Final report

1.1 Project details

Project title	EUDP 14-II, Deltagelse I IEA hydrogen implementation agreement task 31 efterfølgeren
Project identification (program abbrev. and file)	Brint og brændselsceller,EUDP-2014 J.nr. 64014-0534
Name of the programme which has funded the project	Energiteknologisk udviklings- og demonstartionsprogram
Project managing company/institution (name and address)	DTU Civil Enginering, Brovej 118, Dk-2800 Kgs. Lyngby
Project partners	network activity: UTRC (operating agent),Sandia National Laboratory, NREL, Karlsruhe Institute Technology, University Ulster, International Association-HySafe, GexCon, University Pisa, Air Liquide, Ineris, Health & Safety Laboratory, CEA,, Kyushu University, University Warwick, JRC-Petten, NCSRD Democritos, Keio University, Telemark University, Tecnalia
CVR (central business register)	30060946
Date for submission	09.12.2014

1.2 Short description of project objective and results

English:
The projects objective is to participate in the IEA Hydrogen Implementation Agreement (IEA-HIA) task 31 successor and named task 37 after IEA's final approval. It is concerned about safety of hydrogen technologies and application of these in future infrastructures. Task 37 is a networking activity with the purpose of knowledge sharing of open access tools and models to conduct risk analysis for hydrogen technologies. The activities are organised into the following sub-tasks:

A – Tool Kit for Hazards and Risk Assessment

B – Accident Scenario Development

C - Physical Effects

D – Human Reliability Analysis

E – Materials Compatibility

Dansk:
Formålet med projektet er deltagelse i IEA Hydrogen Implementation Agreement (IEA-HIA) i task 31 efterfølgeren, som er blevet til task 37 og omhandler sikkerhedsspørgsmål vedr. brint teknologier og deres implementering i fremtidige infrastrukturer. Task 37 er en netværksaktivitet med fokus på udveksling af fagkundskaben, etablering af open acces værktøjer og modeller til at kunne gennemføre risikoanalyser ifm. brint teknologier. Aktiviteterne er organiseret omkring flere underemner:

A – Tool Kit for Hazards and Risk Assessment

B – Accident Scenario Development

C - Physical Effects

D – Human Reliability Analysis

E – Materials Compatibility

1.3 Executive summary

The IEA HIA task 37 project is an international network project on the topic hydrogen safety. It is the latest task continuing the development of hydrogen safety from task 19 and task 37. It is concerned about safety of hydrogen technologies and to facilitate application of these in future infrastructures. The purpose is knowledge sharing about open access tools and models to conduct risk analysis for hydrogen technologies. Hydrogen safety scenarios are discussed and assessed using the HyRAM tool as well as other internet-based toolboxes for consequence and reliability assessments of these technologies. An IEA Hydrogen safety journal is in the upstart phase providing free access scientific information on hydrogen safety issues. The development of the models and the achieved knowledge is widely disseminated on workshops and as journal papers in various international journals. Main channels for dissemination has been the International Conference on Hydrogen Safety and the International Journal of Hydrogen Energy. The results on this pre-normative safety research are intended to influence the development of improved standards in the field. The gained knowledge enable the project partners to develop further projects and to better service the industrial development of hydrogen infrastructures.

The task 37 was originally planned to end in 2018, but has been prolonged to end of 2021.

1.4 Project objectives

The objective of the network project IEA HIA task 37 is to facilitate the safe implementation of hydrogen infrastructures. Task 37 intents to reach the objective by a coordinated international collaboration and dissemination of the state of the art hydrogen safety knowledge. The network project is an activity of the Hydrogen Implementation Agreement (HIA) being part of the International Energy Agency (IEA). The present task 37 (2015 – 2021)[1] continuous the work of the former hydrogen safety tasks 31 (2010 – 2013) and 19 (2004 – 2010).

Originally, the task 37 was planned for the period 2015 to 2017, but was extended during spring 2018. The final report is therefore a status on the activities up to 2018. Further results will be achieved up to 2021.

The coordinated international collaboration is concerned with the development of integrated tools to predict hydrogen safety risks, on one side. The integrated tools have to be user-friendly to facilitate system analysis and to enable development of risk metrics. On the other side, the development of risk management strategies is regarded to ensure overall safety while implementing hydrogen technology infrastructures. Hereunder, risk management strategies will benefit from knowledge on the reliability of the systems, sub systems and, down to, the component level needed for quantitative risk analysis (QRA). This knowledge comprises not only technical issues, but also human error data.

Such a coordinated collaboration provide an excellent framework enabling a systematic approach to determine gaps in current basic and applied research and around which collaborative research programmes can be conducted.

[1] http://ieahydrogen.org/Activities/Task-37-Hydrogen-Safety-Task.aspx; task 37 er identisk med projektansøgningen's task 31 efetrfølgeren

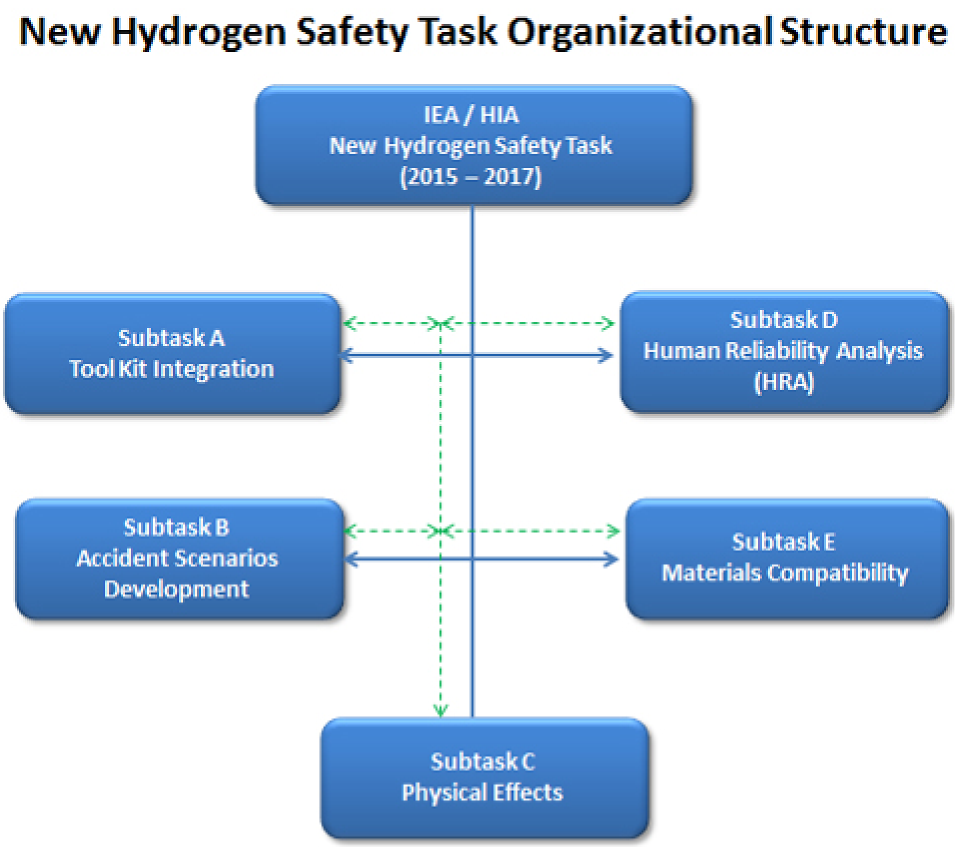


Figure 1 Organizational structure of the Hydrogen Safety task. The solid lines show the organizational structure and the dashed lines signify the information exchange among the five subtasks.

Task 37 is the successor of task 31 and is structured into five subtasks:

Subtask A: Integrated Hazards and Risk Assessment tool kit

> Output: QRA methods and tools to support HyRAM development. An alpha-tested integrated hazards and risk assessment tool kit.

Subtask B: Accident Scenario Development & Analysis

> Output: Identification of generic H2-based systems and accident sequences to be used for alpha testing and validation of the predictive models used in the tool kit in sub-task A.

Subtask C: Physical Effects and phenomena

> Output: Physics based predictive models and experimental data from sub-scale or full-scale tests. This comprises e.g. phenomena like flame propagation, deflagration and detonations, heat release rates, jet and flash fires.

Subtask D: Human Reliability Analysis (HRA)

> Output: Identify and quantify human influence on operational safety of hydrogen infrastructure. Approaches for implementing human influences and recovery actions within QRA models.

Subtask E: Materials Compatibility

Output: Theoretical models , experimental data, and empirical correlations to enable better understanding of hydrogen effects on materials. E.g. enhance understanding of hydrogen effects on material properties and mechanical strength by developing physics of failure (PoF) models.

Organization	**Country**
United Technologies Research Center (UTRC)	USA
National Renewable Energy Laboratory (NREL)	USA
Department of Energy (DOE)	USA
Sandia National Laboratories (SNL)	USA
HySafe	Belgium
Karlsruhe Institute of Technology (KIT)	Germany
Federal Institute or Materials Research and Testing, BAM	Germany
University of Ulster	UK
Health & Safety Laboratory (HSL)	UK
University of Warwick	UK
Kyushu University	Japan
Air Liquide	France
INERIS	France
Technical University of Denmark (DTU)	Denmark
University of Pisa (UniPi)	Italy
Tecnalia	Spain
EC Joint Research Center	European Commission (EC)
GexCon	Norway
University College of South East Norway	Norway
Hefei University of Technology	China

1.5 Project results and dissemination of results

The main goal of the task 37 is to facilitate the safe implementation of hydrogen technologies and infrastructures. Results have been achieved on the development of a Quantitative Risk Assessment (QRA) integration tool kit (HyRAM platform, https://h2tools.org/hyram) and the collection of reliability information of structures, systems and components (SSC) to enable QRA. Different risk management strategies to ensure the safe implementation of hydrogen infrastructures are identified, as e.g. concept of separation or hazardous distances used in the US and Europe, respectively. The task 37 provided risk-informed insights to guide the development of new and improved science-based hydrogen safety codes and standards as NFPA-2 and ISO. These insights are established using both probabilistic and deterministic methods, such as science based models, engineering calculations and CFD.

