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HySafe research priorities workshop report

Summary of the workshop organized in cooperation with US DOE and supported by EC JRC in Washington DC, November 10-11, 2014

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Abstract

The HySafe research priorities workshop is held on the even years between the International Conference on Hydrogen Safety (ICHS) which is held on the odd years. The research priorities workshop is intended to identify the state-of-the-art in understanding of the physical behavior of hydrogen and hydrogen systems with a focus on safety. Typical issues addressed include behavior of unintended hydrogen releases, transient combustion phenomena, effectiveness of mitigation measures, and hydrogen effects in materials. In the workshop critical knowledge gaps are identified. Areas of research and coordinated actions for the near and medium term are derived and prioritized from these knowledge gaps. The stimulated research helps pave the way for the rapid and safe deployment of hydrogen technologies on a global scale. To support the idea of delivering globally accepted research priorities for hydrogen safety the workshop is organized as an internationally open meeting. In attendance are stakeholders from the academic community (universities, national laboratories), funding agencies, and industry. The industry participation is critically important to ensure that the research priorities align with the current needs of the industry responsible for the deployment of hydrogen technologies.

This report presents the results of the HySafe Research Priorities Workshop held in Washington, D.C. on November 10-11, 2014. At the workshop the participants presented updates (since the previous workshop organized two years before in Berlin, Germany) of their research and development work on hydrogen safety. Following the workshop, participants were asked to provide feedback on high-priority topics for each of the research areas discussed and to rank research area categories and individual research topics within these categories.

The research areas were ranked as follows (with the percentage of the vote in parenthesis):

1. Quantitative Risk Assessment (QRA) Tools (23%)
2. Reduced Model Tools (15%)
3. Indoor (13%)
4. Unintended Release-Liquid (11%)
5. Unintended Release-Gas (8%)
6. Storage (8%)
7. Integration Platforms (7%)
8. Hydrogen Safety Training (7%)
9. Materials Compatibility/Sensors (7%)
10. Applications (2%)

The workshop participants ranked the need for Quantitative Risk Analysis (QRA) tools as the top priority by a large margin. QRA tools enable an informed expert to quantify the risk associated with a particular hydrogen system in a particular scenario. With appropriate verification and validation such tools will enable:

- system designers to achieve a desired level of risk with suitable risk mitigation strategies,
- permitting officials to determine if a particular system installation meets the desired risk level (performance based Regulations, Codes, and Standards (RCS) rather than prescriptive RCS), and
- allow code developers to develop code language based on rigorous and validated physical models, statistics and standardized QRA methodologies.

Another important research topic identified is the development of validated reduced physical models for use in the QRA tools. Improvement of the understanding and modeling of specific release phenomena, in particular liquid releases, are also highly ranked research topics.

Acknowledgement

The International Association HySafe, represented here by the authors, would like to thank all participants of the workshop for their valuable contributions. Particularly appreciated is the active participation of the industry representatives and the steady support by the European Commission's Joint Research Centre (JRC). Deep gratitude is owed for the great support by the United States Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Office (EERE/FCTO) for the organization of the 2014 version of the hydrogen safety research priorities workshop.

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Introduction

Background

The International Association for Hydrogen Safety, HySafe, regularly organizes the research priorities workshop. The purpose of this internationally open activity is to update the State-of-the-Art with respect to hydrogen safety knowledge and to prioritize the research activities to address corresponding gaps in the short and medium term.

History

Historically the workshop is rooted in a Phenomena Identification and Ranking Table (PIRT) exercise, first conducted in 2005 by the Network of Excellence NoE HySafe, the precursor of the International Association HySafe. The results have been published on the HySafe website [1].

The prioritization activity was designed to overcome the fragmentation in hydrogen safety research and to coordinate related work on an international level. Close to the end of the NoE, the PIRT was updated, and after the NoE phase the EC JRC in Petten took over the initiative and organized a research priorities workshop. However, this workshop focused on the CFD modeling and development. The HySafe partners realized the value and organized the first workshop with an extended scope on more broad-reaching general hydrogen safety knowledge in 2012 in Berlin. The results have been published at the International Conference on Hydrogen Safety(ICHS) 2013 in Brussels and on the JRC website[2].

This report presents the results of the HySafe Research Priorities Workshop, held in Washington, D.C. from November 10-11, 2014.

Organizing Institutions

International Association for Hydrogen Safety (HySafe)

The International Association for Hydrogen Safety (HySafe)[3] strives to be the main global forum for hydrogen safety related issues. Founded in 2009, it is an international non-profit organization registered under Belgian Law that currently has 34 members from industry, research organizations and universities representing 14 countries worldwide. Its mission is to promote the safe use of hydrogen as a sustainable energy carrier.

The Association facilitates the networking for the further development and dissemination of

[1] http://www.hysafe.net/download/712/HYSAFE_PIRT_D24_V1.pdf

[2] http://publications.jrc.ec.europa.eu/repository/handle/JRC84686

[3] http://www.hysafe.info

knowledge and for the coordination of research activities in the field of hydrogen safety. HySafe experts collaborate to assess the state of-the-art in hydrogen safety approaches and assessments and to identify and prioritise topics for further hydrogen safety research to be fed into the strategic agenda of hydrogen technology research and innovation programmes worldwide.

