Grant agreement No: 325348

Deliverable Number – D3.1

International Curriculum on hydrogen safety training for First Responders

Status: final version

Dissemination level: PU – Public

Partner responsible for the deliverable: UU

Contributing partners: CCS, HELION (AREVA), ALAB

European Hydrogen Emergency Response training programme for First Responders

Authors:

Name[1]: **Svetlana Tretsiakova-McNally**
Name[1]: Vladimir Molkov
Name[2]: Randy Dey
Name[3]: Franck Verbecke
Name[4]: Adrien Zanoto

[1] Partner organisation: UU
[2] Partner organisation: CCS
[3] Partner organisation: HELION (AREVA)
[3] Partner organisation: ALAB

Author printed in bold is the contact person for this document.

Date of this document: 3 July 2015

File name: D3.1_International Curriculum on hydrogen safety training for First Responders_v7.0.doc

Document history

Revision	Date	Modifications made	Author(s)
	10.09.13	Outline of curriculum discussed	Svetlana Tretsiakova-McNally; Vladimir Molkov, Dmitriy Makarov
	19.12.13	Envisaged contents of sections and chapters discussed	Svetlana Tretsiakova-McNally; Vladimir Molkov, Dmitriy Makarov
V1.0	17.02.14	First draft produced and discussed with partners at a teleconference	Svetlana Tretsiakova-McNally
V2.0	07.03.14	Second draft	Svetlana Tretsiakova-McNally
V2.1	15.04.14	Template for curriculum circulated to partners (CCS and AREVA)	Svetlana Tretsiakova-McNally
V2.2	12.05.14	CCS provided its version of the table of contents and references to the 2nd section of the curriculum (RCS)	Randy Dey, Svetlana Tretsiakova-McNally
V3.0	20.05.14	Third draft	Svetlana Tretsiakova-McNally, Vladimir Molkov
V4.0	22.05.14	Fourth draft	Svetlana Tretsiakova-McNally, Vladimir Molkov
V4.1	23.05.14	AREVA provided a table of contents for the 3rd section of the curriculum	Franck Verbecke
V4.2	28.05.14	Modifications made following discussion of the draft at the progress meeting	Svetlana Tretsiakova-McNally, Vladimir Molkov
V5.0	12.06.14	Final version	Svetlana Tretsiakova-McNally, Vladimir Molkov
V6.0	22.06.15	The document modified following the mid-term review comments	Svetlana Tretsiakova-McNally
V7.0	03.07.15	ALAB provided a quality check of the revised version 6.0	Adrien Zanoto, Svetlana Tretsiakova-McNally

Table of Contents

INTRODUCTION **5**
AIM AND OBJECTIVES OF THE EDUCATIONAL TRAINING **5**
THE SCOPE OF THE INTERNATIONAL CURRICULUM (IC) **6**
TARGET AUDIENCE AND THEIR PRE-REQUISITES **6**
TABLE OF THE INTERNATIONAL CURRICULUM CONTENTS **6**
THE EXPECTED DURATION OF DELIVERY OF EACH SECTION DURING THE PILOT SESSIONS **8**
THE ENVISAGED CONTENT OF SECTIONS AND MODULES **9**
SECTION "BASICS OF HYDROGEN SAFETY FOR FIRST RESPONDERS" **10**

Module "Introduction to hydrogen safety for First Responders" **10**
- Overview of hydrogen production, storage, industrial and hydrogen energy usage 10
- Storage of gaseous hydrogen 10
- Liquefied hydrogen storage 10
- Fire resistance rating of hydrogen tanks 11
- Consequences of catastrophic failure of on-board storage (blast waves, fireballs etc) 11
- Solid storage of hydrogen 11
- FCH vehicles 11
- Hydrogen refuelling stations 11
- Hydrogen transportation 12
- Stationary FC applications 12
- Hydrogen-based energy storage systems 12
- Overview of incidents and accidents involving hydrogen 12
- Introduction to hydrogen safety engineering framework 12

Module "Properties of hydrogen relevant to safety" **12**
- Physical properties of hydrogen 12
- Combustion characteristics including flammability and detonability limits 13
- Comparison of hydrogen characteristics with those for other fuels 14

Module "Compatibility of hydrogen with different materials" **14**
- Interaction of hydrogen with metals 14
- Interaction of hydrogen with non-metallic, polymeric materials and gases 14
- Mitigation measures for hydrogen embrittlement and good practices 15

Module "Harm criteria for people and property" **15**
- Health hazards of hydrogen 15
- Thermal effects of fires on humans, structures and environments 15
- Pressure effects from explosions 15
- Comparison of harm criteria for unprotected and protected people (firemen) 15

Module "Unignited hydrogen releases outdoors and their mitigation" **15**
- Compressed hydrogen leaks 15
- Cryogenic leaks 16
- How to decrease a separation distance from a hydrogen release? 16
- Mitigation measures for unignited releases 16

Module "Ignition sources and prevention of ignition" **16**
- Ignition sources 16

Hydrogen ignition mechanisms 16
Spontaneous ignition of sudden releases 16
Prevention of ignition 17

