specimen) versus full scale testing (pressure vessel)

2.4. Evaluation and assessment of integrity of existing pipeline networks for pure hydrogen

2.5. Mechanical performance of polymers under hydrogen service conditions has to be better characterised (including blistering, swelling). Also, studies on the reversibility of these materials

2.6. Better understanding of the role of impurities and inhibitors

2.7. Assessment of materials for specific liquid hydrogen applications

2.8. Definition of appropriate models for lifetime predictions for polymers. In particular, correlation between the behaviour of polymers under low hydrogen pressures and high hydrogen pressures and effects of temperature peaks (or valleys) and temperature excursions in tanks containing polymers. Correlations between permeation and pressure/temperature conditions, especially with the aim of achieving prediction capabilities

As shown in Figure 7.1, topics number 1.2, 1.3, 1.5, 2.2, 2.1 and 2.8 respectively received the top six ratings; these are written in bold above.

Material - 1	tot	%
5.1.1	73	19.47
5.1.2	85	22.67
5.1.3	76	20.27
5.1.4	66	17.60
5.1.5	75	20.00
Material - 2	**tot**	**%**
5.2.1	55	15.28
5.2.2	72	20.00
5.2.3	37	10.28
5.2.4	43	11.94
5.2.5	44	12.22
5.2.6	15	4.17
5.2.7	44	12.22
5.2.8	50	13.89

Figure 7.1 2016 Ranking of priority topics in Materials.

7.3 ANALYSIS OF RPW 2018 PRIORITIES RANKING RESULTS

In the analysis of the RPW 2018 priorities ranking, the review of the state of the art in this category indicated that none of the priorities are completely closed yet. Main progress has been made on metallic materials; polymers and their components need more progress.

Three new topics were added to the 2016 list numbered 2.9 to 2.11. The extended list is presented below with new items in italic.

Material – 1: Testing aspects related to the characterization of materials

1.1. Methodology validation on several metals and components between different laboratories. (priority also relevant for future international standardization efforts)

1.2. International consensus on metrics for qualification of metals for specific applications

1.3. Definition of test protocols, Selection criteria and relevant standards for polymer materials

1.4. Development of non-destructive test methods for liner evaluation

1.5. Activities on seals, gaskets, hoses, valves and joints. They should receive similar attention to the tank material and their behaviour tested under different and realistic conditions.

Material – 2: Performance assessment of materials

2.1. Better understanding on Fatigue Crack Initiation and Propagation. In particular focusing on small cracks and a better understanding of the effect of hydrogen pressure on the threshold of the stress intensity factor range. Special attention to low-temperature / high-pressure conditions is obviously also important. From a general point of view a better understanding of materials behaviour under mechanical stresses is needed

2.2. Database providing fatigue data for the most probable materials to be used for hydrogen pressure vessels

2.3. Scalability of fatigue testing: effect of deep vs shallow cycles, hydrogen accelerating effect for lab (specimen) versus full scale testing (pressure vessel)

2.4. Evaluation and assessment of integrity of existing pipeline networks for pure hydrogen

2.5. Mechanical performance of polymers under hydrogen service conditions has to be better characterised (including blistering, swelling). Also, studies on the reversibility of these materials

2.6. Better understanding of the role of impurities and inhibitors

2.7. Assessment of materials for specific liquid hydrogen applications

2.8. Definition of appropriate models for lifetime predictions for polymers. In particular, the correlation between the behaviour of polymers under low hydrogen pressures and high hydrogen pressures and effects of temperature peaks (or valleys) and temperature excursions in tanks containing polymers needs to be understood. Correlations between permeation and pressure/temperature conditions, especially with the aim of achieving prediction capabilities need to be developed.

2.9. Study of the crack nucleation step for metallic materials

2.10. Classification of failure modes for polymers

2.11. Evaluation of materials and components of NG grids and appliances to be used with H2/NG blends

Ranking of the extended list of priority topics by the experts attending the RPW 2018 is presented on Figure 7.2, and the overall comparison of 2016 and 2018 RPW rankings is presented in Figure 7.3.

Materials - 1

Q	TOT	%	RANK
1	68	16.79	4
2	68	16.79	4
3	103	25.43	1
4	80	19.75	3
5	86	21.23	2

Materials - 2

Q	TOT	%	RANK
1	38	9.38	5
2	24	5.93	8
3	23	5.68	9
4	72	17.78	1
5	40	9.88	4
6	21	5.19	11
7	52	12.84	2
8	34	8.40	7
9	23	5.68	9
10	36	8.89	6
11	42	10.37	3

Figure 7.2 2018 Ranking of identified priority topics in Materials

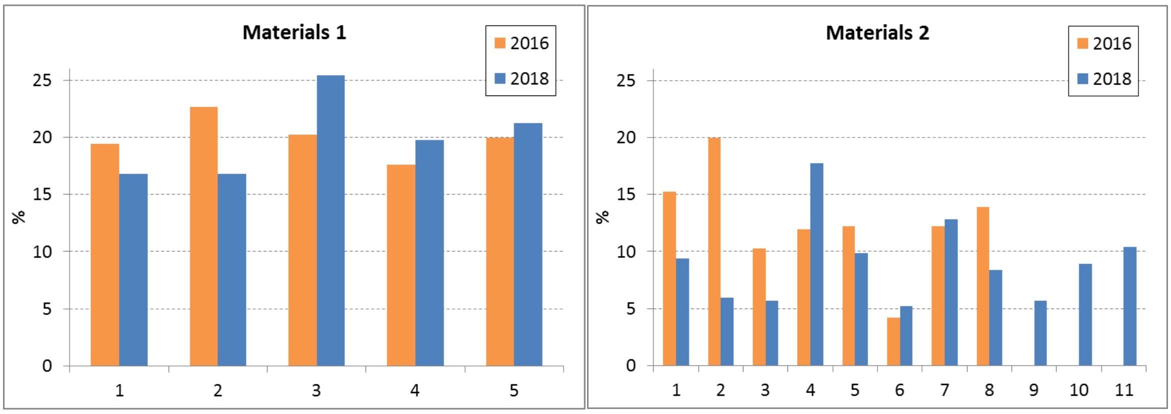

Figure 7.3 Comparison of 2016 and 2018 RPW ranking of identified priority topics in Materials

Table 7.1 Summary analysis of RPW 2018 top priorities in Materials

Index	Top Priorities in Materials					
	Definition of test protocols, selection criteria and relevant standards for polymer	Activities on seals, gaskets, hoses, valves and joints	Development of non-destructive test methods for liner evaluation	Evaluation and assessment of integrity of existing pipeline networks for pure hydrogen	Assessment of materials for specific liquid hydrogen applications	Evaluation of materials and components of NG grids and appliances to be used with H2/NG
PRW2018 Priority sequential number	1.3	1.5	1.4	2.4	2.7	2.11
Ranking Score	103	86	80	72	52	42
1st rankings	9	8	4	9	2	3
Experts Voting	27	27	27	18	16	15
Overall Ranking	1	2	3	4	5	6

7.4 Additional comments from the Chair and RPW Panel

As the rationale for their rankings, the experts attending the RPW 2018 submitted the following comments summarized in Table 7.2 below.