Sandia National Laboratories

Sandia National Laboratories[4] is a Federally Funded Research and Development Lab for the U.S. Department of Energy. Sandia is a national security laboratory involved in a variety of research and development programs to help secure a peaceful and free world through technology. Sandia's Hydrogen Program [5] supports the nation's energy strategy - helping to diversify America's energy sector and reduce our dependence on foreign oil and reduce our greenhouse gas emissions through the advancement of hydrogen and fuel cell technologies.

The Joint Research Centre of the European Commission

The Joint Research Centre[6] is the European Commission's in-house science service. Its status as a Commission service, which guarantees independence from private or national interests, is crucial for pursuing its mission: to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

The JRC has seven scientific institutes, located at five different sites in Belgium, Germany, Italy, the Netherlands and Spain, with a wide range of laboratories and unique research facilities.

As part of its support to EU Policies related to hydrogen, the Institute for Energy and Transport in Petten (The Netherlands) focuses on the development of harmonised and validated measurement techniques, test protocols and safety assessment procedures to support regulatory and standardisation activities at European and international level, covering both vehicles and the hydrogen infrastructure.

Participants

The following table lists the participants of the 2014 workshop:

[4] http://www.sandia.gov

[5] http://hydrogen.sandia.gov

[6] http://ec.europa.eu/dgs/jrc/ http://iet.jrc.ec.europa.eu/

Table 1. Workshop Participants

Participant	Representation	Country
Akiteru Maruta	Technova	Japan
Andrei Tchouvelev	HySafe	
Andrey Gavrikov	Kurchatov	Russia
Antonio Ruiz		
Benjamin Angers	UQTR	Canada
Benno Weinberger	Ineris	France
Bill Collins	US	US
Charles James Jr. (Will)	DOE	US
Ethan Hecht	Sandia	US
Franck Verbecke	Areva	France
Frank Markert	DTU	Denmark
Iñaki Azkarate Peña	Tecnalia	Spain
Jay Keller	HySafe	US
Jennifer Wen	Uni Warwick	UK
John Khalil	UTRC	US
Katrina Groth	Sandia	US
Kristian Kiuru	DOE	US
Laura Hill	DOE	US
Marco Carcassi	UNIPI	Italy
Michael Klauch	RWTH	Germany
Nha Nguyen	DOT	US
Nicholas Barilo	PNNL	US
Pietro Moretto	JRC	EC
Robert Burgess	NREL	US
Ryan Adelman	Air Liquide	US
Shoji Kamiya	KHI	Japan
Stuart Hawksworth	HSL	UK
Suguru Oyama	KHI	Japan
Sunita Satyapal	DOE	US
Thomas Jordan	KIT	Germany
Trygve Skjold	Gexcon	Norway
Tyson Eckerle	CA	US
Ulrich Schmidtchen	BAM	Germany
Vladimir Molkov	Uni Ulster	UK
William Buttner	NREL	US

Workshop Process

The members of IA-HySafe were polled to identify suitable topics of discussion for this workshop. The membership was asked to provide a preliminary list of topics covering their own research, the research funded by their funding agencies currently and future plans. The membership was also asked to identify gaps in the state-of-the-art in understanding hydrogen behavior for unintended releases, material compatibility, and hydrogen safety (e.g., education, training) and applications. The responses to this survey formed the topics for discussion. This approach was taken to make sure the discussions at the workshop remained focused on near term relevant needs of the emerging hydrogen technologies roll out.

The workshop was a two day event full of technical presentations. Following the two day workshop the participants were asked to cast five votes across research areas and within each research area to rank what they felt were the most important topic to address in the near term. Participants were also asked to provide a brief justification for why they voted in the manner they did. This report summarizes the results. The voting responses have been normalized to have a range between 0 and 100%. The individual number of votes has been normalized by the total number of votes first across categories, then by the number of votes within each research area category.

The following ranking of the research areas has been derived from this normalizing of the votes:

1. QRA Tools (23%)
2. Reduced Model Tools (15%)
3. Indoor (13%)
4. Unintended Release-Liquid (11%)
5. Unintended Release-Gas (8%)
6. Storage (8%)
7. Integration Platforms (7%)
8. Hydrogen Safety Training (7%)
9. Materials Compatibility/Sensors (7%)
10. Applications (2%)

The sections that follow are arranged in the order of this prioritization, and contain further discussion on the topics in each research area deemed highest-priority by the workshop participants. The detailed discussion, however, will is limited to the two topics with highest priorities. Finally the conclusions summarize the findings and derive some main recommendations which represent an integrated view on the priorities across the separate research areas.

Research Priorities

1st Rank: Quantitative Risk Assessment (QRA) Tools (23%)

Tools and resources for QRA were identified as the highest priority topic among the ten research areas presented at the workshop, highlighting their importance in enabling the safe deployment of hydrogen and fuel cell technologies. Science-based QRA tools can enable key industry stakeholders comprehensively model and address safety issues. Such tools are of critical importance to entities responsible for designing hydrogen refueling infrastructure or evaluating compliance with safety measures and state or national codes and regulations. Within this research area the following two topics have been voted to have the highest priority.