Each partner has dissiminated their results on international conferences and various international journals. The tools are made available online as e.g https://h2tools.org/ or as part of the project NET tools (Novel Education and Training Tools based on digital Applications related to Hydrogen and Fuel Cell Technology) https://hydrogeneurope.eu/project/net-tools

To improve dissemination an IEA Hydrogen Safety Journal is setup being consistent with the ExCO's goals. The journal is planned to be published semi-annually and will be featured on the IEA H2 homepage to ensure public access.

The following forward looking opportunities to enhance hydrogen safety are proposed. Focus should include the entire H2 supply chain , thus expanding the main focus on HRS. An important area needing more safety research is the physical protection (safety) of hydrogen infrastructures, the Hydrogen supply chain risk management, Life cycle assessment and impact assessment, Performe comparative risk assessments, Quantify associated first party , second party and third party risks as part of the comparative assessment, On-board H2 storage technologies

The in task 37 achieved specific results are described in the following.

Subtask A:
The HyRAM platform version 1.1 is released and available at http://hyram.sandia.gov. Validated models for H2 flame behaviour as well as to conduct hydrogen specific QRA are implemented in order to guide industries development of codes and standards. Hereunder, NFPA-2 to establish separation distances for gaseous hydrogen releases as well as to develop models for calculation of liquid hydrogen separation distances. Within ISO CD-19880-1 to develop of a generalized risk mitigation approach, e.g. safety distances. Failure probability data are provided to enable quantification of QRA models. The HyRAM software has been applied to support risk informed comparisons of reference hydrogen refuelling stations and on-site hydrogen storages. Examples for this are the H2FIRST project where HyRAM was used to calculate the baseline risk for a 300 kg/day refuelling station

Subtask B:
General hydrogen based systems and accident sequences are provided as alpha test input for validation of the HyRAM models. Insides and updates are provided on the 3D risk management framework (HyDRM) and the HySEA projects conducted by Gexcon (www.hysea.eu). Other insides and updates on hydrogen safety projects in Japan are given e.g. leak scenarios)

Subtask C:
The research activities related to the physical effects and phenomena are insights on the effect of heat release rates on the outcome of Bonfire tests (related to Global Technical Regulation 2013) and the SUSANA project (Support to safety analysis of hydrogen and fuel cell technologies). The hazard distances are analyzed due to the radiative heat caused by blast waves and fireballs. The SUSANA project is related to a hydrogen safety CFD models evaluation protocol and to best practices. Other activities have been flow velocity measurements in H2-air explosions, jet release experiments of gaseous hydrogen. In addition, the modelling of deflagration to detonation transition in hydrogen air mixtures with concentration gradients and the physical effects of blast waves and localized deflagration are to mention. New H2 safety engineering tools are nomograms for blast waves to guide first responders and storage tank blowdown time.

Subtask D:
The activities were concerned with risk assessment methodologies related to human and organizational factors. Hereunder modelling of human errors as accident initiating events and modelling of human recovery actions during accident progression

Subtask E:
The activities are concerned with question of embrittlement of quenched and tempered steels. The influence of different hydrogen charging conditions in fatigue tests for high strength quenched and tempered steels were activities hereunder.

The IEA HIA task 37 has provided many valuable results as indicated before. Some examples on the work topics are also given in the attached selected presentations from the consortium meetings. The American partners have developed a tool box HyRAM that is available online for free usage.

The network activity task 37 is not designed to generate a turnover, but will influence the development of improved standards in the field of hydrogen safety. It influenced also the strategic outlook for the continuing activities for the IEA activities (see mentioned safety aspects in The Future of Hydrogen – Seizing today's opportunities; Report prepared by the IEA for the G20 , Japan; June 2019).

The task 37 has been prolonged beyond 2018 until 2021 and more results are expected.

Each partner disseminated its own results on international and national workshops and conferences. Hereunder, a number of papers have been presented and published in the framework of the biannual International conferences on hydrogen safety (ICHS), the international Journal of Hydrogen Energy, IEA Hamburg workshop on hydrogen safety (2018) and for DTU on the Danske Brint og brændselscelle dage 2016 & 2018 (see posters attached). An IEA based journal is started and expected to launch various open access papers on the subject. Another Danish national event was the arrangement "Resultater fra IEA og FCH2-programmet om brint og brændselsceller". (Eigtveds pakhus 18.03.2016).

1.6 Utilization of project results

The results are widely disseminated and therefor public available to all interested stakeholders. By this, the network activity is likely to have a substantial impact on the safe development of hydrogen infrastructures to be built. The project partner uses the outcome and their achieved expertise to generate new proposals for research and technological development. This knowledge is also part of the pre-normative research that influences the standardisation processes in this field. The approach to hydrogen safety is mainly experimental and theoretical and most activities are not subject to patenting. One partner is using the gained knowledge and detected potential hazards to develop a new type of pressure vessels in the context of another project.

1.7 Project conclusion and perspective

The tools and scenarios discussed in this task 37 are useful for the further safe development of hydrogen infrastructures. They are designed to facilitate the implementation of technologies within the field and facilitate the establishing and permission processes of these technologies. The application of these tools combining consequence and reliability as well as deterministic and probabilistic methods are found very useful to predict the overall safety risks of hydrogen installations.

The following forward looking opportunities to enhance hydrogen safety are proposed.
Focus should include the entire H2 supply chain , thus expanding the main focus on HRS
An important area needing more safety research is the physical protection (safety) of hydrogen infrastructures
Hydrogen supply chain risk management
Life cycle assessment and impact assessment
Performe comparative risk assessments
Quantify associated first party, second party and third party risks as part of the comparative assessment
On-board H2 storage technologies

Annex

Homepage: http://ieahydrogen.org/Activities/Task-37-Hydrogen-Safety-Task.aspx

Bilag 1:
Meeting agenda's

Task 37: Hydrogen Safety

Kick-off Meeting
20th-22nd April 2015
23rd April 2015

Place: Karlsruhe Institute of Technology – Campus North; Building 419 (IKET), Room 104

Monday, April 20, 2015 – 1.0 Opening Session and Task Definitions			
1230 – 1300	1.0	Arrival and snacks	
1300 – 1315	1.1	Welcome and Introductions	Head of KIT & John Khalil
1315 - 1330	1.2	Administrative and logistical information -KIT	Mike Kuz-netsov
1330 - 1345	1.3	Recognition of Task 31 Subtasks Leaders	de Valladares
1345 - 1400	1.4	Review of agenda, meeting scope, and priority ob-jectives	John Khalil
1400 - 1415	1.2	Report on the IEA HIA February Meeting	Andrei Tchouvelev
1415 - 1500	1.3	Review of Task Definition	John Khalil
		Work Plan, Deliverables, Further steps for setting up the task	John Khalil
1500 – 1530	Break		
1530 – 1630	1.4	Ulster's progress in physical effects: blast waves, localized deflagration, thermodynamics, DDT model-ing, HRR, and deterministic separation distance.	Vladimir Mol-kov
1630 - 1700	1.5	(Discussion of Priorities and Participation)	Subtask Lead-ers
1700	1.6	Adjourn	All
1900 – open		Come together at the Badisch Brauhaus (just in the backyard of Hotel Kübler)	at own ex-penses
Tuesday, April 21, 2015 – 2.0 Technical Presentations / 3.0 Information Exchange			
0830	Bus to KIT		
0900 – 0910	2.0	Introduction, Day 2 activities	John Khalil
0910 - 0930	2.1	DOE Hydrogen Safety, Codes, and Standards	Will James
0930 - 0945	2.2	Update on ISO/TC197 activities	Andrei Tchouvelev
		Subtask A Presentations: Integrated Tool Kit for Hazards and Risk As-sessment	
0945 - 1030	2.3	HyRAM demo/walkthrough, requirements for an integrated toolkit	Katrina Groth
1030 - 1100	Break		

		Subtask B Presentations: Accident Scenario Development	
1100 - 1200	2.4	Discussion on ISO TC 197, WG 24 - - risk assessment workshop in Munich	Katrina Groth
	2.5		
	2.6		
	2.7		
1200 – 1300	Lunch Break		
		Subtask C Presentations: Physical Effects	
1300 - 1315	2.8	Wall attached jets, preparations for fire tests of pressure tanks, flame acceleration in free semi-sphere	Thomas Jordan
1315 - 1330	2.9	Cyber Laboratory / SAGE work	Thomas Jordan
1330 - 1345	2.10	Temperature development during tank filling and emptying	Pietro Moretto
1345 - 1400	2.11	Modeling related to mining project	Andrei Tchouvelev
1400 - 1415	2.12	Wall attached jets, Gas turbine project	Stuart Hawksworth
1415 - 1430	2.13	Updates on Hy3DRM and HySEA	Trygve Skjold
1430 - 1445	2.14	Towards determining design fires and HRR curve for onboard hydrogen storage systems through coupled CFD/FE analysis	Jennifer Wen
1445 - 1500	2.15	Ongoing international efforts between Warwick, Kingston, Technische Universität München and Hefei University of Technology on modelling hydrogen explosions and DDT in mixtures with concentration gradients.	Jennifer Wen
1500 - 1515		Hydrogen leakage incident	Knut Vagsather
1515 - 1545	Break		
		Subtask D Presentations: Human Reliability Analysis (HRA)	
1545 - 1600	2.16	Technical risk assessment related to human and organizational factors	Frank Markert
		Subtask E Presentations: Materials Compatibility	
1600 - 1615	2.17	Update from Japan	Matsunaga
1615 - 1630	2.18	An overview of hydrogen safety project in Japan	Tadahiro Shibutani
1630 - 1645	2.19	Update from Spain	Iñaki Azkarate
1645 - 1700	2.20	Discussion of Day 2, actions items, next Task 37 meeting in Japan, instructions for Day 3 Tour	John Khalil, Thomas Jordan & All participants
1700		Adjourn	
1815		Group Transport to Dinner starting in front of Hotel Kübler	
1900 – open		KIT Invited Dinner (place to be determined)	
Wednesday, April 22, 2015 – Lab Tour / 5.0 IPHE RCS Group Meeting			
0830	Bus to		