Table 7.2 Rationale comments submitted by RPW 2018 experts

Material 1	Material 2
Hoses, gaskets, valves, etc. suitable for liquid hydrogen will be critical	Hoses, gaskets, valves, etc. suitable for liquid hydrogen will be critical
Important to validate the materials used and their reproducability	Duarbility and degradation of materials is important
Standardization in testing, consensus, validation is critical to determine if the results of testing is to be of value.	Understanding of fatigue crack growth is critical to designing fault tolerant designs
Material characteristics is quite important	Material characteristics for H2/NG is quite important
Whole chain of storage has to be evaluated with defined methods	select suitable materials before starting to investigate failure modes of all
Seals, gaskets, hoses valves and joints make up a large part of installations and should be studied more closely.	I'm not an expert in materials, but a relevant application is for the re-purposing of NG grids.
NDE is extremely important for carbon wrapped tanks.	Polymers are a key component of all systems.
Last topic is a partial repetition of topic 3 (or even a sub-unit of it, because prenormative research is needed for the formulation of testing protocols, selection criteria and std's).	Metals above polymers in view of their major role in the whole value chains ibitor and impurities can change considerable the behaviour, or at
Seats, seals, gaskets etc pose a high risk for leakage	Enabling the use of existing facilities will provide huge potential for NG to
test protocols as well as the methodology validation between different laboratories should be prioritised to have a uniform set of repeatable	liquid hydrogen and pipeline are most likely going to store/transport large quantities of hydrogen, therefore, a better understanding of the material
Priority was given to testing over standardization. Ancillary materials	Favour was given for pipeline related issues.
All components Need to work reliably	Most relevant for this section
Standard harmonization and definition of recognized international methodologies for material compatibility. High pressure hydrogen effect on the seals and polymers should be	Mixture of hydrogen with NG is a very important issues, as well development of standards for pipeline design in hydrogen. Material database should be further developd and publicly available.
Test method are critical	Fundamental studies are useful
Higher Focus on standardization for Materials in hydrogen needed	Still a Lack of Knowledge regarding Crack mechanisems
NDE Liner evaluation is the most critical.	Polymers are very critical today.
The judgement was done on a limited insight in these materials topic...	The judgement was done on a limited insight in these materials topic...
There is a lack of standardized test methods for evaluation of compatibility of plastics with hydrogen	There is a need to devolop standardized approach for plastic material performance
There is a clear need of consensus on the evaluation of materials	All important for heat programme development.
Needs to be clearly defined.	Better understanding of crack innitiation is needed.
Few requirements today for polymeric materials	In practical term the most important point is to have a liste of materials and composnents of NG grids that can be used withe the previewed
Seals, gaskets, hoses, valves and joints are often the source of leaks this is why they should be very well charaterized	Using existing pipelines for H2 could be a game changer, if they are suitable. Just like before, lots of work to be done on polymers.
I think polymers need more attention than metals, as leaks are more likely through polymeric materials.	

There is a clear coincidence on comments related to **the need of studies on polymer components behaviour** that are much less studied than metallic ones. Very often the reason of a leak is based on the failure of a component manufactured with these materials.

8 SESSION 8: MITIGATION, SENSORS, HAZARD PREVENTION AND RISK REDUCTION

Chair: William Buttner (NREL) - Panelists: A. Tchouvelev (AVT), L. Gardner (Canadian Nuclear Laboratory), D. Melideo (JRC), with input from E. Hecht (SNL) and B. Ehrhart (SNL)

8.1 Introduction and Stage Setting

Two main themes pertaining to hydrogen safety sensor research priorities were addressed in separate sessions of the 2018 RPW. The primary focus for Session 8 (Mitigation, Sensors, Hazard Prevention, and Risk Reduction) was to explore the interrelationship between mitigation strategies, including sensors, to achieve risk reduction in the design and operation of hydrogen facilities. This was a new session for the 2018 RPW, and accordingly did not have a historical gap prioritization record. The incorporation of design features, such as fire walls and sensors, have been used to lower set back distances for GH2 facilities, but such approaches have had limited applications in LH2 facilities. The implementation of mitigation strategies, such as active monitoring, may reduce the setbacks for LH2 facilities, which are viewed as being prohibitively large for urban environments. This is recognized as a critical issue, and the development of approaches to assure the safe use of liquid hydrogen (LH2) is an active international area of concern (e.g. FCH-JU, (2018) for Europe and the NFPA 2 (NFPA, 2016) Hydrogen Storage Task Group for the U.S.). The current setbacks prescribed in codes and regulations for LH2 appear to have been established on consensus rather than a scientific basis, and it has been recognized that to implement mitigation strategies to lower the prescribed setbacks it will be necessary to fully understand the behaviour of real-world hydrogen releases, especially cold hydrogen releases. Thus, one critical role for sensors is the characterization of hydrogen dispersion behaviour, which can be used to validate theoretical models and integrated into QRA to guide the design of a facility to optimize and exploit the effectiveness of active monitoring and other mitigation strategies. This is germane for indoor and outdoor GH2 and LH2 operations. An active monitoring system deployed within a facility that can quickly detect unintended releases and guide corrective measures has been identified by the NFPA 2 Hydrogen Storage Task Group as one strategy that may be used to lower LH2 setbacks. Thus, in addition to validating the fundamental behaviour of released hydrogen dispersion, sensors (or other detection methods) will be needed for active monitoring. Hydrogen safety sensors have been part of a hydrogen safety system for many years to assure safety integrity level compliance.

As with the common use of hydrogen sensors as part of a facility safety system, the elements of an active monitoring system must cost-effectively meet stakeholder expectations with respect to critical performance metrics. Thus, a second role for sensors pertains to the performance of hydrogen sensors, which was primarily covered in the General Aspects of Safety (Session 10) of the 2018 workshop and in past RPWs (Dolci et al., 2018) but will be summarized here. The distinction between and interrelation of the two sensor applications is illustrated in Fig. 8.1. Table 8.1 summarizes the research needs prioritized by the experts for hydrogen sensors at the 2018 HySafe RPW. Guidance on sensor placement was clearly identified as the top safety research priority with regards to sensors and garnered a large majority of the top priority votes (20) given by the experts participating in the workshop. Optimal sensor placement will be controlled by hydrogen plume behaviour. Other gaps were identified by the experts for consideration, but received no votes; these, are however, covered in the discussion provided in Chapters 8.21 and 8.22.

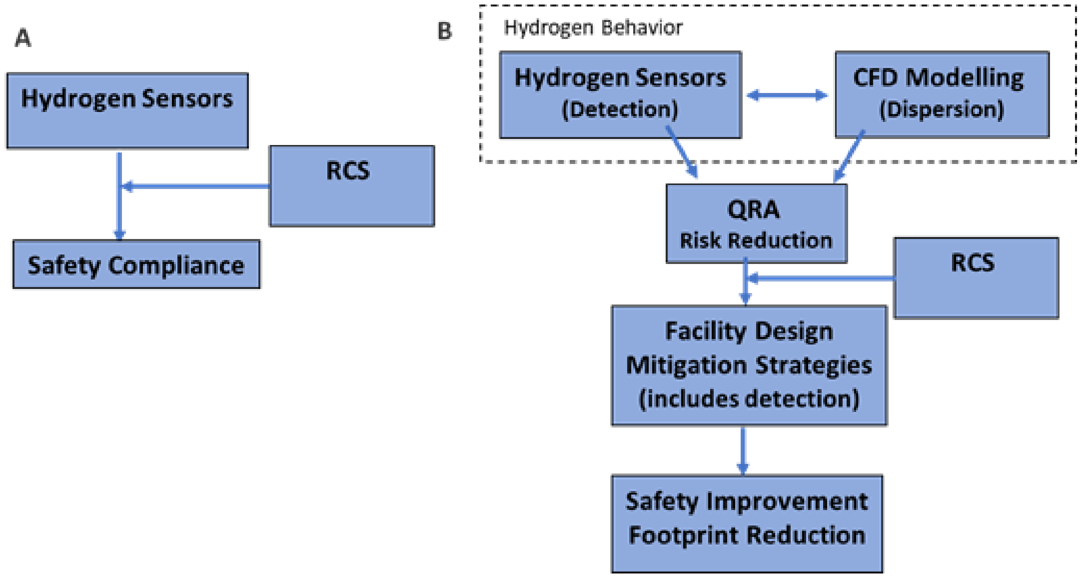

Figure 8.1 (A) H2 sensors are used as part of a facility safety system to achieve an appropriate SIL while at the same time can assure compliance to prescriptive code requirements. (B) Detection is also needed to verify released hydrogen behaviour (e.g., using HyWAM) to validate dispersion models, and for a facility active monitoring system. Coupled with other mitigation strategies, active monitoring can assure improved safety in smaller footprints

It is noted that active monitoring represents only one element in a mitigation strategy that may be employed to minimizing LH2 setbacks or improving hydrogen safety in general, and that additional elements should be considered in a facility design. The development of hydrogen recombiners are being deployed in the nuclear industry to eliminate the build-up of free hydrogen and were included in this session of the RPW. Other proposed approaches to eliminate hazards within a hydrogen facility can include improved ventilation systems, fire walls and other fire suppression methods, enhanced maintenance procedures, but these have yet to be addressed for LH2. Nor have their effectiveness for LH2 been assessed, such as through QRA. Integration of the various mitigations into a QRA will assist in ascertaining the effectiveness of various mitigations and thus guide facility design, which *ought to* lead to improved safety in a more reasonable facility footprint. Although an emphasis was placed on achieving alleviated LH2 setbacks, mitigation strategies for safety assurance are also relevant to GH2 systems.