User-friendly, industry-focused software tools to enable risk-informed decision making (22%)

The top priority in the QRA research topic area emphasized the importance of a strong scientific foundation and rigorous documentation to underpin QRA-informed methodologies and tools intended for use by a broad range of users. This will help establish credibility for the tools and ensure that station design criteria adhere to all relevant safety measures and comply with acceptable risk parameters and station design codes as laid out in NFPA 2, for instance. Development and deployment of rigorous, yet user-friendly software tools will facilitate the communication of risks and mitigation techniques associated with hydrogen energy applications to key stakeholders. Participants indicated this research topic would have both near- and long-term benefits.

Guidance on the use of risk insights in decision making (18%)

The second-highest priority was identified as the need for proper guidance, perhaps in the form of a methodology, manual, or a best practice compilation on the use of risk insights in decision making for the siting and design of hydrogen systems. There is a strong need for consistent and open documentation for safety strategies delivering repeatable results and user-friendly tools that can be used by the necessary stakeholder groups. QRA guidance targeting the hydrogen industry will help facilitate further adoption of QRA and safety research methodologies and approaches. This can also initiate and accelerate the closing of other research gaps and further proliferate the use of a scientific basis to inform the deployment of hydrogen and fuel cell technologies. Participants indicated this research topic would have both near- and long-term benefits.

Summary of Voting for the "QRA Tools" Category

A summary of the results of voting for the category of "QRA Tools," including all of the research topics identified at the workshop, can be found in Table 2.

Table 2. Results of voting (QRA Tools)

Topic Number	Topic	Number of Votes	% of Votes Received
1.1	User-friendly, industry-focused software tools to enable risk-informed decision making	21	22%
1.2	Guidance on the use of risk insights in decision making	17	18%
1.6	Validated probability models and consequence scenarios including: overpressure, cryo-release, barrier walls, and detonation/ignition probability	16	17%
1.4	Comprehensive incident databases and guidelines for estimating the probability of events	14	15%
1.7	Development of static and dynamical QRA systems to facilitate reproducible risk assessments for a variety of scenarios	13	14%
1.3	Hydrogen-specific data for updating probability models	11	11%
1.5	Statistics on initiation data	4	4%

Interestingly, the statistics on event initiation/occurrence frequency received lowest priority within the QRA Tools topics. Without statistics, however, QRA Tools degenerate to the Reduced Model Tools, ranked on position 2.

2nd Rank: Reduced Model Tools (15%)

Reduced model tools were recognized as a significant need to address a technical gap in hydrogen safety R&D activities worldwide. An enhanced understanding of hydrogen behavior and a broad and easy access to it through simplified physics models can facilitate the evaluation and help accelerate the proliferation of viable risk mitigation measures. This represents a direct link to the QRA Tools, wherein the Reduced Model Tools shall be implemented.

Model of barrier wall effects on flame and overpressure behavior (22%)

The highest priority research topic related to reduced model tools is the need for a model of barrier wall effects on flame and overpressure behavior. Barriers provide a simple means for reducing hazards but there is currently a lack of reduced-order evaluations of flame and overpressure wall interactions. Credible data and validated models are critical for QRA of this mitigation measure. Participants indicated this research area would have primarily near-term benefits.

Collect tools published in peer reviewed journals and develop/support an online tool for hydrogen safety research and engineering (20%)

Participants also noted the need for collecting models/tools published in peer reviewed journals and developing an online tool for hydrogen safety research and engineering information resources. The development and/or support of such an online tool that consolidates peer reviewed models/tools and other resources would provide easy access for all stakeholders. This research area was indicated to have primarily long-term benefits.

Summary of Voting for the "Reduced Model Tools" Research Area Topics

A summary of the results of voting for the category of "Reduced Model Tools," including all of the research topics identified at the workshop, can be found in Table 3.

Table 3. Results of voting (Reduced Model Tools)

Topic Number	Topic	Number of Votes	% of Votes Received
2.2	Model of barrier wall effects on flame and overpressure behavior	22	22%
2.7	Collect tools published in peer reviewed journals and develop/ support an online tool for hydrogen safety research & engineering	20	20%
2.1	Cryogenic release behavior prediction	16	16%
2.3	Validated two-zone notional nozzle model and notional nozzle model for non-circular orifice	11	11%
2.4	Integration of tools to provide a systematic approach	10	10%
2.5	Deflagration overpressure prediction	10	10%
2.8	Transient models	10	10%
2.6	Incompressible/phase change network flow model	0	0%

3rd Rank: Indoor (13%)

Improved knowledge of hydrogen behavior indoors and in enclosures can inform development of improved systems engineering and relevant safety measures. A body of knowledge exists, which needs to be consolidated, built on, and its gaps identified to allow technology to be taken forward.

Behavior and dispersion of cryogenic jets (24%)

The behavior and dispersion of cryogenic jets was identified by workshop participants as being the most important topic for indoor use/release of hydrogen. Cryo-compressed storage is becoming increasingly relevant. Currently, there is insufficient data or scientific understanding of the behavior of cryogenic hydrogen, especially when one considers such conditions as under-ventilation, surface interactions, etc. Key impacts of prioritizing this topic include having better, simplified predictions, as well as being able to understand a complex technology at an early stage. Participants identified this issue as having both long- and near-term benefits.