	KIT		
0900 – 1200	4.1	KIT Technical Tour	Thomas Jordan & All
1200 – 1300	Lunch Break		
1300 - 1700	5.0	IPHE RCS Meeting	IPHE Group members and guests
1700	Bus to hotel		

Kawasaki, Tokyo, Japan

Friday, October 23, 2015 9:00 am – 5:30 pm

Host organization: Kawasaki Heavy Industries, Ltd.

HYDROGEN IMPLEMENTING AGREEMENT

International Energy Agency

Task 37: Hydrogen Safety Agenda

9:00 – 9:15 am	Welcome and meeting logistics	Oyama-san, KHI
9:15 - 9:30	Introduction & planning	John Khalil, UTRC
Subtask A Presentations: Integrated Tool Kit for Hazards and Risk Assessment		
9:30 – 10:00	Update on Sandia's HyRAM toolkit	Katrina Groth
Coffee break: 10:00 – 10:20 am		
10:20 – 10:40	Status update: hydrogen safety related work at KIT/Germany	Thomas Jordan
10:40 – 11:00	Suggestions for improving HyRAM, fill in existing gaps, and how to align this tool to serve the Hydrogen Safety	All
Subtask B Presentations: Accident Scenario Development		
11:00 – 11:20 am	*JRC numerical simulations of gas release in the HyIndoor project"*	Daniele MELIDEO
11:20 – 12:00	Update on Hy3DRM and HySEA".	Trygve Skjold
Lunch: 12:00 – 1:00 pm		
1:00 – 1:15	informal discussions between partners on cooperation projects	Lead:Trygve Skjold All participants
Subtask C Presentations: Physical Effects		
1:15 – 1:40	Numerical simulations of fireball and blast wave from high-pressure tank rupture in a fire	Vladimir Molkov
1:40 – 2:00	Lift-off and blow-out of under-expanded jets: experiments versus simulations	Vladimir Molkov
2:00 – 2:20	Comparison of flame length of round, plane and fan jet	David Yates / Vladimir Molkov
2:20 – 2:40	The increase of fire resistance rating of hydrogen storage beyond fire duration	Dmitriy Makarov
2:40 – 3:15	Modeling thermal response of polymer composite hydrogen cylinders subjected to extermnal fires	Jennifer Wen
3:15 – 3:40	Numerical simulation of flame acceleration and deflagration-to-detonation transition in hydrogen-air mixtures with concentration gradients	Changjian Wang
Coffee break: 3:40 – 4:00 pm		
Subtask D Presentations: Human Reliability Analysis (HRA)		
4:00 – 4:20	Application of dynamic systems modelling –RA off-shore model	Frank Markert
4:20 – 4:25	Highlights of a new book on "Human Error in Process Plant Operations a practitioners guide" by J.R. Taylor	Frank Markert
4:25 – 4:45	Introduction to human reliability analysis (HRA)	Katrina Groth
Subtask E Presentations: Materials Compatibility		
4:45 – 5:10	Presentation on materials compatibility	Mr. Hisao MATSUNAGA (Kyushu Univ.)
5:10 – 5:30	Action items & planning for 2016 meetings	John Khalil & All
5:30 pm	Adjourn	

Meeting Location: IEA HIA, Bethesda, MD
Host: Mary-Rose Valladares, IEA HIA Manager

Monday November 28, 2016 (1:00 pm – 5:00 pm)		
Speaker	**Time**	**Topic**
	12:00 – 1:00 pm	Lunch
Mary-Rose Valladares (Host)	1:00 – 1:10 pm	Welcome and meeting logistics
Mary-Rose Valladares	1:10 – 1:30 pm	IEA HIA Update
John Khalil	1:30 – 2:30 pm	Presentation title will be added
Katrina Groth	2:30 – 3:30 pm	HyRAM current status & future applications
Tadahiro Shibutani	3:30 – 4:00 pm	Leakage-type-based analysis and lesson learns of accidents involving hydrogen fueling stations
All	4:00 – 5:00 pm	Planning for end of Task 31 workshop
Tuesday November 29, 2016 (9:00 am – 5:00 pm)		
Speaker	**Time**	**Topic**
	9: 00 – 9:30 am	Coffee & Continental Breakfast
Mary-Rose Valladares & John Khalil	9:30 – 9:40 am	Logistics and review of meeting agenda
Stuart Hawksworth	9:40 – 10:20 am	Update on Activities at HSL and the UK More Widely
Vladimir Molkov	10:20 – 10:50 am	Simulations of blast wave and fireball after tank rupture in a fire using real gas EOS
Vladimir Molkov	10:50 – 11:20 am	Simulation of cryogenic jet fires
Tuesday November 29, 2016 (9:00 am – 5:00 pm)		
Speaker	**Time**	**Topic**
Frank Markert	11:20 – 12 pm	Risk modelling of H2 supply chains including human aspects
	12:00 – 1:00 pm	Lunch
William Buttner	1:00 – 1:30 pm	NREL and JRC Sensor Testing Laboratory Programs H2 Safety Sensor Gap Analysis and Support of Safety Codes and Standards
Pascal Tessier	1:30 – 2:00 pm	TBD
Knut Vaagsaether	2:00 – 2:30 pm	Image processing of high speed movies of jet release of hydrogen
	2:30 pm – 3:00 pm	Coffee Break
Djurre Siccama	3:00 – 3:20 pm	1. Update on the Hy3DRM and HySEA projects
Djurre Siccama	3:20 – 3:40 pm	2. Blind-prediction study for hydrogen filling station
John Khalil / All	3:00 – 4:00 pm	New action items & final remarks
Adjourn	4:00 pm	

Hosted by Health & Safety Executive (HSE)

Buxton, UK

July 3 – 4, 2017

12:30 – 2:00 pm	Lunch at HSL	
2:00 – 2:15 pm	Welcome and meeting logistics	Stuart Hawksworth HSE
2:15 - 2:30 pm	Introduction & planning	John Khalil, UTRC
		Stuart Hawksworth
2:30 – 3:00 pm	KIT current work related to hydrogen safety and code development.	Thomas Jordan
3:00 – 3:30		
3:30 – 4:00 pm	Update on the Hy3DRM and HySEA projects. Needs 20 min	Trygve Skjold
4:00 0 4:10 pm	The future of IEA-HIA Task 37 on Hydrogen Safety needs 10 min	Trygve Skjold
Tuesday July 4, 2017		
9:00 – 9:30 am	CFD and engineering models for vented hydrogen deflagrations	Jennifer Wen Warwick U.
9:30 – 10:00 am		Tadahiro Shibutani
10:00 – 10:30 am	DTU- Current work related to hydrogen safety in infrastructures (20 min) Brief introduction to DTU Civil Engineering (10 min)	Frank Markert
10:30 – 11:00 am	Defalagration-to-detonation transition and detonation in hydrogen-air mixture with concentration gradients	Changjian Wang Hefei Univeristy of Technology
Coffee break: 11:00 – 11:20 am		
11:20 – 11:50		
Lunch 12:00 – 1:00 pm		
1:00 – 3:00 pm	HSE Facility Tour	
3:00 – 4:00 pm	Discussion & plan for Task 31 End of Task Workshop	John Khalil & All
4:00 pm	Adjourn	

Hosted by
Air Liquide Centre de Recherche Paris-Saclay

October 19, 2018

Meeting Agenda

Time	Presentation Topic	Speaker
9:00 – 9:10	Welcome and meeting logistics	Simon Jallais, AL
9:10 – 9:20	Introduction & planning	John Khalil, UTRC, USA
9:20 – 9:45	Update on KIT work on H2 safety issues.	Thomas Jordan, KIT, Karlsruhe, Germany
9:45 – 10:10	PRESLHY project.	Thomas Jordan, KIT Karlsruhe, Germany
10:10 – 10:25	Coffee break	
10:25 – 11:00	DTU new research related to hydrogen car fires in enclosures.	Frank Markert, DTU Denmark Technology University, Denmark
11:00 – 11:30	Research activities on comprehensive social risk assessment for hydrogen refueling station.	Tadahiro Shibutani, YNU, Yokohama, Japan
11:30 – 12:00	Update on the HySEA project and brief introduction to the SH_2IFT project	Trygve Skjold, Gexcon
12:00 – 1:00 pm	Lunch	
1:00 – 2:00 pm	Tour at the Hydrogen Station Facility@ Air Liquide R&D	

Bilag 2:

Poster på Den danske brint- og brændselscelledag 2016 & 2018

Den danske brint- og brændselscelledag 2016

IEA HIA Task 37 Hydrogen Safety

Categories

Program EUDP
Fælles overordnet teknologiområde - Brint og brændselsceller
Projekttype Forskning - Journalnummer 64014-0534

DTU contact: Frank Markert (fram@dtu.dk)

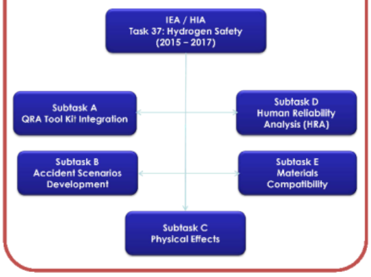
Keynumbers

Periode: 4/2015 - 3/2018
Egen finansiering: 0,03 mio.
Støtteprocent: 90%

Bevillingsår: 2014
Støttebeløb: 0,30 mio.
Projektbudget: 0,33 mio.