Table 8.1 Identification and prioritization of Sensor Research Gaps as Prioritized by the IA HySafe RPW

	Prioritization Rankings		
Prioritized Gaps	1st	2nd	3rd
Guidance on Sensor Placement	20	3	3
Long Term Stability	3	13	10
Sensor Selectivity	3	10	13

8.2 Research Priorities

Hydrogen Safety Sensors (in conjunction with General Aspects of Safety, Session 10)

This has been an on-going sub-topic in the General Aspects of Safety session since 2016. The 2016 RPW workshop identified several critical hydrogen sensor performance gaps (see Table 10.2 in Dolci et al., 2018). The highest concerns were reliability testing and sensor placement. There was also a concern about "complex and overbearing code requirements/limited internal harmonization". The prioritized gaps in the 2016 RPW differed slightly from the gap priorities identified by stakeholders at a 2016 international hydrogen sensor workshop that was jointly organized by the FCH-JU, JRC, and NREL (Ortiz et al., 2017), which explicitly identified lifetime as a major metrological gap. Sensor lifetime was, however, a prioritized gap in the 2018 RPW. In general, the gaps identified in 2018 focused on practical use and performance of hydrogen sensors for assuring safety. The primary research priorities identified in the 2018 RPW for the general application of hydrogen safety sensors pertained primarily to their metrological performance. While there have been ongoing advances in performance parameters, several were still identified as an issue:

- Long-term Stability (ranked #2). Long-term stability affects the capital cost of the monitoring system owing to the need for periodic sensor replacement, often perceived as too frequent. A second impact is the need for regular calibration and adjustment. The frustration with regular maintenance also impacts stakeholder confidence in sensors. Although sensor lifetime is improving, manufacturers are still not routinely specifying a five-year operational lifetime (a 10-year lifetime is desired for some applications (Ortiz et al., 2017)). There also remains a large variability in stability from one model to another (e.g., see Fig. 10.3 of the 2016 RPW Summary Report (Dolci et al., 2018)).
- Sensor Selectivity (ranked #3). This was a mixed assessment, with some acknowledgement that selectivity requirements can be an application-specific issue, and that there are published data available on cross-sensitivity (e.g. Palmisano et al., 2015). Sensor selectivity is improving at least with regards to some interferents, but this is often sensor platform dependent and can even vary among different models of the same platform. One special application of increasing importance was the use of sensors to monitor hydrogen in natural gas, and this was identified as a priority gap for some participants in the 2018 RPW, although it did not receive any formal ranking.
- Emphasis was placed on sensor-user interaction in the General Aspect of Safety session, although this was unranked in the 2018 RPW. Such considerations are necessary to optimize the effectiveness of sensors as a safety tool.
- Another unranked gap in 2018 suggested by a workshop participant was the need for accelerated life test (ALT). This could serve as a life-time predictor, but the development of a validated ALT is impeded by a lack of data and understanding of basic failure mechanisms of deployed sensors.
- Another unranked issue with hydrogen sensors is the variability of performance among commercial sensor models (e.g., see Fig. 10.3 of the 2016 RPW Summary Report (Dolci et al., 2018)). The impact of this may be alleviated by a low-cost, facile performance standard. Certification to ISO 26142 (ISO, 2010) might address this issue, but certification costs remain prohibitively expensive for the current market. SAE has addressed this issue for FCEV manufacturers by developing a guidance document on sensor performance evaluations to be performed by suppliers (SAE, 2018).

Mitigation, Sensors, Hazard Prevention, and Risk Reduction

This was a new session, and accordingly, a historical record of gaps was not available, although aspects of this topic have overlapped with other sessions in past RPWs. The need for rational as opposed to intuitive deployment of hydrogen sensors to enhance their effectiveness was identified as the top priority in the 2018 RPW:

- Guidance on Sensor Placement (ranked #1). Optimal sensor placement will allow earlier detection at lower levels of incipient leaks, leading to improved SIL and significant reduction in overall hazards at a facility

Sensor placement guidance requires an understanding of hydrogen behaviour within the deployment environment, which requires the development of validated models (see Figure 8.1). In an indoor study for a GH2 facility, CFD modelling of the hydrogen dispersion (performed by AVT, Inc. and independently by the JRC) was validated by the NREL Sensor laboratory using a Hydrogen Wide Area Monitor (HyWAM)[12] system based upon an array of point sensors (preliminary results were briefly presented in Buttner (2018)). As expected, it was shown that the dispersion of indoor hydrogen releases is predicated upon the facility ventilation flow patterns. Somewhat unexpectantly, however, the modelling demonstrated that optimal sensor placement may be achieved in locations of low ventilation flow within the facility (as modelled by CFD), and that in doing so, leaks can be more predictably and quickly detected than by placing the sensor in front of a ventilation exhaust system as is currently more frequently performed. Furthermore, low-level leaks can be detected that would have been undetectable by other means (e.g., pressure sensors mounted on pneumatic lines). A more thorough analysis will be formally presented at the 2019 International Conference on Hydrogen Safety[13]. The effectiveness of optimized sensor placement to reduce hazards has not yet quantified by a QRA. Expansion of indoor releases to other larger facilities and incorporation into QRA tools, such as HyRAM (Groth, 2016) is planned.

Sensor placement is germane for both indoor and outdoor applications. However, investigations are only beginning for outdoor releases, including especially cold hydrogen plumes associated with LH2. HyWAM methods are being developed to quantify hydrogen release behaviour to support modelling studies. HyWAM may be based upon stand-off strategies, such as Raman (Hecht and Panda, 2018), Schlieren (Kebler et al., 2005) and acoustic, or through a distributed network of point sensors (Buttner et al., (2018). However, no HyWAM approach has been extensively used or fully validated for outdoor applications suitable for research purposes (e.g., a “research” HyWAM) or for routine deployment as an integral component of a facility safety system (e.g., a “deployed” HyWAM). A point sensor system has been deployed in preliminary study of real-world LH2 releases (Buttner et al., 2018). Actual data on real world cold plume dispersion remains sparse and currently inadequate for model verification or even accurate intuitive prediction (e.g., until actual field measurements demonstrating otherwise, buoyancy had been viewed by some on the NFPA 2 committee to sufficiently dominate hydrogen dispersion such that no hydrogen would be observed below the horizontal point of release from a vent stack). Factors in addition to buoyancy that affect dispersion of hydrogen have not been completely quantified, but may include ambient temperature, humidity, wind speed and direction, as well as surrounding physical structures.

Detection has been identified as one mitigation strategy to alleviate LH2 setbacks; there are others. The elimination of free hydrogen is one means to directly lower hazards. Passive Autocatalytic Recombiners (PAR units) are now being deployed in the nuclear industry to detect hydrogen while eliminating its build-up of hydrogen within indoor facilities and this technology was explicitly discussed at the RPW by Lee Gardner of the Canadian Nuclear Industry in this session). Such systems can be optimally used in facilities where hydrogen dispersion has been characterized. As indicated

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[12] Hydrogen Wide Area Monitoring (HyWAM) is the quantitative spatial and temporal 3-dimensional profiling of either planned or unattended hydrogen releases. HyWAM is being used to elucidate the dispersion behaviour of released hydrogen and is being investigated as an active monitoring strategy for LH2 setback minimization.

[13] https://www.hysafe.info/ichs2019/ (accessed 13-05-2019)

in the Background Chapter, other mitigation strategies may include improved ventilation systems, fire walls and other fire suppression methods, and enhanced maintenance procedures.

8.3 Summary

Hydrogen sensors have been successfully used for many years to assure facility safety. Active monitoring is viewed as a potential strategy to minimize facility footprints. Optimal utilization of active monitoring will require improved understanding of hydrogen dispersion (through CFD) and incorporation into QRA to guide facility design features. As an initial step this requires the development of a HyWAM system for research purposes, and one for facility deployment. Active monitoring with hydrogen sensors or other detection approach is only one element in a comprehensive mitigation strategy, and multiple mitigations may be necessary to lower LH2 facility setbacks and to further improve operations of other hydrogen facilities.