Improve understanding of hydrogen behavior indoors (22%)

Current correlations do not take into account all possible configurations and all relevant parameters. As an example, a study should be performed looking at different release points. Validated models are necessary for hydrogen technology deployment in indoor spaces and enclosures. Consideration should be given to, but not limited to, such factors as obstacles, outside wind conditions, size and type of enclosures, types of release (amount of release gas, flow rate, shape, direction and size of the leak, subsonic and sonic), vent shapes and positions, vent number, thermal effects, forced and natural ventilation. It should also be noted that prioritization of this topic impacts integrated modeling and QRA efforts as well. Participants identified this issue as having both long- and near-term benefits.

Summary of Voting for the "Indoor" Research Area Topics

A summary of the results of voting in the category of "Indoor," including all of the topics identified at the workshop, can be found in Table 4.

Table 4. Results of voting (Indoor)

Topic Number	Topic	Number of Votes	% of Votes Received
3.3	Behavior and dispersion of cryogenic jets	23	24%
3.1	Improve understanding of hydrogen behavior indoors	21	22%
3.10	Simplified model development for indoor accidents and incidents	14	15%
3.5	Passive ventilation approaches	9	9%
3.4	Validation of pressure peaking phenomenon for releases in realistic enclosures like garages	8	8%
3.7	Extinction of fire in a garage by water vapor generated during combustion of moderated release from TPRD in a garage	8	8%
3.9	Further numerical investigation of fire regimes indoors by taking into account water condensation	8	8%
3.6	Wind/vent modeling, two-vent model	5	5%
3.2	Validated turbulent models	0	0%
3.8	Effect of soft/acoustic absorbing walls/boundaries on flame acceleration and on DDT	0	0%

4th Rank: Unintended Release – Liquid (11%)

Safety research focused on liquid hydrogen applications is imperative to the long-term growth of non-industrial hydrogen fueled applications. The anticipated use of liquid hydrogen in high volume market scenarios provides additional impetus for this topic area. The potential for increased handling and distribution of liquid hydrogen highlights a need to address unanswered questions from experimental and other activities. Specifically, the potential for condensed-phase explosions needs to be understood given the significantly different hazard that it poses compared to that of a gas phase deflagration.

Laboratory tests for behavior of liquid hydrogen releases: pools, spreading, ice formation, evaporation and fires (21%)

The need for laboratory tests for behavior of liquid hydrogen releases (i.e., behavior in pools, spreading, "ice" formation, evaporation, and fires) was identified as the highest priority topic in this research area. Releases of liquid hydrogen can pool and flow along the ground behavior which is often required to be included in modeling of such systems. Modeling of interactions with barrier walls and the behavior of plumes and flames, along with improved representation of the two-phase plume and its interaction with atmospheric turbulence is necessary. The appropriate tests and data can inform both models and the needed codes and standards. This work may also be required to fully understand detailed behavior of releases and associated air liquefaction and other related phenomena. Participants indicated this issue would have both near- and long-term benefits.

Flashing liquid hydrogen jet releases (16%)

Further research is also needed in the area of flashing liquid hydrogen jet releases. Accurate models to represent the sources of flashing jet releases should include insight and predictive tools for ignited releases and account for solid deposition of oxygen and nitrogen. It was noted that a secondary explosion occurred in one of the test carried out by the UKs Health and Safety Laboratory (HSL) the conditions of its occurrence and potential consequences need to be better understood. Participants identified this issue as having both near- and long-term benefits.

Summary of Voting for the "Unintended Release – Liquid" Research Area Topics

A summary of the results of voting for the topics within the research area "Unintended Release Liquid," including all of the research topics identified at the workshop, can be found in Table 5.

Table 5. Results of voting (Unintended Release – Liquid)

Topic Number	Topic	Number of Votes	% of Votes Received
4.9	Laboratory tests for behavior of liquid hydrogen release: pools, spreading, "ice" formation, evaporation and fires	23	21%
4.1	Flashing liquid hydrogen jet releases	18	16%
4.7	Explanation of why windy conditions during spills could create conditions for explosion of non-gaseous phase	16	15%
4.2	Consequence modeling of liquid hydrogen release in congested areas	12	11%
4.3	Boiling Liquid Expanding Vapor Explosion or Fireball (BLEVEs)	11	10%
4.4	Carefully controlled cold hydrogen release data	11	10%
4.5	Accurate state modeling implementation	7	6%
4.8	Formation of liquid hydrogen/liquid oxygen mixes of hydrogen/hydride-air/water systems and behavior	7	6%
4.6	Multi-phase flow models with velocity slip	5	5%

5th Rank: Unintended Release – Gas (8%)

The study of unintended gaseous hydrogen release is necessary, both to increase the body of knowledge, but also for its impact on other topics, particularly on QRA and reduced model tools. The development of models for the behavior of gaseous hydrogen can inform regulations, codes and standards and have long-term impacts on the growth of the hydrogen industry.