Operating Agent:
Dr. John Khalil (KhalilYF@UTRC.utc.com)
Term: 2015-2018
United Technologies Research Center (UTRC)
411 Silver Lane, East Hartford, CT USA

Project details



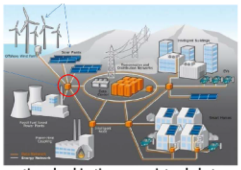
Partners

1. United Technologies Research Center (UTRC) USA
2. National Renewable Energy Laboratory (NREL) USA
3. Department of Energy (DOE) USA
4. Sandia National Laboratories (SNL) USA
5. HySafe Canada
6. Technova Inc Japan
7. Karlsruhe Institute of Technology (KIT) Germany
8. Federal Institute Materials Research and Testing, BAM Germany
9. University of Ulster UK
10. Health & Safety Laboratory (HSL) UK
11. University of Warwick UK
12. Air Liquide France
13. INERIS France
14. Technical University of Denmark (DTU) Denmark
15. University of Pisa (UniPi) Italy
16. Tecnalia Spain
17. EC Joint Research Center European Commission (EC)
18. GexCon Norway
19. University College of South East Norway Norway

Work plan / objective / goals

The work plan and objectives of this task are designed to support the acceleration of safe implementation of hydrogen infrastructure through coordinated international collaborations and hydrogen safety knowledge dissemination.

- Development of a hydrogen safety integration model (or tool):
  A user-friendly integrated hydrogen safety model (tool) that facilitates system analysis and determines appropriate risk metrics.
- Development of risk management strategies to ensure safety implementation of hydrogen infrastructure:
  To provide a systematic approach to determine gaps in current basic and applied research.
- Collection of systems, subsystems, and components reliability (i.e., field failure) data and human error (HE) probabilities (i.e., human factors) to support quantitative risk analysis (QRA):
  To collect information on effects of components failures on hydrogen systems and infrastructure
- Performance of consequence analysis to facilitate the accelerated adoption of hydrogen technologies.



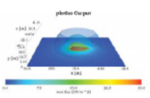
The above-mentioned objectives are intended to support the overarching goal of enhancing safe implementation of hydrogen-based technologie.

Progress/results

HyRAM toolkit developped by Sandia National Laboratories.

- A tool to do probabilistic risk assessment using fault and event trees as well as state-of-the –art consequence models.
- The HyRAM toolkit integrates state-of-the-art models and data for assessing hydrogen safety.

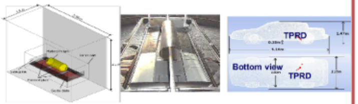
HyRAM provides a common platform for stakeholders conducting quantitative risk assessment and consequence analysis for hydrogen systems. The resulting information provides the scientific basis to ensure code requirements are consistent, logical, and defensible.



Scenario	End State Type	Avg. Events/Year
100pct Release	No Ignition	0.0008
10pct Release	No Ignition	0.0012
1pct Release	No Ignition	0.0015
0.1pct Release	No Ignition	0.0050
0.01pct Release	No Ignition	0.0348

Lit.: http://hyram.sandia.gov; Katrina M. Groth and Ethan S. Hecht. HyRAM: A methodology and toolkit for Quantitative Risk Assessment of Hydrogen Systems In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 19-21, 2015

BONFIRE tests and simulation by K.I.T. and University Ulster



- Modelling heat radiation essentially affects the fire resistance rating (FRR) of a bare hydrogen tank in bonfire test simulations
- The use of resins with different T_d for CFRP tank jackets can result in drastic difference in FRR.
- Burner has a significant influence on the FRR. Burner(s) should be standardised.
- Heat release rate affects FRR for the same design burner. HRR should be standardised.
- The current GTR fire test protocol can result in incomparable results of the same storage tank in different laboratories around the globe.

Lit.: V. Molkov; Progress in physical effects at Ulster, presentation April 20th ,2015 IEA HIA Task37, Karlsruhe (ulster.ac.uk)

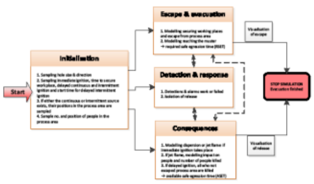
Next steps

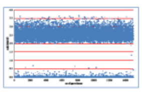
A number of other tools and outputs resulting form the activities in the sub-tasks as indicated in the orgainsational scheme are under development. Hereunder, a tool under development by DTU to integrate Human error into QRA calculations:

Integration of human behavior / errors into a dynamic model of a hydrogen installation.

Monte Carlo approach enables to model and simulate many more hazard scenarios including the effects of insufficient maintenance of e.g. detectors and evacuation. This enables to predict worst case scenarios opposite to the worst case assumptions made by risk experts.

- Event sequences are simulated in parallel.
- Dynamic interaction of events
- Events taking place in one sequence change the conditions in the other sequences
- Data are sampled statistically,
- e.g. hole size, wind speed, number and position workers
- Multiple runs (many!) are performed to extract risk numbers (IR, PLL, group risk)
- Individual scenarios can be simulated graphically (animation)





Ratio of Available vs. Required Safe Egress Times ASET/ RSET. Values above 1 indicate safe egress conditions. Each point represent a specific scenario.

Lit.: F. Markert, I. Kozine, N. J. Duijm; process Risk Assessment using Dynamic Simulation of Scenarios; Chemical Engineering Transactions; 48 (2016); ISBN 978-88-95608-39-6

Conclusion and perspectives

The task 37 supports a transition to a new HYDROGEN ECONOMY. The work is a continuation of IEA HIA tasks 19 and 32. The consortium has close relationships to the International Association HySafe and to the standardization activities according to TC197.

- build–up of new safe and sustainable infrastructure e.g. for safe hydrogen delivery from production site to refueling stations
- Safe use of hydrogen in various kinds of applications
- Safety standards for garages, car parks, tunnels etc..

The goal is to support an inherently safer approach to build the future hydrogen energy infrastructure in Denmark and internationally.

The hydrogen infrastructure may:

- Integrate energy supply and fuel supply infrastructures energy sector and transport sector
- New hydrogen applications will develope through time, as e.g. hydrogen trains as alternative for diesel trains on tracks were electrification is too expensive, e.g.:

A passenger train connecting two towns in Germany is the first in the country to run on hydrogen. The train will begin operation in December 2017, and will run between Buxtehude, a small city, and the beach town Cuxhaven. Three other German states have also expressed interest in adopting similar projects.
The Coradia iLint passenger train, built by Alstom in France and revealed this month, uses hydrogen recycled from the chemical industry to travel 497 miles on one charge. It can run up to 87 miles per hour, storing any excess energy in Lithium batteries slung on the bottom of the train car.

(https://www.manufacturing.net/news/2016/09/germanys-first-hydrogen-train-uses-recycled-fuel)

Den danske brint- og brændselscelledag 2018

IEA HIA Task 37 Hydrogen Safety

DTU

Category

Program EUDP Fælles overordnet teknologiområde - Brint og brændselsceller
Projekttype Forskning - Journalnummer 64014-0534
DTU contact: Frank Markert (fram@dtu.dk)

Keynumbers

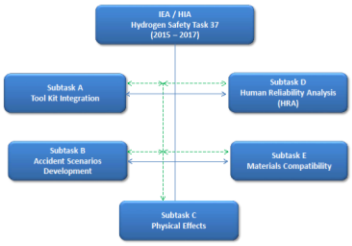
Periode: 4/2015 - 12/2018
Bevillingsår: 2014
Egen finansiering: 0,03 mio.
Støttebeløb: 0,30 mio.
Støtteprocent: 90%
Projektbudget: 0,33 mio.

Operating Agent: Dr. John Khalil (KhalilYF@UTRC.utc.com)
Term: 2015-2018 United Technologies Research Center (UTRC) 411 Silver Lane, East Hartford, CT USA

Partners

United Technologies Research Center (UTRC) USA
National Renewable Energy Laboratory (NREL) USA
Department of Energy (DOE) USA
Sandia National Laboratories (SNL) USA
HySafe Canada
Technova Inc Japan
Karlsruhe Institute of Technology (KIT) Germany
Federal Institute Materials Research and Testing, BAM Germany
University of Ulster UK
Health & Safety Laboratory (HSL) UK
University of Warwick UK
Air Liquide France
INERIS France
Technical University of Denmark (DTU) Denmark
University of Pisa (UniPi) Italy
Tecnalia Spain
EC Joint Research Center European Commission (EC)
GexCon Norway
University College of South East Norway Norway

Tasks

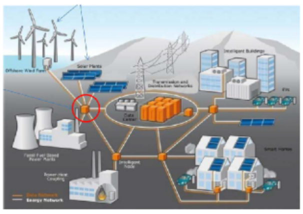


Project description

Decision support to accelerate the implementation of a hydrogen infrastructure. The overarching goal is to enhance safe implementation of hydrogen-based technologies: a) Through coordinated international collaborations and b) Hydrogen safety knowledge dissemination

The Activities

Development of a hydrogen safety integration model (or tool)
Development of risk management strategies to ensure safety implementation of hydrogen infrastructure
Collection of systems, subsystems, and components reliability (i.e., field failure) data and human error (HE) probabilities (i.e., human factors) to support quantitative risk analysis (QRA)
Performance of consequence analysis to facilitate the accelerated adoption of hydrogen technologies.