9 SESSION 9: INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT

Chair: Andrei Tchouvelev (AVT) – Panelists: Frank Markert (DTU), Thomas Jordan (KIT), Donatella Maria Chiara Cirrone (Ulster University), Chris LaFleur (Sandia)

9.1 Introduction and Stage Setting

The RPW 2016 identified the following 9 topics as research priorities in the Integrated Tools for Hazard and Risk Assessment (H&RA):

1. Develop suitable models for accounting for the effects of different mitigation measures appropriately
2. Data/probabilities for hydrogen system component failures (e.g.: leak frequencies, detection effectiveness, etc.) from operational experiences
3. Features and models to enable deeper system-specific insights to enable overcoming station-siting barriers: i) uncertainty & sensitivity analysis capabilities and ii) higher fidelity and depth of QRA.
4. Develop validation, testing, training and design decision making strategies of such QRA tools
5. Uncertainty Quantification (UQ) for the CFD in the consequence analysis tools
6. Models based on fault & event trees, Bayesian networks, cause-consequence and barrier diagrams are still not able to handle dynamic events
7. Models for accurate prediction of pressure-peaking phenomena for ignited releases
8. Models for accurate prediction of radiation from hydrogen fireball after high-pressure CGH2 tank rapture in a fire
9. Models for accurate prediction of buoyancy effects on jet fire hazard distances

As shown on Figure 9.1 below, topics number 2, 1 and 4 respectively received the top three ratings, while topic 8 was a relatively distant fourth – these are highlighted in bold above.

Integration Computational Tools	tot	%
3.0.1	65	17.33
3.0.2	92	24.53
3.0.3	27	7.20
3.0.4	49	13.07
3.0.5	30	8.00
3.0.6	26	6.93
3.0.7	30	8.00
3.0.8	35	9.33
3.0.9	21	5.60

Figure 9.1 2016 Ranking of identified priority topics in Integrated Tools for H&RA category

Two important points are worth making in this regard. The first point is that the top three ranked priorities although very desirable are most challenging to achieve, particularly the first one that seems unreachable. Until industry is willing to share failure frequencies and other component reliability data this priority is doomed to stay in the wish list. Achieving priorities 2 and 3 would require a significant level of maturity of hub-type QRA tools (e.g. HyRAM), which seems like years away. In this regard, the second point is that it makes sense to look beyond the first three ranked priorities drawing the line at around 10% of total ratings (or around 40 points in absolute value) as an indicator of importance. This broader view brings only one other priority into consideration – number 8 – radiation from a H2 fireball resulting from H2 tank rupture in a fire. We will apply the same approach for analysis of the results of the RPW 2018 priority ranking.

9.2 Analysis of RPW 2018 Priorities Ranking Results

In preparation for the RPW 2018, the review of the state of the art and progress in this category within 2016-2018 based on panellists' contributions indicated that none of the above priorities (or identified gaps) have been closed. There is significant work-in-progress presented by the contributing panellists Alice B. Muna on HyRAM (Sandia), Donatella Cirrone on e-Laboratory of Hydrogen Safety, NET-Tools project (UU) and Frank Markert on human reliability analysis using Bayesian networks and cause-consequence and barrier diagrams (DTU). The progress is mostly related to incremental improvements and tweaking rather than any radical leap-frog-type changes. There was no progress made on the Canadian toolkit due to no funding being available.

Three more topics were added to the 2016 list by the session chair (numbered 10 to 12) in order to better address on-going and escalating commercialization and market deployment needs. The extended list is presented below.

1. Develop suitable models for accounting for the effects of different mitigation measures appropriately
2. Data/probabilities for hydrogen system component failures (e.g.: leak frequencies, detection effectiveness, etc.) from operative experiences
3. Features and models to enable deeper system-specific insights to enable overcoming station-siting barriers: i) uncertainty & sensitivity analysis capabilities and ii) higher fidelity and depth of QRA.
4. Develop validation, testing, training and design decision making strategies of such QRA tools
5. Uncertainty Quantification (UQ) for the CFD in the consequence analysis tools
6. Models based on fault & event trees, Bayesian networks, cause-consequence and barrier diagrams are still not able to handle dynamic events
7. Models for accurate prediction of pressure-peaking phenomena for ignited releases
8. Models for accurate prediction of radiation from hydrogen fireball after high-pressure CGH2 tank rapture in a fire
9. Models for accurate prediction of buoyancy effects on jet fire hazard distances
10. Develop a plug-in capability to a hub-type QRA toolkit (e.g. HYRAM) to enable the expanded use of independent (stand-alone) physical effects models
11. Develop an interactive model for predicting effects of human reliability in risk assessment
12. Develop a realistic model for high-pressure hydrogen releases inside ventilated enclosures

Ranking of the extended list of priority topics by the experts attending the RPW 2018 is presented on Figure 9.2, and the overall comparison of 2016 and 2018 RPW rankings is presented on Figure 9.3. While this is undoubtedly a useful presentation of the ranking balloting, it misses an important insight related to the #1 rankings and the number of experts voting for each of the identified priority topics. A deeper analysis is presented in Table 1, which highlights that probably all priorities that have multiple #1 rankings and have at least 50% of experts voting for them are worth serious considerations for future research. The numbers presented in Table 9.1 shows that the priorities ranked between 2 and 5 all have three (3) #1 rankings, and priorities between 3 and 6 have their overall rankings around 10% of total votes and 40 points in absolute value. All other priority topics were ranked significantly lower with no #1 rankings and only 10 or less experts voting for them. The above analysis underscores the point that when the identified number of priority topics is greater than 5, a simple cut line under the first 3 or 5 may lead to overlooking something important.

Integrated computational tools

Q	TOT	%	RANK
1	74	16.44	2
2	101	22.44	1
3	24	5.33	7
4	44	9.78	4
5	21	4.67	9
6	9	2.00	11
7	7	1.56	12
8	23	5.11	8
9	10	2.22	10
10	40	8.89	6
11	42	9.33	5
12	55	12.22	3

Figure 9.2 2018 Ranking of identified priority topics in Integrated Tools for H&RA category

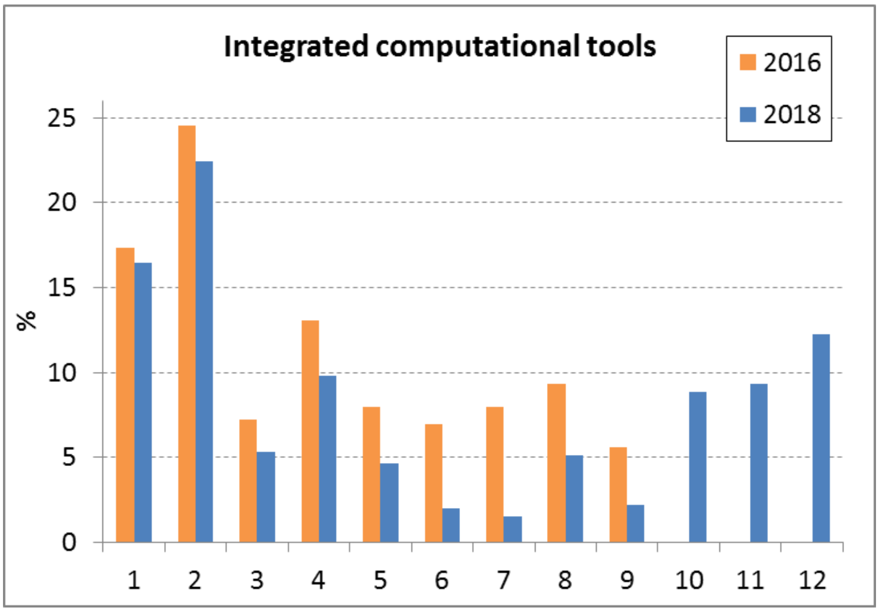

Figure 9.3 Comparison of 2016 and 2018 RPW ranking of identified priority topics in Integrated Tools for H&RA category

Index	Top Priorities in Integrated Tools for H&RA Category					
	Develop suitable models for accounting for mitigation	Data/ probabilities for hydrogen system component failures	Develop validation, testing, training and design decision making strategies of such QRA tools	Develop a plug-in capability to a hub-type QRA toolkit (e.g. HYRAM)	Develop an interactive model for predicting effects of human reliability in risk assessment	Develop a realistic model for high-pressure hydrogen releases inside ventilated enclosures
PRW2018 Priority sequential number	1	2	4	10	11	12
Ranking Score	**74**	**101**	**44**	**40**	**42**	**55**
# of 1st rankings	**3**	**13**	**3**	**2**	**3**	**3**
# Experts voting	**21**	**26**	**16**	**15**	**15**	**20**
Overall Ranking	**2**	**1**	**4**	**6**	**5**	**3**

Table 9.1 Summary analysis of RPW 2018 top priorities in Integrated Tools for H&RA category

9.3 Additional comments from the Chair and RPW Panel

As the rationale for their rankings, the experts attending the RPW 2018 submitted the following comments summarized in Table 9.2 below.