Effect of ignition location in gradient mixtures (22%)

The effect of ignition location in gradient mixtures was identified by workshop participants as being the most pressing topic regarding unintended release of gaseous hydrogen. For risk assessment, the location of ignition in inhomogeneous pre-mixed clouds plays a major role. Systematic experimental investigation of the pressure evolution for different ignition locations in the premixed cloud is required. In studying ignition location, confinement of the premixed clouds should be varied. Participants identified this issue as having both long- and near-term benefits.

Validation of notional nozzle models in real configurations (20%)

Modeling sonic jets requires a notional nozzle model in order to reduce the computer time to reasonable and feasible levels. By validating notional models using configurations with a real-world basis, the behavior of gaseous hydrogen under these conditions can be used to support further development QRA tool. Participants identified this issue as having both long- and near-term benefits.

Summary of Voting for the "Unintended Release - Gas" Research Area Topics

A summary of the results of voting on the topics within the research area "Unintended Release - Gas," including all of the topics identified at the workshop, can be found in Table 6.

Table 6. Results of voting (Unintended Release – Gas)

Topic Number	Topic	Number of Votes	% of Votes Received
5.5	Effect of ignition location in gradient mixtures	11	22%
5.1	Validation of notional nozzle models in real configurations	10	20%
5.7	Radiation hazard from jets, etc.	9	18%
5.6	Effect of transition from momentum- to buoyancy-generated jet of deterministic separation distances	8	16%
5.4	Blow-down times in built-up areas	7	14%
5.2	Validated turbulence models	3	6%
5.3	Behavior and dispersion of cryogenic jets	2	4%

6th Rank: Storage (8%)

Storage-related topics were identified as having long-term benefits, particularly when considering the use of enclosures or underground storage. Those topics dealing specifically with tank performance and tank protection were prioritized.

Vent sizing and tank protection (22%)

Vent sizing and tank protection was identified by workshop participants as being the most urgent topic relating to storage of hydrogen fuel. A better thinking behind blowdown times and secondary phenomena or mitigation techniques supports progress in both vent sizing and tank protection from a scientific perspective. Given that equipment enclosures are being utilized in large numbers in the deployment of hydrogen and fuel cell technology equipment, focused research on the following issues could be beneficial for establishing long-term safety benefits and supporting code development activities:

- Leak rate, which is a function of hydrogen pressure and what components are inside the enclosure
- Probability of a leak, accounting for scenarios such as normal equipment degradation, incompatible materials and improper installations
- Ventilation required (natural or mechanical) to prevent flammable hydrogen ceiling layer concentrations from developing

- Explosion protection measures other than leak prevention and ventilation
- Some secondary consequences need to be moderated.

Participants identified this issue as having both long- and near-term benefits.

Wrap material performance in fires (17%)

Improved design of storage tank wrap materials should be pursued. Although there has been some progress in this area, further development would be greatly beneficial. In particular, the effect of glass transition temperature of resin on the fire resistance rating of on-board storage tanks should be investigated. A key area of impact for prioritizing this topic is for onboard storage. Participants identified this issue as having long-term benefits.

Summary of Voting for the "Storage" Research Area Topics

A summary of the results of voting on the topics within the research area "Storage," including all of the topics identified at the workshop, can be found in Table 7.

Table 7. Results of voting (Storage)

Topic Number	Topic	Number of Votes	% of Votes Received
6.3	Vent sizing and tank protection	14	22%
6.4	Wrap material performance in fires	11	17%
6.11	Safety strategies and engineering solutions for thermal protection of storage tanks	8	13%
6.6	Prediction of blast wave strength from high-pressure storage tank rupture in a fire	6	10%
6.1	Type-approval testing for on-board and stationary compressed storage systems needs a thoroughly review	5	8%
6.2	High pressure storage fire performance	4	6%
6.8	Effect of heat release rate in bonfire test on fire resistance rating of on-board storage	4	6%
6.7	Prediction of fireball size after high-pressure storage tank rupture in afire and calculation of radiation from fireball	3	5%
6.9	FA and DDT in double-wall bounded layers	3	5%
6.5	suitability/practicality of pneumatic test	2	3%
6.12	Study on loss-of-containment modes and consequences for hydrogen solid-state storage containers.	2	3%
6.10	Design of location and release from innovative TPRD with reduced flame length	1	2%

7th Rank: Integration Platforms (7%)

Improved integration platforms can enable the wide-spread use of models and adoption of related methods for evaluating hydrogen safety or safety assessment procedures. Such platforms are essential for the dissemination and adoption of international best practices and to make validation data available to a broad range of potential users. These efforts are essential to ensuring that the hydrogen safety community can trust the software tools available to them.

Model verification and validation (55%)

The most important topic in this research area was model verification and validation. Integration platforms are useful, necessary, and very timely given that a wider class of stakeholders other than scientists is increasingly involved in the deployment of hydrogen infrastructure. Verification and validation efforts can assure the repeatability, verifiability, and robustness of models and ensure credibility for prospective users and other relevant stakeholders. This is an important consideration, specifically relating to documenting the validity range, experimental support, reproducibility, and clarification of assumptions for models informing or supporting hydrogen safety measures. Participants indicated this research topic would have both near- and long-term benefits.