The Intended Results

Develop a user-friendly integrated hydrogen safety model (tool) that facilitates system analysis and determines appropriate risk metrics. Provides a systematic approach to determine gaps in current basic and applied research. Provide a framework around which collaborative research programs can be conducted. Collect information on effects of components failures on hydrogen systems and infrastructure

Progress

Knowledge exchange on the safe application of pressurized and liquid hydrogen technologies. Hereunder, discussion on the required optimal footprint of hydrogen installations. This is directly dependent on the appropriate safety distances that must be established for safety reasons.

Plans are under development to establish an IEA journal to communicate research based knowledge on hydrogen safety.

Book on hydrogen supply chains including the safety aspects has been published in 2018: Markert, Hansen: Risk analysis of complex hydrogen supply chains in HYDROGEN SUPPLY CHAINS: DESIGN, DEPLOYMENT AND OPERATION ed. Azzaro-Pantel: Springer.

EIGA safety distances

EIGA DOC 06/02/E

ITEMS	DISTANCE (M)
90 min fire resistive walls	2.5
Technical and unoccupied buildings	10
Occupied buildings	20
Air compressor intakes, air conditioning	20
Any combustible liquids	10
Any combustible solids	10
Other LH2 fixed storage	1.5
Other LH2 tanker	3
Liquid oxygen storage	6
Flammable gas storage	8
Open flame, smoking, welding	10
Place of public assembly	20
Public establishments	60
Railroads, roads, property boundaries	10
Overhead power lines	10

Pre-normative research: Application of LH2

PRESLHY

NFPA 2 safety distances

Table 1 –Summary of separation distances from NFPA 2 (2011 edition) – critical distances used in developing the diagrams in this report are shown in bold.

Separation Distances and Areas Required		
Fuel system descriptions: GH2 – 12,500 psi (862 bar) storage, 100 kg, 0.4 in (10 mm) ID tubing with a barrier wall LH2 – 3,500 - 15,000 gallon (13,250-56,780 liters) with barrier wall and insulation	GH2 ft (m)	LH2 ft (m)
Lot lines	**24 (7.3)**	**33 (10)**
Public streets, alleys	24 (7.3)	33 (10)
Parking (public assembly)	13 (4.0)	**75 (23)**
Buildings (sprinklers, fire rated)	10 (3.0)	5 (1.5)
Building openings or air intakes	**24 (7.3)**	**75 (23)**
Flammable and combustible liquid storage, vents or fill ports	10 (3.0)	50 (15)
Parking from fill concentrations on bulk storage	13 (4.0)	25 (7.6)
Class 1 Division 2 area diameter	15 (4.6)	15 (4.6)
Maximum bulk storage equipment dimension with lot lines	54 (16)	40 (12)
Minimum bulk storage equipment dimension with lot lines	49 (15)	40 (12)
Maximum bulk storage dimension with separation distances	78 (24)	123 (37)
Minimum bulk storage dimension with separation distances	68 (21)	123 (37)
Reference Area: bulk storage equipment with lot lines	2646 ft^2 (246 m^2)	1600 ft^2 (149 m^2)
Reference Area: storage with separation distances	**5304 ft^2 (493 m^2)**	**15129 ft^2 (1406 m^2)**

Note: Add 5 feet (1.5 meters) for vehicle protection on vehicle facing sides of equipment

Conclusion and Future topics concerning hydrogen safety

The task 37 supports a transition to a new HYDROGEN ECONOMY. The work is a continuation of IEA HIA tasks 19 and 32. The consortium has close relationships to the International Association HySafe and to the standardization activities according to TC197.

Build–up of new safe and sustainable infrastructure e.g. for safe hydrogen delivery from production site to refueling stations

Safe use of hydrogen in various kinds of applications

Safety standards for garages, car parks, tunnels etc.. The goal is to support an inherently safer approach to build the future hydrogen energy infrastructure in Denmark and internationally. The hydrogen infrastructure may:

Integrate energy supply and fuel supply infrastructures energy sector and transport sector

New hydrogen applications will develope through time, as e.g. hydrogen trains as alternative for diesel trains on tracks were electrification is too expensive

The knowledge exchange contributed to the development of new pre-normative research projects within hydrogen application in large and complex infra structures and the application of liquid hydrogen. The latter is seen as the next step to facilitate large scale application of hydrogen.

Den danske brint- og brændselscelledag 2018

Sustainable Cars & Car Park Fire Spread

Category

Application of hydrogen in car parks, complex infra-structures and buildings

DTU master thesis at DTU Civil Engineering – Building Design and processes, Fire Group

Partner

Master thesis: Denice Kirstine Søgård

Supervisors: associate professors Frank Markert & Luisa Guilliani

Contact: Frank Markert (fram@byg.dtu.dk)

Background

- stor ca park
- on Lan Rove burste in flame
- 140(car engulfe in the fire
- n casulatie !

[redacted]

- ope ca park
- 5 car burne in th fire
- n casulatie !

[redacted]

Fires in Dk and EU

- Fasanvænget Kokkedal, DK (2001 Sept.) - 30 cars burned in open car park
- Odense Parking Garage, DK (2014 Apr.) – 10 cars involved
- Schipol Airport Fire, NL (2002 Oct.) – 52 cars burned in open car park
- Brøndby Øster sheltered car park (2016 March) – 19 cars involved in the fire
- Von Lingens Väg Malmö, SW (2017 Apr.) - 30 cars burned in a closed car park
- Stansted Airport (2010 Aug.) – 24 cars involved in the fire
- Edinburgh Parking Facility (2014 Apr.) – 21 cars involved in the fire
- Liverpool Echo Arena (2018 Jan.) - 1400 cars burned in open car park

Project description/objective/goals

Real fires proved faster and wider fire spread than the design rules indicate. The determine parameters are:

- Distance between cars
- Layout of parking spot
- Thermal feedback from ceiling

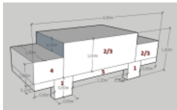
New sustainable car may contribute more to fire spread scenarious:

- New lightweight cars contain more combustible plastic
- New fuels as hydrogen, larger batteries, etc. are used

Research questions:

- How will the new sustainable fuels affect such scenarios?
- Is there a difference in fire spread from HFV?
- Is there a need for specific design rules for HFV?

The car model implemented in the Fire Dynamic Simulator



(a) Dimensions of Toyota Mirai [6]

Materials chosen:

1. Rubber
2. Polyurethane foam (PU)
3. Polyvinyl chloride (PVC)
4. Polypropylene (PP)
5. Polycarbonate (PC)

Car model chosen:
Comparable with Toyota Avensis, Toyota Mirai, …
Car dimensions:
Length: 4,8m Width: 1,8m Height: 1,6m

Scenarious

[redacted]

Used to calibrate the car model against experimental HRR curve.

[redacted]

Fire starts in the back right tire of the left car

Used to compare with fire spread from HFC

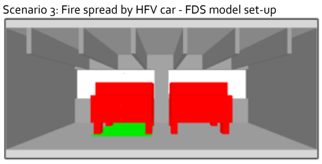
3. *Scenar : FIRE SPREAD BY HFV CAR*

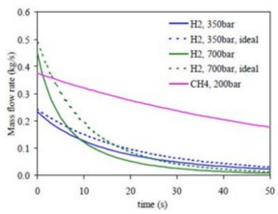
[redacted]

Modelling hydrogen safety valve activation:

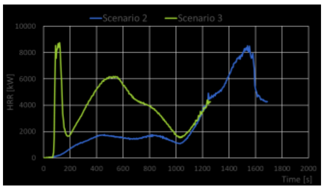
- Hydrogen is modelled as a burner under the car
- Mass flow rate curve assígned
- Activation of the TPRD at 100°C
- TPRD modelled as a thermocouple on the burner

Scenario 3: Fire spread by HFV car - FDS model set-up





Results



Ignition of HFC car: Activation of TPRD hydrogen at 72 s
Fire spread to 2[nd] car: Ignition of car 2 at 130 s

- HFV does affect the fire spread in the car park design
- High sensitivity to activation time of TPRD
- Fast fire spread to car 2

Further work:

- Effect of ceiling – radiation model
- Firespread to several cars
- Improved hydrogen release modelling
- Modelling of additional fuels
- Development of more detailed car model
- Two new master of Fire engineering students are currently working on a more advanced model

Tunnel training facility in Balsthal

Conclusion and perspective

There has been reported a large number of car-park fires. The latest happend in Liverpool where 1400 cars burned in a fire. The start of the fire was immediatly recognized by cark-park visitors and the fire brigade arrived in short time thereafter. Still the fire load of the SUV ignited the naboring cars and the fire spread to the whole 7-stories car park in very short time. The loss is monetarian and no people have been injured or died. Nevertheless, the loss had been very substancial and also resulted in a destroyed car park building.

Such a fire scenario involving future cars fueled by e.g. hydrogen, batteries need to be investigated more deeply. The objective will be to find the best car-park designs implementing the best prevention and mitigation startegies.