Integrated models has very useful role to play in hydrogen safety
It seems important to put effort into collection of reliable data on which to base QRA tools.
quality consequence modelling (validated experimentally) is required for QRA human reliability modelling should be removed at this stage as it is far too complex - we have entire teams working on this area and is difficult to apply on smaller assets
Lack of reliable data for estimating the expectation value of event frequencies represents the main uncertainty in many risk assessments.
Integrated QRA tools need to be expanded to include additional validated physics AND to provide the ability to swap out different physical models for confidence and validation
human misbehavior might spoil complete event tree
The main problem for the development of reliable QRA tools is the absence of data and probabilities on hydrogen systems component failures. therefore, QRA analysis is nowadays based on strong assumptions on failure rates or events probabilities or data from conventional industries, increasing their level of uncertainty.
A modular QRA toolkit to accommodate different parameters seems important
DNV GL undertook a validation exercise with Osaka gas in 2005 for their engineering model for HP H2 release into natuallry ventillated enclosures. All models need validation and express notification when the model is being used outside of its scope of validation.
It is very important to me to make the QRA tools easily used and validated to reduce user impact. Physical models are developing besides and should not be addressed in this session
Training and qualification on these tools is critical on how to use and interpret results. Expanded areas the tools cover would be very useful. This includes physical effects, mitigation measures, component failures, etc.
Need to develop innovative approaches here, not just traditional routes.
My priority is data on component failures .
I am still Not sure if Data from system failures from all applications had been collected
I think that it is important to validate the risk analysis through the operative experiences
mitigation and dynamic modelling go hand in hand
For FCV most relevant items.
Lots of very important work going on in this field, and starting to be able to apply it in industry more easily.
This session is on integrated tools, not on individual models improvement. Still for me is essential to have available statistically reliable failure modes for all components.
It is critically important to expand the usability of hub-type QRA tools like HyRAM to broaden the use of validated engineering physical effects models as well as for comparing the effects of various risk mitigation measures. Ventilated enclosures is a preferred way of supplying hydrogen equipment to hydrogen fueling stations and thus needs to be looked more carefully. Human reliability becomes a more important topic in view of growing number of public and trained professionals involvement and thus needs more attention.
Data for hydrogen specific components (failure data) is severely lacking and the largest source of uncertainty in risk analyses.Also, we really need the ability to assign credit to mitigation measures so we can properly account for them.
Today the lack for all QRA is that the datas are missing
Leak frequencies are sorely needed, especially for LH2. Effective means of handling mitigations is also needed, then some of the underlying models need to be improved/developed.
In general we think that integrated tools are relevant, on the condition that these concentrate on vehicles and their use of hydrogen as a fuel. On the short term vehicle knowledge and improvement will have a larger contribution to safety than tunnel related measures.

Table 9.2 Rationale comments submitted by RPW 2018 experts.

As suggested gaps for future surveys, there were 3 submissions, which in the opinion of the session chair are redundant to the existing priorities. These are as follows: “Need to develop simple analytical tools for risk analysis without the need of CFD”, “Develop simple engineering tools” and “APIs for tools such as HyRAM that will allow for seamless integration towards other tools, such as CFD tools”. The Integrated Tools by design are “simple” low order engineering tools. And the last submission is addressed by the priority 10, which was ranked 6 (close to 4 and 5).

As a concluding remark, the “old” 2016 RPW priorities ranked at RPW 2018 as 1,2 and 4 still remain far-reaching. This leaves new priorities 10 to 12 ranked 6, 5 and 3 respectively more practical to address and achieve results.

10 SESSION 10: GENERAL ASPECTS OF SAFETY

Chair: Frank Markert (DTU) – Panelists: Nick Barilo (PNNL), Thomas Jordan (KIT), Donatella Maria Chiara Cirrone (Ulster University)

10.1 Introduction and Stage Setting

RPW 2016 recognized and voted on the following gaps indicated in Table10.1. This RPW's session on "The general aspects of safety" included the topic of sensors. For the current RPW 2018, a decision was taken to give the sensor topic more space and to move it into a separate session. Therefore, these latter findings are not discussed further in this chapter.

For the RPW 2016, the following gaps had been identified as listed in related to this are indicated in Table 10.1. In the table the text marked in grey relates to the sensor topic. The result of the voting is shown in Figure 10.1. Taking out the gaps for the sensors, the most important gaps for the general aspects of safety was gap 1): "Training of first responders trainers and Hazmat officers" followed by gap 6): "Addressing safety barrier types and their PFD changes by human behaviour". The least priority was given to gap 5): "Development of Monte Carlo methods using simplified models for RA of dynamic systems"

Table10.1 Gaps identified on the RPW 2016. The grey text relates to sensors

	General Aspect of Safety
1	Training of First Responders' trainers and Hazmat Officers
2	Guidance on sensor placement
3	Long-term stability and accelerated stability testing for sensors
4	Selectivity testing for sensors to be used with complex gas mixtures
5	Development of Monte Carlo methods using simplified models for RA of dynamic systems
6	Addressing safety barrier types and their PFD (Probability of Failure on Demand) changes by human behaviour

General Aspect of Safety	tot	%
1	78	20.80%
2	93	24.80%
3	53	14.13%
4	53	14.13%
5	29	7.73%
6	69	18.40%

Figure 10.1 Priorities from the RPW 2016, where the grey marked numbers relate to sensors

10.2 Analysis Of RPW 2018 Priorities Ranking Results

The topic sensors has been moved to a separate session. The contribution and discussion resulted in the following 7 gaps from which gap 1, 2 and 3 had been already discussed during the last RPW. The list was updated by introducing gaps 4 to 7 dealing with accidents in complex infrastructures as tunnels, evacuation and certification of hydrogen equipment.

1. Training of First Responders' trainers and Hazmat Officers

2. Addressing safety barrier types and their PFD (Probability of Failure on Demand) changes by human behaviour
3. Development of Monte Carlo methods using simplified models for RA of dynamic systems
4. Evacuation modelling to mitigate hydrogen accidents in tunnels and complex buildings
5. Best practice for decisions and actions following detection of hydrogen in tunnels and complex buildings.
6. Certification of hydrogen equipment (EU / US /other markets)
7. Safe design concepts for tunnels, car parks and complex buildings to prevent and mitigate hydrogen accidents

As listed in Table 10.2, it is seen the following result: The gap 1: Training of first responders and hazmat officers is still ranked very high and ranked 1st in the RPW2018. Second is the gap 7: Safety design concepts for tunnels, car parks and complex buildings to prevent and mitigate hydrogen accidents. The third priority is concerned gap 5: Best practice for decisions and actions following detection of hydrogen in tunnels and complex buildings.

General aspects of safety

Q	TOT	%	RANK
1	94	22.38	1
2	44	10.48	6
3	5	1.19	7
4	59	14.05	4
5	73	17.38	3
6	52	12.38	5
7	93	22.14	2

Figure 10.2 Prioritisation of the RPW 2018 "general aspects of safety"

In Figure 10.3 the score in percent are compared to the former RPW results for the suggested gaps 1 to 3. Gap 1 is at a similar high priority while gap 2 is decreased in the priority as well as gap 3.