Platform completeness (25%)

Efforts should also focus on integrating all appropriately related models into a single platform to maximize user-friendliness and provide a high-level overview of hydrogen hazards in one tool. A common platform for appropriate hydrogen safety models would enable completeness, applicability, comparability, repeatability, and verifiability of modeling methods and results. This necessitates the definition of the requirements for an integration platform. The suggested platform should address the needs of and provide valuable insight for all stakeholders, including an application programming interface (API) for developers. Use cases need to be defined and rules for development, quality assurance, and use should be included. Participants suggested this research topic would have both near- and long-term benefits.

Summary of Voting for the “Integration Platforms” Research Area Topics

A summary of the results of voting on the topics within the research area “Integration Platforms,” including all of the research topics identified at the workshop, can be found in Table 8.

Table 8. Results of voting (Integration Platforms)

Topic Number	Topic	Number of Votes	% of Votes Received
7.2	Model verification and validation	22	55%
7.1	Platform completeness	10	25%
7.3	Software testing	8	20%

8th Rank: Hydrogen Safety Training (7%)

Hydrogen safety training is vital to the safe and rapid deployment of hydrogen infrastructure. A need for developing training education on an international level has been identified by workshop participants, emphasizing the development of long-term strategies for training and coordinated international safety efforts.

Higher education in hydrogen safety engineering (17%)

Higher education in hydrogen safety engineering was identified by workshop participants as being the highest priority topic under the hydrogen safety training category. It is vital to the progress of hydrogen safety to implement a "train the trainer" strategy. Building comfort with H_2 safety systems/understanding is crucial to market acceptance–if First Responders/AHJs are comfortable with it, their neighbors are more likely to be comfortable. Participants identified this issue as having long-term benefits.

Establish an international forum to facilitate discussion on FR training with a focus on user experiences, needs and products (12%)

A properly trained first responder community is critical to the successful introduction of hydrogen fuel cell applications. Providing resources with accurate information and current knowledge is essential to the delivery of effective hydrogen and fuel cell-related first responder training. International collaboration in this area facilitates efficient use of international training resources. Establishing an international forum will help ensure that needs are identified and resources shared and have a direct impact on safety around the world. Participants identified this issue as having near-term benefits.

Summary of Voting for the "Hydrogen Safety Training" Research Area Topics

A summary of the results of voting on the topics within the research area "Hydrogen Safety Training," including all of the topics identified at the workshop, can be found in Table 9.

Table 9. Results of voting (Hydrogen Safety Training)

Topic Number	Topic	Number of Votes	% of Votes Received
8.4	Higher education in hydrogen safety engineering	16	17%
8.10	Establish an international forum to facilitate discussion on FR training with a focus on user experiences, needs and products	11	12%
8.9	Research issues identified by the Hydrogen Safety Panels work on enclosures (i.e., ventilation, leak rates, explosion protection, separationdistances, etc.)	10	11%
8.7	First responder training	10	11%
8.2	Fitter/operator training	9	10%
8.8	Publication of textbooks in different areas of hydrogen safety	9	10%
8.3	Identify better hydrogen leak rate data	8	9%
8.11	Needs based on the NFPA Research Foundation Report	7	8%
8.6	Establishment of European or International University of Hydrogen Safety	5	5%
8.1	Identify minimum natural ventilation rates for enclosed space	5	5%
8.5	Interaction of water spray and flame front	2	2%

9th Rank: Materials Compatibility/Sensors (7%)

Although this section included discussion on both materials compatibility and sensors, participants clearly prioritized sensors as a vital topic. Sensors are a key component of many release mitigation strategies. This is seen by participants as a core safety issue–it is important to ensure sensors perform as advertised so that accidents are prevented or avoided.

Reliability testing and validation of sensors for specific applications (22%)

Reliability testing and validation of sensors for specific applications was identified by workshop participants as being the most urgent topic in materials compatibility and sensors. Field experience has shown that some sensors work well in one environment but may perform poorly in another. Manufacturers can validate and even certify to laboratory conditions, but these are not necessarily mimicking real-world conditions. Extensive deployment of sensors in industrial conditions has revealed some issues with sensor performance degradation that warrants further investigation in order to improve sensor reliability. The development of performance tests targeting real-world operative conditions is required. Typical deployment conditions would include sensors for the FC-vehicle exhaust (i.e., high temperature gradients, quick response, and hydrogen concentration above 4% LEL) and sensors in industrial settings where presence of contaminants can be expected. Guidance describing best practice for testing is also essential for effective use of sensors.

Participants identified this issue as having both long- and near-term benefits.

Sensor placement to maximize effectiveness in specific applications (21%)

Sensors provide an additional layer of defense for many systems, but there is very little science-based guidance regarding their placement. Sensors must be deployed properly in order to maximize effectiveness. Many facilities will be relying on detection of H_2 leaks and the positioning is an essential part of that strategy (like smoke and fire detectors). This is not always intuitive, especially for large scale or mobile operations (i.e., fork lifts in a warehouse, FCEVs driving to work bays in repair facilities). New tests for specific operative conditions as well as optimal installation strategy in case of complex applications are necessary. Field deployment conditions of sensors may include exposure to harsh environmental conditions as well as to contaminants. In addition, deployment guidelines are needed to answer such questions as where sensors should be located or how many are necessary. This topic was identified for prioritization because it is a critical safety issue any accident that occurred would have the potential to bring down the entire system. Participants identified this issue as having both long- and near-term benefits.