Fire spread in car-parks are not the only scenarios of interest. The usability and resilient use of new hydrogen based technologies have to be investigated more widely. Scenarious and calculations as well as fire tests have to be made for e.g.:

- Tunnels
- Ferries
- Closed / underground car-parks

Part of such investigations will be made in the forthcomming Horizon 2020 JTI-FCH project starting early 2019:

Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces (HyTunnel-CS)

The scope related to confined traffic infrastructures, e.g. tunnels, according to the implementation of EU directive 2004/54/EC and the effectiveness and interaction of conventional and innovative safety measures in case of accidents with hydrogen-powered vehicles or hydrogen transport in tunnels. To providing guidance and suitable performance-based requirements to regulatory bodies, technology suppliers and operators.

Consortium composition
The HyTunnel-CS consortium includes 13 partners from 11 EU and non-EU countries. They are recognized global leaders in hydrogen safety and tunnel safety.

Bilag 3:

Hydrogen Safety Journal (H2SJ) – A publication by the International Energy Agency (IEA)

DESCRIPTION

The Hydrogen Safety Journal aims to provide a leading platform for publishing high-quality interdisciplinary papers on research and practice related to safety of hydrogen technologies and applications. Types of article published by this journal include original research, applied research, perspectives, short communications, and review papers. All papers should include some elements of product safety thinking and should clearly demonstrate that they are addressing topics related to hydrogen technologies risk assessment, risk management, and codes & standards.

The areas and topics covered by the journal include but are not limited to:

- Fundamental research (experimental and theoretical) & Applied research
- Solid-state hydrogen storage materials dust cloud explosions and combustion characterization
- Hydrogen storage materials' reactivity and safety
- Accident sequence development and quantification (e.g., hydrogen leak scenarios leading to fires and explosions, etc.).
- Consequence analysis of hydrogen fires and explosions (e.g., property damage, injuries, etc.).
- Safety analysis of hydrogen vehicles and infrastructure & Hydrogen safety best practices, training, and communications
- Safety of hydrogen production, transportation, and distribution
- Hydrogen supply chain risk management
- Quantitative risk assessment and qualitative risk assessment methods
- Safety of hydrogen storage tanks
- Hydrogen products safety (e.g., PEM fuel cells, portable hydrogen generators)
- Unmanned aerial vehicles power by hydrogen
- All-electric aircraft powered by hydrogen and fuel cells.
- Safety of hydrogen-based mobile and portable applications (e.g., forklifts, generators, etc.)
- Hydrogen safety codes and standards

EDITORIAL BOARD

Bilag 4:

IEA H2 EUROPEAN WORKSHOP

Hydrogen Safety: Prospects for Hydrogen Technologies & Applications
Hamburg, Germany, 14 September 2017

PRESENTATIONS

- IEA H2 IEA H2 Safety Workshop Overview (Mary-Rose de Valadares replacing Jan Jensen)
- IEA Task 37 Overview (John Khalil)
- Safety of Hydrogen in the Energy System (Stuart Hawksworth)
- Recent advances in hydrogen safety research at Ulster – Part I (Vladamir Molkov)
- The new version of the Hydrogen Incident Accident Database - HIAD (Daniele Melideo)
- DTU- Current work related to hydrogen safety in infrastructures (Frank Markert, see below)
- Numerical modelling of vented lean hydrogen–air deflagrations using HyFOAM (Vendra C Madhav Rao)
- Evaluation of engineering models for vented lean hydrogen deflagrations (Anubhav Sinha)
- Flame propagation (deflagration, DDT, and detonation) in hydrogen-air (Knut Vagsaether)
- Prospects for improved consequence modelling and risk management for hydrogen applications (Trygve Skjold)
- What are the main challenges to mass adoption of hydrogen-based technologies and how do we address them? (Panel Discussion)

Presentations attached below are Presentation John Khalil- "IEA Task 37 Overview" and DTU "Current work related to hydrogen safety in infrastructures" iea hydrogen

Task 37 – Hydrogen Safety

Dr. Y. (John) Khalil*
Operating Agent

Presentation at the
IEA Hydrogen Stakeholder Workshop on Hydrogen Safety

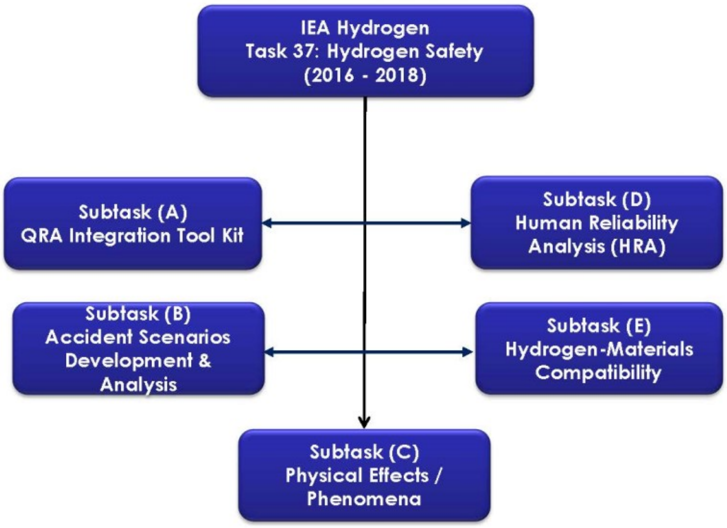
September 2017, Hamburg, Germany

* Associate Director, Research, United Technologies Research Center (UTRC), USA
Fellow of the University of Oxford, UK

Presentation topics

- Task's organizational structure, goal, and objectives
- Task's activities and deliverables (by subtask)
- New hydrogen safety expert joined IEA Hydrogen
- Task 37 website and Hydrogen Safety Journal initiation
- Proposed forward looking opportunities for Task 37
- Challenges for hydrogen-based industry
- Message for hydrogen safety stakeholders

Task 37 organizational structure



Task 37: goal and objectives

Overarching goal:

Support acceleration of safe implementation of hydrogen technologies and infrastructures through coordinated international collaborations and dissemination of safety knowledge.

Objectives:

i) Support development of QRA integration tool kit (***HyRAM platform***)

ii) Identify risk management strategies (*e.g.*, **separation distances**) to ensure safe implementation of hydrogen infrastructures

iii) Collect **reliability information** (field failure data) of structures, systems, and components (SSC) to enable quantitative risk assessment (QRA)

iv) Provide risk-informed insights (a blend of **probabilistic & deterministic***) to guide development of new and/ or revised science-based **hydrogen safety C&S** (*e.g.*, NFPA-2 and ISO standards).

* *Physics-based models, engineering calculations like computational fluid dynamics (CFD), etc.*

Subtasks: Leaders, deputies, and participants

- **Subtask (A): QRA Integration Tool Kit (HyRAM)**

  Output: QRA methods and tools to support HyRAM development
  Leader: Thomas Jordan (past leader: Katrina Groth)
  Deputy: TBD
  Participants: KIT, Ulster, DTU, HySafe, Gexcon, UniPi, UTRC

- **Subtask (B): Accident Scenarios Development & Analysis**

  Output: Identification of generic H2-based systems and accident sequences to be used for alpha testing and validation of Subtask (A) predictive models
  Leader: Trygve Skjold
  Deputy: Julie Flynn
  Participants: KIT, Ulster, DTU, HySafe, GexCon, UniPi, NREL, APC, Air Liquide, InerisAPC, HSE, CEA

Subtasks: Leaders, Deputies, and Participants

- **Subtask (C): Physical Effects / Phenomena**
  Output: Physics-based predictive models and experimental data (e.g., (flame propagation, jet/ flash fires, deflagration, detonation, heat release rates, … etc.)

  Leader: Stuart Hawksworth
  Deputy: Jennifer Wen
  Participants: KIT, Ulster U., HySafe, GexCon, UniPi, NREL, Air Liquide, Ineris, HSL, CEA, Warwick U., JRC, NCSRD*, Keio University, Telemark Univ.

  * NCSRD = National Center for Scientific Research Demokritos

- **Subtask (D): Human Reliability Analysis (HRA)**
  Output: Approaches for implementing human influence and recovery actions within QRA models.
  Leader: Frank Markert
  Deputy: TBD
  Participants: HSE, Ineris, NCSRD, DTU, UTRC

Subtasks: Leaders, Deputies, and Participants

- **Subtask (E): Hydrogen-Materials Compatibility**

  Output: Theoretical models, experimental data, and empirical correlations to enable better understanding of hydrogen effects on materials such as embrittlement, permeation … etc.

  Leader: Iñaki Azkarate
  Deputy: TBD
  Participants: UTRC, NREL, Kyushu U., Air Liquide, Tecnalia

New members in Task 37

Professor Changjian Wang
Hefei Univeristy of Technology
China

Task 37 activities & deliverables (by Subtask)

Subtask	Activities & Deliverables
Subtask (A) QRA integration toolkit (HyRAM platform, release 1.1) Available at http://hyram.sandia.gov	1) Validated models for H2 flame behavior and H2-specific QRA to guide industry C&S. Examples of current uses of HyRAM in C&S: 1.1) NFPA 2: • Establishing gaseous hydrogen separation distances. • Developing models for calculating liquid hydrogen separation (LH2) distances. 1.2) ISO CD-19880-1: development of generalized risk mitigation approaches such as safety distances.
	2) Providing failure probability data to enable quantification of QRA models.