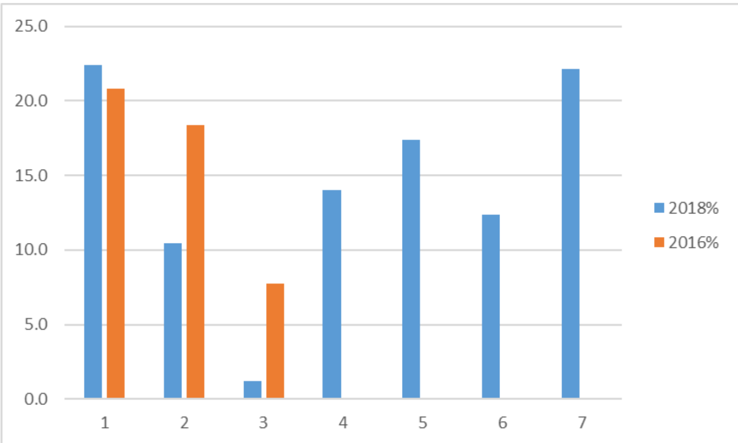

Figure 10.3 percent scores RPW 2018 compared to RPW 2016

In Table 10.2 the gaps with the highest priorities are further analysed. The gap given the 1st priority also received a very high number of 1st rankings. This suggests a broad consensus of the experts on this topic. Similar though having less 1st rankings may be considered for the 2nd prioritised topic. The 4th prioritised topic concerning evacuation has been only ranked 1st by one expert, but many experts found it important ranked on the 3rd to 5th position. The analysed results for the topics given a priority five and six are listed in Table 10.3. It is seen that they both got a higher number of 1st rankings compared with the evacuation topic, but only remarkable few experts have voted on these two topics.

Table 10.2 Detailed results for the highest prioritised gaps 1 to 4

	1: Training of First Responders' trainers and Hazmat Officers	7: Safe design concepts for tunnels , car parks and complex buildings to prevent and mitigate hydrogen accidents	5: Best practice for decisions and actions following detection of hydrogen in tunnels and complex buildings.	4: Evacuation modelling to mitigate hydrogen accidents in tunnels and complex buildings
Ranking score	94	93	73	59
Overall Ranking	1	2	3	4
# of 1st rankings	11	7	3	1
# Experts voting	26	25	26	24

Table 10.3 Detailed results for gaps at priority 5 and 6

	6: Certification of hydrogen equipment (EU / US /other markets)	2: Addressing safety barrier types and their PFD (Probability of Failure on Demand) changes by human behavior
Ranking score	52	44
Overall Ranking	5	6
# of 1st rankings	3	3
# Experts voting	17	19

10.3 Additional Comments from the Chair and RPW Panel

The free text comments (Table 10.4) given by the experts have been ordered according to their main topic they are related to. Three main topics have been found: 1) emergency related rationale; 2) Tunnel and infrastructure rationale; and 3) others. This corresponds very well with the highest ranked priorities and it is supporting the conclusion of the survey. It clearly highlights that the topic of emergency response as well as the use of hydrogen in complex infrastructures and buildings such as tunnels and car parks is seen very important. In Table 10.5 very few future items are suggested, but there is a request for community education and one on more full scale crash tests concerning tunnel and other "real world" scenarios.

Table 10.4 Free text comments by the experts

Please explain here the rational of your ranking
Emergency related rationale
I feel that it is necessary to give practical instructions for a correct response in case of emergency
All safety aspects related to public space need to receive still outmost attention, including response

strategies
Training of responders, knowledge of safety barriers are clearly needed
First responders are one of the main players in mitigation of accidents, however at the moment they do not have sufficient information and training on how to intervene and limit life safety issues for people but also for themselves
Training of first responders is an important issue.
First responders training has to be an ongoing topic to ensure the safe progress of the hydrogen industry
first responders need to be better qualified to permit and to respond
Emergency response is quite important for hydrogen first responders.
Important to close all gaps between Fire Fighters and developers of Equipment resp. Hydrogen systems
At the moment the First responders are inventing their own wheels. Knowledge dissemination is crucial.
Lots of misinformation about what to do in the case of a hydrogen leak/fire. Need to make sure first responders aren't over or under-reacting to different scenarios. Certification can reduce risk. Then safe design practices and concepts are important.
Tunnel and infrastructure rationale
H2 in tunnels is secondary to material qualifications and training 1st responders.
tunnels are critical to acceptance of FCV in all jurisdictions
No further comments to make, but ties in with hytunnel cs and cen/CLC Tc 6 wg3
Confined spaces with many people present have to be prioritised. One bad incident here early on and there is a huge PR implication.
Safe design concepts for tunnels , car parks are important
My ranking takes into account the anticipated results of HyTunnel-CS project. Otherwise I would rank tunnel topics higher.
Safe design of tunnels and public spaces will be most effective
Tunnel safety is critical and will need multi safety approaches
Other
Safe design concepts are definitely the most important topic
More effort needs to be given on human aspects of safety topics also, dynamic systems need to be captured in modeling efforts.

I have ranked the design concepts highly because of the introduction of hydrogen infrastructure into society I think it is also important to look into first responder and training aspects
Certification of hydrogen equipment to the full extent of component standard requirements, not just electrical componentry, is critical for ensuring public safety of HRS and other publicly accessible equipment.
The choice of mitigation strategy can have profound influence on the outcome of accidents.
clever design helps reducing risks and facilitate mitigation

Table 10.5 Suggestions by the experts

Please suggest gaps you would like to vote in the future survey
I would suggest the future chair of this session to critically review items which may be deleted because no more a priority
Need for more full scale crash test data to inform the feasibility and probability of tank failure in real world crash scenarios in tunnels and in the open.
Community education.

11 DISCUSSION

Chapters 2 to 10 of this document presented the individual reports from the session chairs, chapter 2 giving an overview of activities in key countries, followed by chapters identifying the priorities and summarising recent progress in terms of applications (chapter 3) and specific risk control topics (chapters 4 to 10). In this discussion the top priorities from each of chapters 3 to 10 are identified and refined into a tabular form. A challenge here is the number of priorities identified, which is associated with the need to underpin safety across many quickly developing technologies and applications.

To briefly summarise Chapter 2, (Industrial and National Programs) it describes there are now many hydrogen programs around the world, which brings an associated need to underpin safety across many quickly developing technologies and applications. While no prioritisation took place in Chapter 2, the presentations offered gave a clear steer to the workshop attendees in terms of the direction of travel in key countries: **USA -** H2@Scale project, focusing on large scale production and utilization; other specific priorities include hydrogen in tunnels and liquid hydrogen (LH2); **Europe** - FCH2JU programme; setup of the RCS Strategic Coordination Group (SCG) and the European Hydrogen Safety Panel (EHSP); Key projects PRESLHY (LH2 safety), HYSEA (safety of ISO container-based solutions) and HyLAW (addressing the regulatory framework for hydrogen); **South Australia** - strategic commitment to export green hydrogen, LH2 and LOHC; **United Kingdom** - Heat and hydrogen networks/grids in including H21, HyDeploy, H100 projects; Fuel switching for industry, rail and maritime; **France** - Decarbonising transport and injection into the gas grid.

In Chapters 3 to 10 of this the findings of the research prioritisation exercises across the topical areas identified and discussed. In the following tables, the key priorities (the top 3) from each topic area are summarised with a view to identifying common themes. In addition, a brief commentary is included with each table to give some context where appropriate.

TABLE 11.1 THE THREE TOP PRIORITIES FOR DIFFERENT APPLICATIONS CONSIDERED.

HFS (from a possible seven)	**1st priority**: Reduce over conservative and expensive design, raising safety and efficiency concerns – still a priority despite some progress on this topic; **2nd priority**: cascading effects including effects of various accidental releases of large inventories in complex real geometries, including co-location with conventional fuels; **3rd priority**: material and processing (welding) issues for high pressure components. For public supply infrastructure, i.e. HFS scale up and efficiency requirements implies increasing usage of LH2.
Land transport (brings together FCEVs, Rail & Heavy-Duty Trucks)	**1st priority**: Credible Accident Scenarios with high pressure hydrogen/ LH2 storage and interaction with infrastructure (i.e. in tunnels and other enclosed spaces) are identified as key for all land vehicle applications; **2nd priority:** Fire attack and implications of increasing on board inventories are generic issues, focused particularly for the rail and trucks, and clearly needs attention, noting suggested on-board storage inventories of 50-100 kg for trucks, 200-500 kg for rail; **3rd priority**: Part of same generic picture is operation of TPRDs across these applications and for rail, hydrogen risks in the presence of high voltage systems is a concern.
Maritime	**1st priority**: Optimal large scale venting strategies – radiation/blast loads from ignited events; **2nd priority**: Tolerable blast and impulse loads – how high are pressures that are tolerable for structures and people when duration is only a few ms?; **3rd priority:** Significant releases (5, 10, 20 g/s) into confined spaces.
Aerospace/ Aviation:	**1st priority**: Multi-phase physical processes in heat transfer, mixing with air, and initial thermodynamic status of LH2; **2nd priority:** Behaviour of liquid hydrogen and liquid oxygen mixtures; **3rd priority:** Determining the probability of detonation with inhomogeneous gaseous clouds.
Power to Hydrogen and Heat	**Priority 1:** Behaviour of H2 in H2/NG on plastics pipes, valves, fittings in house gas installations, storage cylinders - effect on component, linked to the control of leaks in buildings and buried pipework; **Priority 2:** Review of testing procedures such as embrittlement & fatigue life test for H2/NG, **Priority 3:** Certification of mitigating safety measures (TPRD, Explosion Protection Systems, etc.) for H2/NG.