Summary of Voting for the "Materials Compatibility/Sensors" Research Areas Topics

A summary of the results of voting in the categories of "Materials Compatibility/Sensors," including all of the topics identified at the workshop, can be found in Table 10.

Table 10. Results of voting (Materials Compatibility/Sensors)

Topic Number	Topic	Number of Votes	% of Votes Received
9.1	Reliability testing and validation of sensors for specific applications	17	22%
9.3	Sensor placement to maximize effectiveness in specific applications	16	21%
9.7	Hydrogen metals interaction studies need to be expanded to further alloys of interest, and fundamental research is still needed to understand the role of all parameters	12	15%
9.5	Complex and overbearing code requirements/limited international harmonization	11	14%
9.6	Improve understanding of embrittlement of hydrogen service candidate materials (metallic, non-metallic)	9	12%
9.8	Degradation modeling	8	10%
9.4	Reduce sensor cost and identify common performance metrics for cross-cutting applications	5	6%
9.2	Introduce testing of sensors for high concentration releases	0	0%

10th Rank: Applications (2%)

The field of hydrogen safety research would also benefit from more focus on additional hydrogen applications and their associated hydrogen safety measures and technologies. Guidance will be needed in the development and deployment of such applications as power-to-gas, hydrogen gas turbines, vehicle tank protection, and pre-combustion systems (PCS).

Vehicle tank protection (50%)

The highest priority topic in this research area was identified as additional protection for vehicle storage tanks. Improved protection through tank design or safety measures need to focus on allowing safely optimized blow-down times. The potential for long flames from temperature and pressure relief devices (TPRDs), pressure-peaking phenomena, and other secondary consequences need to be appropriately addressed and mitigated. Participants indicated this research topic would have both near- and long-term benefits.

Gas turbines (21%)

Additional research is needed on gas turbine applications with hydrogen. Efforts should focus on the safety issues surrounding the use of hydrogen and hydrogen-rich waste streams in gas turbines. Given the growing interest in waste-to-energy applications, credible data and science-based guidance will be required to further develop this market. Participants identified this issue as having primarily long-term benefits.

Summary of Voting for the "Applications" Research Area Topics

A summary of the results of voting for on the topics of the research area "Applications," including all of the research topics identified at the workshop, can be found in Table 11.

Table 11. Results of voting (Applications)

Topic Number	Topic	Number of Votes	% of Votes Received
10.3	Vehicle tank protection	12	50%
10.2	Gas turbines	5	21%
10.1	Power-to-gas	4	17%
10.4	Pre-combustion systems (PCS)	3	13%

Conclusions

Summary of Recommendations

The detailed results of the voting are presented above. The scores are in terms of percentage of total votes first across the all research areas and then across all topics within each research area. The need for user friendly validated QRA tools was clearly recognized as a critical need for this industry. Support of the QRA tools was also a recognized need, with validated Reduced Model Tools also being highly ranked. These modeling tools can be used for simple but accurate modeling of hydrogen behavior for all relevant scenarios and for use in the QRA toolkits. Further support for the first two ranked research areas is provided by the integration platforms ranked in seventh position. The low rank of the statistics topic within the QRA Tools research area is potentially caused by the generally recognized lack of specific basic operational data. This implies a shift of the focus towards the consequence modelling part of the QRA Tools, or towards the Reduced Model Tools research area respectively.

The next set of priorities identified by workshop participants are phenomena related to scenarios where hydrogen behavior is not well understood. Understanding the behavior of indoor releases ranked first with 13% of the votes, and close behind are unintended release of liquid hydrogen with 11%, followed again close behind are unintended gas phase releases with 8%. The storage research area, which is a slightly lower priority than these release phenomena categories, is closely related, as it represents the associated technical application, where releases start from. The Safety Training and Sensors research areas were ranked with a fairly low priority, possibly because there are already coordinated activities and they require the basic understanding of relevant phenomena first. Applications have lowest rank, because they are also based on the fundamental understanding of the hydrogen behavior, provided by the other research areas logically ranked before the actual application.

Similar to the precursor workshops, this 2014 workshop has already proven valuable, as the results have been communicated to funding agencies that have taken these results and used them to help guide there research plans. Also, these results have been used to help structure the new IEA HIA Task 37 on hydrogen safety where the toolkit idea provides the general backbone for the research coordination.