Task 37 activities & Deliverables per Subtask

Subtask	Activities & Deliverables
Subtask A (cont'd) QRA integration toolkit (HyRAM platform, release 1.1)	3) HyRAM has been used to support risk-informed comparisons among reference HRS and on-site storage (rooftop, underground, or at grade). Example: H2FIRST reference station design (project participants ANL, NREL, and SNL). HyRAM has been used for calculating baseline risk for a 300 kg/day reference HRS.
	4) Examples of future applications: NFPA and ISO codes revisions for enclosures' designs by comparing safety impacts of different designs and identifying critical risks associated with components such as compressors and H2 storage tanks.

Task 37 research activities & Deliverables (by Subtask)

Subtask	Activities & Deliverables
Subtask (B) Accident Scenarios Development & Analysis This Subtask defines generic systems, scenarios, and mitigation strategies to be used for validating models' predictions from Subtask A.	1) Provide insights and updates on the 3D risk management framework (Hy3DRM) and HySEA (started 9/1/2015 and to be completed by 2018) projects at Gexcon. Source: www.hysea.eu 2) Provide insights and updates on hydrogen safety projects in Japan (HRS leak scenarios). 3) Provide general hydrogen-based systems and accident sequences to serve as alpha-tests to validate HyRAM models.

Task 37 research activities & deliverables per Subtask

Subtask	Research Activities
Subtask (C) Physical Effects / Phenomena	1) Effect of heat release rates (HRR) on results of Bonfire test in Global Technical Regulation (GTR) 2013 (GTR#13). 2) Effect of radiative heat on hazard distances from blast wave and fireball. 3) SUpport to SAfety aNAlysis of Hydrogen and Fuel Cell Technologies (SUSANA) project related to model evaluation protocol using CFD analysis for H2 safety issues and best practices. 4) Flow velocity measurements in H2-air explosions. 5) Jet release of gaseous hydrogen. 6) Modeling deflagration to detonation transition (DDT) in H2/Air mixtures with concentration gradients. 7) Physical effects research: blast waves, localized deflagration (Ulster's progress).

Task 37 research activities & deliverables per Subtask

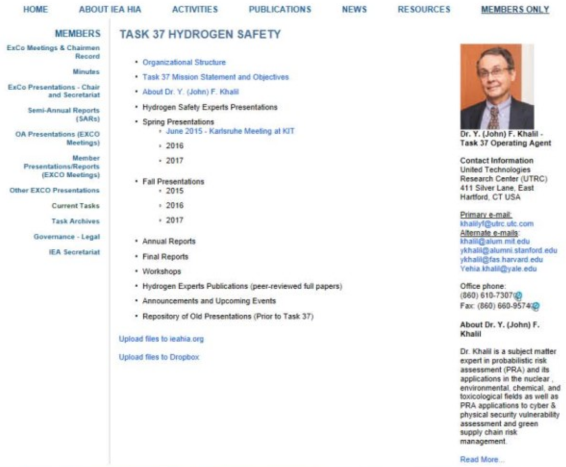
Subtask	Activities & Deliverables
Subtask C (Cont'd)	8) KIT's research on fire tests, flame acceleration in free semi-sphere, etc. 9) Ongoing international efforts (between Warwick, Kingston, Technische Universität München and Hefei University of Technology) on modelling hydrogen explosions and DDT in mixtures with concentration gradients. 10) Development of new H2 safety engineering tools: Examples include: - A nomogram for blast waves (to guide first responders). - A nomogram for blowdown time of storage tank. - Modeling H2 leakage incidents.

Task 37 research activities & deliverables per Subtask

Subtask	Activities & Deliverables
Subtask D Human Reliability Analysis (HRA)	1) Risk assessment related to human and organizational factors. 2) Modeling human errors as accident initiating events. 3) Modeling human recovery actions during accident progression.
Subtask E Hydrogen-Materials Compatibility	1) Hydrogen embrittlement of quenched and tempered steels. 2) Fatigue tests (under different hydrogen charging conditions) for high strength quenched and tempered steels.

Task 37 website

With support from Mary-Rose Valladares and her staff at the IEA Hydrogen office in Bethesda, MD, Task 37 now has a dedicated website. The Hydrogen Safety Experts can access the folders and subfolders under this website to download past and current Task 37 presentations.



The URL for this website is as follows:
https://ieahia.org/Members/PrivateTask-Websites-(current)/Task-37-Hydrogen-Safety.aspx

IEA Hydrogen Safety Journal

IEA Hydrogen Safety Journal

- Formation of this Journal is consistent with the ExCo's goal of "improving H2 Safety outreach and branding through increased publications."

- The Journal will be published semi-annually to disseminate hydrogen safety knowledge (research, safety C&S support activities, etc.).

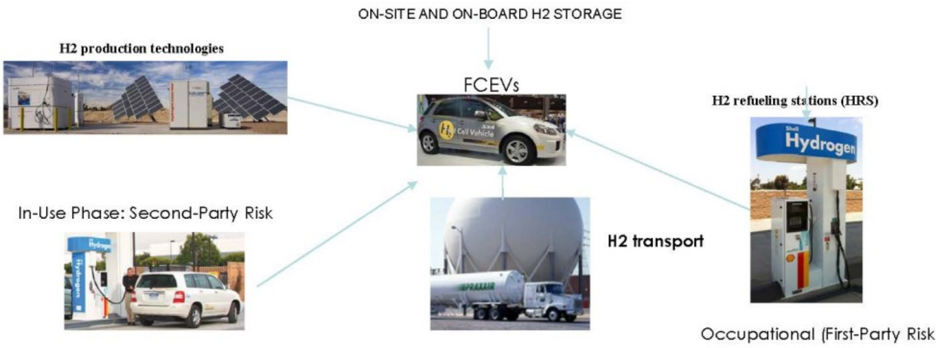
- Will be featured on the IEA H2 homepage to ensure public access to the content of this Journal.

- Editorial Board Members: (*please let's know if you're interested to join*)

  Editor-in-Chief: Dr. John Khalil, Associate Director, Research, UTRC
  Dr. Stuart Hawksworth, Head of the Energy Innovation Center, HSE, UK
  Ms. Mary-Rose Valladares, Manager, HIA Hydrogen, USA
  Prof. Frank Markert, Technical University of Denmark (DTU), Denmark
  Prof. Tadahiro Shibutani, Yokohama National University, Japan
  Prof. Changjian Wang, Hefei University of Technology, China

Hydrogen supply chain risk management

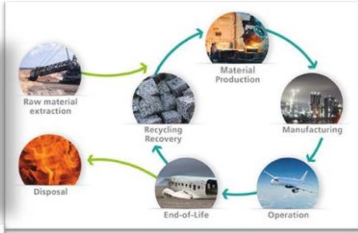
Hydrogen production, transport, storage in infrastructure & dispensing, storage on-board FC-vehicles, and in-use.



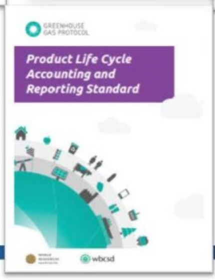
Life cycle assessment (LCA), impact assessment (LCIA), and carbon footprint accounting

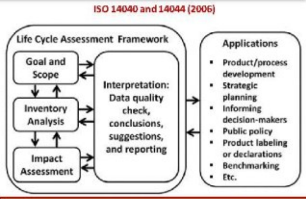
- Perform comparative risk assessments: *e.g.*, HRS vs. gasoline refueling stations and compressed natural gas (CNG) refueling stations.
- Quantify associated first-party, second-part, and third-party risks as part of the comparative assessment.

Benefits of product LCA
- Identify *"hotspots"*
- Largest source of adverse impacts?
- Where to make improvements/ innovation?
- Comparative LCA
- Which is "greener"?



Value-chain risk "Risk Disk."





<u>**Impact categories**</u>: Human health (carcinogens, particulates/ respiratory effects), eco-system (GWP, PDP, AP, EP, etc.), and resource depletion.

Hydrogen-based technological breakthroughs

- **Boeing and JetBlue** are funding research on the <u>all-electric propulsion aircraft</u>.
- Boeing's <u>hybrid electric aircraft</u>: a new concept.
- **NASA Armstrong Flight Research Center** predicts that in the near future, aircraft will be powered by electric motors.
- **Hydraulic and pneumatic actuation systems** are progressively being replaced by electrical ones and aircraft with electric engines will soon be a reality.

A new era for aviation: Airbus is going after key technological enablers of its long-term goal to '***electrify the skies.***'

H2 + PEM fuel cells ➔ hybrid electric & all-electric aircraft

Areas needing more research and safety tests

- Onboard H2 storage technologies
  - Solid-state storage (metal hydrides, complex metal hydrides, chemical hydrides, and adsorbents (AC, MOF)
  - Liquid-based storage media (e.g., ionic liquids)
  - Compressed H2 gas (350 bars & 700 bars)
  - Cryogenic H2

DOE Contract: Safety tests for selected solid-state hydrogen storage materials for on-board light-duty fuel cell vehicles

Fig. 1. Mechanical impact test rig.

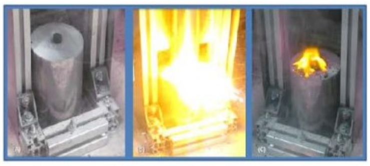


Fig. 2. A 4-gram $NaAlH_4$ wafer ignited upon first impact (free fall height = 1 m).

Fig. 3. Contact of $NaAlH_4$ powder compact (wafers) with a hot metal surface.

Under DOE contract, safety tests were performed to determine suitability of candidate solid-state materials for storing H2 on-board FC vehicles.