Notes for Table 11.1 (Applications): Input from key industry representatives associated with each application contributed to the session, to bring real experience of challenges arising now and foreseen in the coming years. The top three priorities identified across the applications. Land transport (brings together FCEVs, Rail & Heavy-Duty Trucks): Main progress on this topic has been driven through United Nations General Technical Regulations 13 Phase II addressing issues of thermal attack and tests protocols. l Maritime: Topic growing quickly for clean propulsion for shipping and means of transporting stored renewable energy over long distances. A number of safety issues were raised (16 in total). Aerospace/ Aviation: Strong similarity for this topic with LH2 session. Power to Hydrogen and Heat: There is a close synergy between these two topic areas strong focus on gas grids/ networks. Progress noted in the area includes: Evaluation of hydrogen diffusion rates and embrittlement mechanisms in several applied materials in the NG networks; Confirmation of absence of stratification effects for NG/H2 mixtures; LEL & UEL, Minimum Ignition Current, MESG, MIE up to 20% H2 admixture in CH4 determined; A number of large heat focused projects now underway in this area, particularly in the UK.

TABLE 11.2 STORAGE

1st priority: tank fire resistance (previously identified as a priority in 2016), **2nd priorit:**; non-destructive testing techniques for manufacturing, **3rd priority**: understanding the effects of tank overheating on the structural performance and lifetime of the tank – highlighted as key by session chair to underpin refuelling protocols.

Notes on Table 11.2 (Storage): See main text for full details, but progress/closed gaps identified include cylinders and Tubes for Stationary Vessels; European Standards prEN 17339 (development of), for permanently mounted, fully wrapped transportable composite cylinders; Hydrogen compatibility standards (ISO11114-4:2017); Non-destructive examination (ISO/TS 19016); cylinder recycling. Top three priorities identified from a possible 12.

TABLE 11.3 ACCIDENT PHYSICS GASEOUS AND LIQUID

Accident Physics Gaseous Hydrogen	**1st priority:** Premixed combustion associated with large scale problems with obstacles, flame acceleration and particularly DDT; **2nd priority**: Hydrogen venting: **3rd priority:** Ignition statistical approaches and spontaneous ignition. These priorities are key to growing application inventories and preventing and understanding the consequences of accidental releases in these new and developing scenarios.
Accident Physics Liquid Hydrogen	**1st priority:** Multi-phase accumulations with explosion potential; **2nd priority:** Combustion properties of cold gas clouds, especially in congested areas; **3rd priority**: Knowledge and experience related to releases of large quantities. As reference to the main text of this document illustrate, this is an area with a number of outstanding issues, many of which are beginning to be addressed by international efforts such as the PRESLHY project. These efforts are essential, as LH2 as a technology is key to a number of applications, as noted with the strong overlap in priorities with aerospace and maritime, and others that will need larger hydrogen inventories.

Notes on Table 11.3 (Accident Physics): Chapters 5&6 address unintended release of gaseous and liquid hydrogen respectively, to understand the causes and consequences. This is central to the ensuring the safe deployment of this technology, hydrogen storage systems and applications, and the development and refinement of associated codes and models. The international community have made significant progress in this area, building understanding of hydrogen spontaneous ignition, pressure peaking, flame acceleration and DDT, and identifying condensed phase hazards with LH2 spills. These priorities reflect the need to develop the underpinning evidence base to allow the shift to larger scale, novel and innovative applications to be implemented safely.

TABLE 11.4 MATERIALS

Materials – 1: Testing aspects related to the characterization of materials (top three priorities from possible five)	**1st priority:** International consensus on metrics for qualification of metals for specific applications **2nd priority:** Definition of test protocols, selection criteria and relevant standards for polymer materials **3rd priority:** Activities on seals, gaskets, hoses, valves and joints. They should receive similar attention to the tank material and their behaviour tested under different and realistic conditions.
Materials – 2: Performance assessment of materials (top three from eight)	**1st priority:** Database providing fatigue data for the most probable materials to be used for hydrogen pressure vessels **2nd priority:** Better understanding on Fatigue Crack Initiation and Propagation. In particular focusing on small cracks and better understanding of the effect of hydrogen pressure on the threshold of the stress intensity factor range. Special attention to low-temperature / high-pressure conditions. From a general point of view a better understanding of materials behaviour under mechanical stresses is needed **3rd priority:** Definition of appropriate models for lifetime predictions for polymers. In particular, correlation between the behaviour of polymers under low hydrogen pressures and high hydrogen pressures and effects of temperature peaks (or valleys) and temperature excursions in tanks containing polymers. Correlations between permeation and pressure/temperature conditions, especially with the aim of achieving prediction capabilities.

Notes on Table 11.4 (Materials): The rapid development and deployment of hydrogen applications leads to an expectation that the materials that enable the novel use of hydrogen today must become the normal, common place and safe materials (or their equivalents) for tomorrow. To meet this expectation, it is essential that the characteristics and long term performance and reliability of materials across all applications is understood, evidenced, catalogued and applied.

TABLE 11.5 INTEGRATED TOOLS FOR HAZARD AND RISK ASSESSMENT AND GENERAL ASPECTS OF SAFETY

Integrated Tools for Risk Assessment	**1st priority:** Data/probabilities for hydrogen system component failure **2nd priority**: Develop models for accounting for mitigation. **3rd priority:** Develop a realistic model for high-pressure hydrogen releases inside ventilated enclosures.
General Aspects of Safety	***1st priority:*** *Training for First Responder trainers and Hazmat Offices* ***2nd priority:*** *Safe design concepts for tunnels, car park and complex buildings to prevent and mitigate hydrogen accidents;* ***3rd priority****: Best practice for decisions and actions following detection of hydrogen in tunnels and complex buildings.*

Notes on Table 11.5 (Integrated tools for hazard and risk assessment): While there has been progress, a review of the state of the art and progress in this category within 2016-2018 based on panellists' contributions indicated that none of the 2016 priorities (or identified gaps) have been closed.

11.1 PRIORITY MATRIX OVERVIEW

As an approach to more usefully summarise the priorities identified in Tables 11.1 to 11.5, a further analysis was performed to cross reference priorities from the applications sessions (Chapter 3) with those identified in the remaining Risk Control sessions. Although not perfect, this approach has provided more a consolidated and useful view of the priorities. There are some important points to note regarding the imperfections in this process, which are:

1. Like any survey approach there is always the potential for anomalies arising from inconsistencies in the inputs. In this case inputs drawn from parties with different experiences and knowledge and consequently some interpretation of this has been required in the analysis.
2. Some inconsistencies appear in the data associated with the key focus of particular industries, or key parts of the world and not others. These inconsistencies relate to the tier one priorities and perhaps more significantly to tier two priorities. These instances are highlighted by the * foot note. Some of these inconsistencies have been highlighted within the data with a view to addressing them.
3. The list of topics to be voted on during the workshop have been prepared by the chairs. This is a process still in need of some refining and improvement. For example, some priorities inevitably overlap between different topic areas, which has almost certainly introduced confusion to the voting process. To address this, the priorities lists need to be further harmonised across sessions before voting in future Priority Workshops.
4. In certain instances there are topics which are already part of key projects (e.g. FCHJU funded projects PRESLHY and HyTunnel are highlighted. It is clear that these priorities have already been identified by specific gaps and prioritisation exercises of these projects. However, although they have been identified as incumbent high priorities, in future there needs to be further analysis to refine the knowledge gaps and understand more clearly to what extent it is, or has been filled.