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Appendix A

Workshop Agenda

HySafe Research Priorities Workshop
Location: Energetics Offices Suite 100, 901 D Street SW, Washington DC
November 10-11, 2014

November 10, 2014

- **8:30: EST: Welcome and Opening Remarks (Andrei Tchouvelev MC) – 5 min**
- **8:35: FCTO Welcome (Sunita Satyapal) – 10 min**
- **8:45: Software Tools (1) (Chair – Andrei Tchouvelev) – 95 min**
  - Introduction (Andrei Tchouvelev) – 15 min
  - Integration Platforms – 80 min
    - HyRam (Katrina Groth) – 20 min
    - SAGE (Thomas Jordan) – 20 min
    - Cyber-Laboratory and its hydrogen safety engineering tools (www.h2fc.eu) – (James Keenan, Vladimir Molkov) – 20 min
    - Canadian Platform (Benjamin Angers) – 20 min
- **10:20: Break – 20 min**
- **10:40: Software Tools (2) (Chair – Jay Keller) – 100 min**
  - QRA Tools – 40 min
    - Gaps, Methods, Models Tools (Katrina Groth) – 20 min
    - Gaps, Methods, Models Tools (Julie Flynn) – 20 min
  - Reduced Model tools – 60 min
    - State of the Art for Gaseous Release Models (Ethan Hecht) – 20 min
    - Correlations for venting of localized and full volume deflagrations in low strength equipment and buildings (Boris Chernyavskiy, Dmirtiy Makarov, Vladimir Molkov) – 20 min
  - Deterministic separation distance from stationary & on-board hydrogen storage tank: calculation of blast wave decay (Sergii Kashkarov, Vladimir Molkov) – 20 min
- **12:20: Priorities and Gaps Discussion (Thomas Jordan) – 20 min**
- **12:40: California Station Rollout (Tyson Eckerle (via Webex) / Jennifer Hamilton) – 20 min**
- **13:00: Lunch - 60 min**
- **14:00: Indoor (Chair - Stuart Hawksworth) – 80 min**
  - Passive ventilation of enclosures with one vent, the uniformity criterion, and validation of pressure peaking phenomenon for unignited releases (Volodymyr Shentsov, Vladimir Molkov) – 20 min
  - Regimes of indoor hydrogen jet fire and pressure peaking phemonenon for jet fires (Volodymyr Shentsov, Vladimir Molkov) – 20 min
  - Hyindoor, passive ventilation (Stuart Hawksworth) – 20 min
  - Effect of wind on passive ventilation (Boris Chernyavskiy) – 20 min
- **15:20: Priorities and Gaps Discussion (Jennifer Wen) -- 20 min**
- **15:40: Break – 20 min**
- **16:00: Unintended Release – 60 min**

- **Gas phase – (Chair – Ethan Hecht) – 60 min**
    - Delayed ignition (Dmitriy Makarov, Volodymyr Shentsov, Vladimir Molkov) – 20 min
    - Simulation of hydrogen release from TPRD under the vehicle (Zhiyong Li, Dmitriy Makarov) – 20 min
    - Combustion of inhomogeneous mixtures (Thomas Jordan) – 20 min
- **EOD @ 17:00 – HySafe Hosted Dinner**

November 11, 2014

- **8:30 -- Unintended Release – 40 min**
  - **Liquid phase (Chair – Vladimir Molkov) – 40 min**
    - Knowledge gaps in liquid hydrogen safety (Jennifer Wen) – 20 min
    - Vision for Validating the LH_2 Plume Model @ T < 80K (Ethan Hecht) – 20 min
- **9:10: Priorities and Gaps Discussion (TBD) – 20 min**
- **9:30: Storage (Chair -- John Khalil) – 40 min**
  - Gaps in Safety of Storage in Solid-state-systems (Pietro Moretto) – 20 min
  - Effect of heat release rate and resin glassing temperature on fire resistance rating in bonfire test (Sergii Kashkarov, Dmitriy Makarov, Vladimir Molkov) – 20 min
- **10:10: Break – 20 min**
- **10:30: Hydrogen Safety Learnings and Training (Chair -- Steve Weiner) – 40 min**
  - Learnings and Direction – Hydrogen Safety Panel and First Responder Training (Nick Barilo) – 20 min
  - Hydrogen Emergency Response Training Program for First Responders – HyResponse (Franck Verbecke) – 20 min
- **11:10: Applications (Chair – Thomas Jordan) – 60 min**
  - HRS – fast filling (Pietro Moretto) – 20 min
  - Turbine (Stuart Hawksworth) – 20 min
  - PEM Electrolizer (Larry Moulthrop) – 20 min
- **12:10: Priorities and Gaps Discussion (TBD) – 20 min**
- **12:30: Lunch – 60 min**
- **13:30: Country Safety Programs (Chair –Pietro Moretto) – 120 min**
  - ISO (Andrei Tchouvelev) – 15 min
  - US (Will James) – 15 min
  - Norway (Trygve Skjold) – 15 min
  - EU (Pietro Moretto) – 15 min
  - FCH-2-JU (Pietro Moretto) – 15 min
  - Japan (Aki Maruta-san) – 15 min
  - Germany (TBD) – 15 min
  - UK (Stuart Hawksworth) – 15 min
- **15:30: Break - 20 min**
- **15:50: Materials Compatibility / Sensors (Chair - Brian Somerday) – 60 min**
  - Metals (Brian Somerday) – 20 min
  - Components (Rob Burgess) – 20 min
  - Sensors (Bill Buttner) – 20 min
- **16:50: Working Group Participation Gaps and Priorities Summary Discussion** (TBD) **–** 40 min
- **17:30: EOD**

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