Measurements (ASTM tests)
- P_{max}, $(dP/Dt)_{max}$, K_{st} (E1226)
- Minimum Concentration (E1515)
- Minimum Ignition Energy (E2019)
- Minimum Ignition Temperature (E1491)

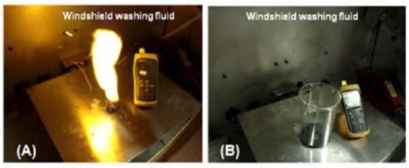


Fig. 4. $NaAlH_4$ reactivity: loose powder (A) vs. powder compact (B).

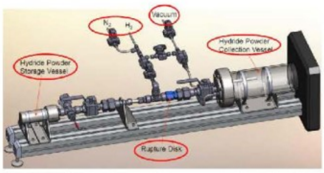


Fig. 5. Fast blowdown (depressurization) test rig to mimic rupture on of the on-board storage vessel.

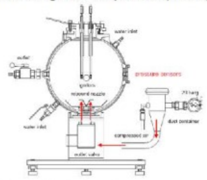


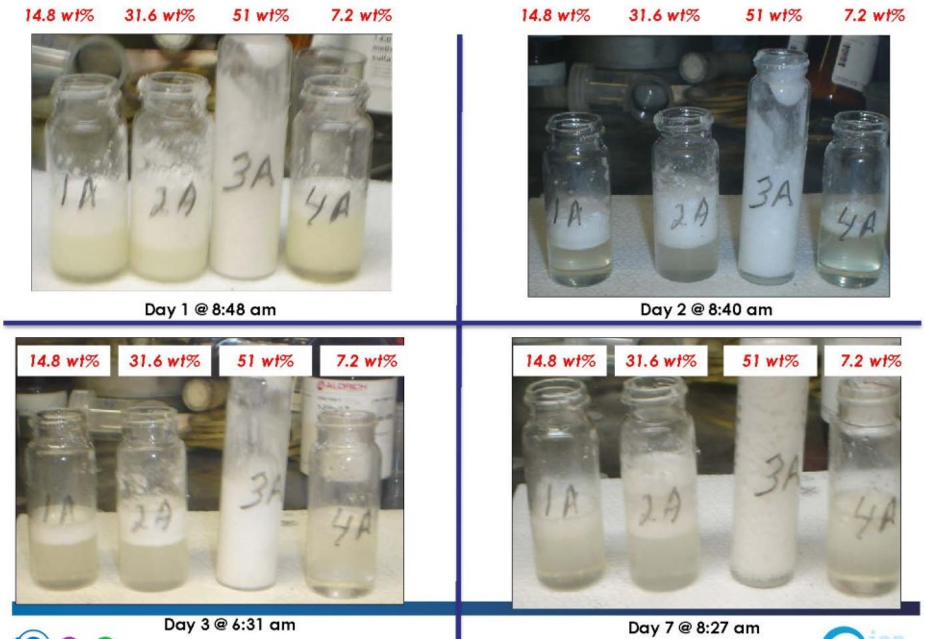
Fig. 6. Dust cloud explosion tests in standard 20 L Kühner apparatus (ASTM E1226 & E1515)

Powder ammonia borane (NH3BH3) in ionic liquids

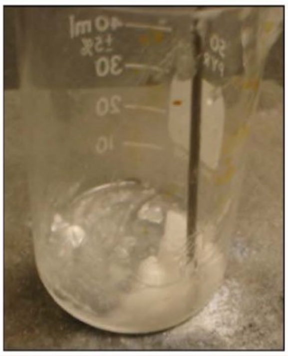
- Types of ionic liquids tests with AB powder:
  - 1-Butyl-3-methylimidazolium bis(trifluoro methyl sulfonyl) imide
  - 1-Ethyl-3-methylimidazolium ethyl sulfate
  - 1-Butyl-3-methylimidazolium chloride (bmimCl)

- Other related safety tests for AB loose powder and powder compacts:
  - Dust could characterization.
  - Mechanical impact sensitivity.

Solid AB in 1-Ethyl-3-Methyl Imidazolium Ethyl Sulfate at Room Temperature



1-Butyl-3-MethylImidazolium Chloride (bmimCL)
(50 wt% AB in IL)



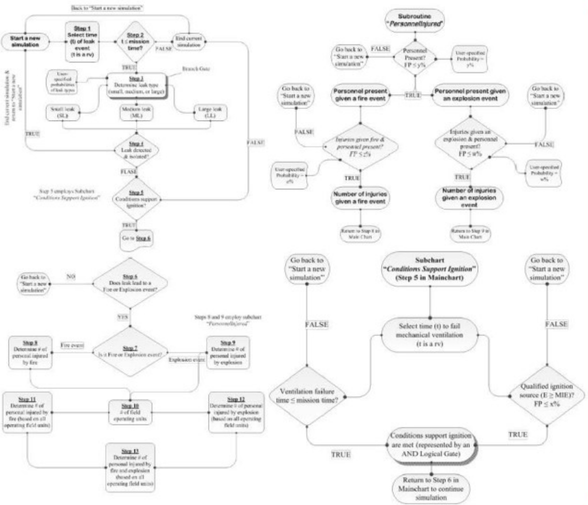
- IL (bmimCl) is a <u>white power</u> at room temperature.
- As soon as power AB is added to IL powder, the mixture started to melt as shown in Figure (A).
- The IL/AB mixture was then gradually heated and more melting occurred at the temperature increased to about 70 °C.
- At temperature ≥ 70 °C, <u>thermolysis reaction</u> gases bubbled through the liquid mixture.

- At about 100 °C, the single phase liquid mixture swelled as shown in Figure (B).
- From a life cycle analysis (LCA) perspective, it doesn't seem that (bmimCl) IL can be easily separated and recycled after the AB dehydrogenation reaction is completed.

Uncertainty quantification (UQ)

- **Aleatory uncertainty**
  - Caused by <u>stochastic nature of events</u> such as hardware failures.
  - <u>Irreducible</u> by improving the current state of knowledge about the failure event.
- **Epistemic uncertainty**
  - Associated with phenomenological events such as dust cloud explosion, deflagration, detonation, fire events (jet or flash)
  - Could be related to scaling up (geometrical) issue.
  - <u>Reducible</u> by improving the state of knowledge about the event (e.g., performing tests, physics-based models, etc).
- **Model completeness**
  - Related to whether a probabilistic model (e.g., a fault tree model) is <u>realistic</u> and sufficient to be <u>representative</u> to a real-world situation
- **Experimental uncertainty**
  - Repeatability of test results.
  - Human errors during testing.
  - Instruments' accuracy and calibration issues.

UTRC capability project: A probabilistic visual-flowcharting-based model for consequence assessment of fire and explosion events involving leaks of flammable gases



- The model quantifies probabilistic consequences of H2 leaks in a confined space.
- Leak source could be a hydrogen compressor in a hydrogen refueling station.
- This model predicts risks of fire- and explosion-related injuries resulting from ignition of leaked H2 in the confined space.
- Model's predictions are compared to acceptable occupational risk (first-party) level of 1.0E-4/yr to identify whether risk is unacceptable.

1 million Monte Carlo trials are performed in each simulation to propagate data uncertainty.

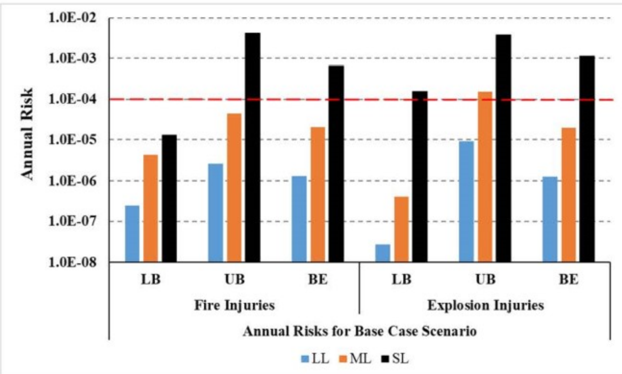


Fig. 4. Calculated annual risks of fire and explosion injuries for the base case scenario. ***Note: the horizontal dashed line represents the occupation risk acceptance threshold of 1.0E-4/year.*** **The SL results are shown below:**

- Fire-related injuries: 6.62E-4/year (BE) and 4.26E-3/year (UB)
- Explosion-related injuries: 1.12E-3/year (BE) and 3.85E-3/year (UB)

Challenges for the hydrogen-based industry

- Potential for hydrogen leaks remains a major safety concern particularly in refueling stations (*see Sakamoto, J. et al. (2016). IJHE, 41, 21564-21570*)

- Proposed revision to harm criteria in NFPA2 (separation distance based on 8% vs. 4% H2 concentration)

- Limited availability of probability data to support quantitative risk assessment (QRA).

- Restriction on use of FCEV in road tunnels: Currently FCEV are not allowed to use road tunnels (such as Baltimore Harbor tunnel and Fort McHenry tunnel)

Note: CNG and LNG vehicles are allowed to use these road tunnels under certain conditions (http://www.dsd.state.md.us/comar/comarhtml/11/11.07.01.03.htm)

Message for hydrogen safety stakeholders

There is a **need for creating harmonious hydrogen safety C&S** to accelerate worldwide adoption of hydrogen-based technologies.

Examples:

- The term "**Hazard Distance**" is commonly used in Europe and the term "**Safety Distance**" is commonly used in the U.S. These terminologies could be interpreted differently.

- Should 8% instead of 4% H2 concentration be used for deriving the separation distances?

- First-party (occupational), second-party (users), and third-part (general public) risk acceptance criteria are not consistent (vary by a factor of 10 in some cases).

Current work related to hydrogen safety in infrastructures

IEA H2 European Workshop
Hydrogen Safety: Prospects for Hydrogen Technologies & Applications
September,14th 2017 – Hamburg, Germany

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