Taking the above into account, the first and second tier priorities have been identified both from the "top-down" application point of view (a need for guidance/ information/ engineering solution) and a "bottom-up" associated need for underpinning knowledge and understanding from the scientific/engineering/ safety community. This analysis is summarised in Figure 11.1, where the red dots represent the key priorities identified where the both the Risk Control and Scenario scored high, generally the top or occasionally second priority. The amber dots represent the second tier priorities, where the topic was second or third in one of the risk Control or Scenario in the prioritisation process scoring. In addition, additional input from the session chairs and panel (reported in each Chapter) was also used to shape priorities.

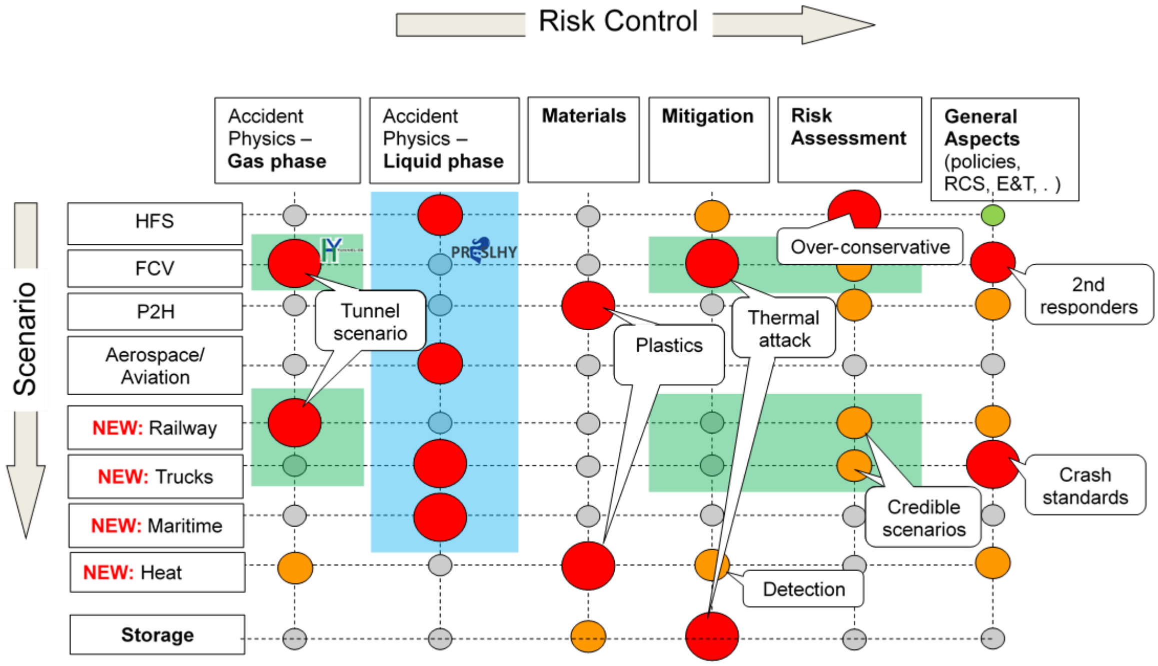

Figure 11.1 Matrix summarising findings and highlighting Tier 1 and Tier 2 priorities.

12 CONCLUSIONS & RECOMMENDATIONS

Globally, there is a strong and diverse interest in and uptake of hydrogen technologies. This is expected to lead to:

- quantitative growth in more traditional and established applications and its impact on existing and existing infrastructure to supply ever increasing quantities of hydrogen in more diverse ways.
- qualitative change as hydrogen now increasingly attracts interest/studies/attention/projects on the potential of hydrogen for decarbonising heat, energy and transport sectors that are more difficult to be decarbonised by other low and zero emission solutions, creating a clear expectation for hydrogen's use in more diverse environments and in increasing volumes.

The findings of the Research Priority Workshop organised in 2018 reflect this evolution, highlighting a number of hydrogen safety priorities. To attempt to rationalise these diverse findings, an analysis has been performed to identify common themes and aspects between the applications identified. Consideration should therefore be given to focus future research on these areas to ensure the continued safe uptake of hydrogen technologies.

To take this into account the matrix in Figure 11.1 was developed to illustrate priorities in terms of Risk Controls (in their broadest sense to include normative data, etc) applied across the range of currently considered Applications (or Scenarios). With the rapid development of hydrogen technologies, this application aligned approach is essential to guarantee that safety knowledge and approaches moves at the same pace as technological progress.

As explained in Chapter 11, the red dots represent the key priorities identified where the both the Risk Control and Scenario scored high, generally the top priority. The amber dots represent the second tier priorities. In addition, additional input from the session chairs and panel (reported in each Chapter) was also used to shape priorities. Below is brief commentary on key priorities identified working through the Risk Control topics to draw out commonality between Applications. In doing so, groups of topics are identified which it is recommended are investigated together for efficiency.

Identified areas recommended for further investigation then include:

- Accident Physics in the Gas Phase applied to FCV and Railways Applications, and a second-tier priority relating to Heat.
- Accident Physics in the Liquid Phase relating to HFS, Aerospace and Aviation, Trucks, Rail* and Maritime applications
- Materials Knowledge for P2H and Heat applications, and a second-tier priority relating to storage.
- Mitigation key priorities relate to FC for mobility and transport (also off-road) and Storage, with second tier priorities relating to HFS and Heat.
- Risk Assessment has one key priority relating to HFS and over-conservatism. There are though a number of second tier priorities relating to FCV, P2H, Rail and Trucks.
- In terms of General Safety, key aspects are around FCV (issues around 1st and 2nd responders) and Trucks (a need for crash standards). Second tier priorities identified include P2H applications, Rail and Heat applications.

In terms of specific priorities which need to be addressed the safe transfer of hydrogen through gas grids of various materials, and the scale of transport applications to use larger inventories would appear to be two key areas for the next five years. Recognising this, it is clear that there is bigger picture with a rapid and important expansion in potential safety priorities. It is therefore suggested that a process of critical assessment and rationalisation is considered internationally to more fully evaluate what related work is underway and how all activities could be more effectively be coordinated. To achieve this a more structured and harmonised approach to the RPW is suggested, to include:

- Still further involvement of international industry and stakeholders to shape and enrich the process,
- Greater emphasis on the life cycle of technologies (employing the Technology Readiness Levels approach of the European Commission) to more clearly establish specific priorities.
- Front loading of activity prior to the workshop to maximise effectiveness of the session structure, to more effectively understand, and address potential overlaps, inter dependencies and conflicts.

An international collaborative activity to coordinate safety research, taking account of the issues above, should be considered to ensure maximum progress and impact is achieved moving forward. This process will be initiated through a broadened workshop approach organised by IA HySafe .

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Health and Safety
Executive

Published by the Health & Safety Executive 05/20

HSE

Health and Safety Executive

International Association for Hydrogen Safety 'Research Priorities Workshop', September 2018, Buxton, UK

Hydrogen has the potential to be used by many countries as part of decarbonising the future energy system. Hydrogen can be used as a fuel 'vector' to store and transport energy produced in low-carbon ways. This could be particularly important in applications such as heating and transport where other solutions for low and zero carbon emission are difficult. To enable the safe uptake of hydrogen technologies, it is important to develop the international scientific evidence base on the potential risks to safety and how to control them effectively. The International Association for Hydrogen Safety (known as IA HySAFE) is leading global efforts to ensure this. HSE hosted the 2018 IA HySAFE Biennial Research Priorities Workshop. A panel of international experts presented during nine key topic sessions: (1) Industrial and National Programmes; (2) Applications; (3) Storage; (4) Accident Physics – Gas Phase; (5) Accident Physics – Liquid/ Cryogenic Behaviour; (6) Materials; (7) Mitigation, Sensors, Hazard Prevention and Risk Reduction; (8) Integrated Tools for Hazard and Risk Assessment; (9) General Aspects of Safety.

This report gives an overview of each topic made by the session chairperson. It also gives further analysis of the totality of the evidence presented. The workshop outputs are shaping international activities on hydrogen safety. They are helping key stakeholders to identify gaps in knowledge and expertise, and to understand and plan for potential safety challenges associated with the global expansion of hydrogen in the energy system.

ISBN 9780717667055

RR1159

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