Module "Separation from hydrogen flames and fire fighting" 17
Microflames 17
Jet fires and three separation distances 17
Effect of buoyancy on separation distances 18
Radiation heat fluxes from jet fires and fireballs 18
Liquefied hydrogen fires 18
Detection, mitigation and fire-fighting of hydrogen flames 18

Module "Dealing with hydrogen explosions" 18
Deflagrations and blast waves 18
Detonations and blast waves 19
Physical explosions and blast waves 20
Super-high overpressures during rapid phase transition (RPT) phenomenon 20
Possible mitigation measures for explosions 20

Module "Hazards of hydrogen use indoors and relevant mitigation techniques" 20
Hazards and associated risks for the use of hydrogen in enclosures 20
Permeation leaks 21
Indoor hydrogen releases and dispersion 21
Natural and forced ventilation 21
Pressure peaking phenomenon 21
Venting of hydrogen-air deflagrations 21
Regimes of indoor jet fires including phenomena of self-extinction and external flame 22
Hydrogen sensors and hydrogen fire detectors 22

SECTION "REGULATIONS, CODES AND STANDARDS (RCS) FOR FIRST RESPONDERS" 22

Module "Regulations, Codes and Standards (RCS) for First Responders" 22

SECTION "INTERVENTION STRATEGIES AND TACTIC FOR FIRST RESPONDERS" 22

Module "Intervention strategies and tactic for First Responders" 22

REFERENCES AND SOURCES 24
Essential reading list 24
Further reading 24

GLOSSARY 43

APPENDIX 1. SCHEDULE OF ONE WEEK COURSE ON HYDROGEN SAFETY TRAINING FOR FIRST RESPONDERS (AN EXAMPLE) 45

APPENDIX 2. INTERNATIONAL AND EUROPEAN RCS LIST RELEVANT TO HYRESPONSE 47

INTRODUCTION

This document describes the International Curriculum in Hydrogen Safety Training for First Responders (FRs) developed to address the task 3.1 set within Work Package 3 (WP3) "Development of educational training for assessing accident scene status and decision making" of the HyResponse project. European Hydrogen Safety Training Platform (EHSTP) is the first comprehensive training programme for First Responders. EHSTP is a threefold training programme and will be implemented through: educational training, operational training on mock-up real-scale transport and hydrogen stationary installations, and innovative virtual training exercises reproducing the entire accidental scenarios.

The International Curriculum (IC) on hydrogen safety training for First Responders (FRs) is a foundation for the development of educational training programme for FRs. It will serve as a basis for the development of teaching materials in: basics of hydrogen safety (task 3.2); regulations, codes and standards (task 3.3) and intervention strategies and tactics (task 3.4) for FRs. The draft of the developed curriculum was presented and discussed at the first meeting of the Steering Group. The IC presented in this document is developed to the maximum degree of detail possible at the moment and reflects the state-of-the-art in hydrogen safety science and engineering. Educational materials in their intermediate and final forms will be prepared in month 21 (D3.2; D3.4; D3.6) and month 36 (D3.3; D3.5; D3.7) of the project, respectively.

Aim and objectives of the educational training

The *aim* of the educational segment of EHSTP is for FRs to acquire a professional knowledge and an understanding of hydrogen properties, phenomena and the main principles of hydrogen safety with the view to contribute to FCH permitting process as an approving authority and to implement safe fire-fighting functions at a scene of an incident/accident. The educational training will provide FRs with the fundamental knowledge as well as deep understanding of principles of hydrogen safety prior to the operational and virtual reality exercises.

The *objectives* of educational training are:

- to provide FRs with an awareness, knowledge and understanding of the specificities of hydrogen as a new vector of energy carrier during its production, transportation, delivery and uses;
- to familiarise FRs with the operational principles and safety aspects of a range of FCH applications including FC vehicles, refuelling stations, materials handling, back-up power generation and stationary fuel cell systems for combined production of heat and power, etc (linked to WP2);
- to develop in FRs a critical awareness of safety issues associated with hydrogen physical, chemical and combustion properties and to achieve a systematic understanding of why the safety of hydrogen differs from that of conventional fuels;
- to provide FRs with a knowledge of potential hazards, relevant safety concepts and safety features for targeted FCH systems and infrastructure;
- to introduce FRs to typical risk scenarios and to instruct them on the correct way of intervention and tactics on how to deal with potential consequences of incidents/accidents that may occur at FCH systems and infrastructure;

- to develop in FRs an ability to recognise and professionally deal with hazardous phenomena involving unwanted hydrogen releases (e.g. leaks), hydrogen fires and explosions by applying the principles of hydrogen safety engineering;
- to provide FRs with an analysis of hydrogen safety approaches and requirements defined in Regulations, Codes and Standards (RCS) related to FCH systems and relevant to the appropriate actions to be taken by FRs;
- to provide FRs with a clear picture of the safety requirements prescribed in RCS with respect to mitigation measures; assessment of the incident/accident scenes; safety strategies for the operation of FRs at the scene of an accident.

The scope of the International Curriculum (IC)

The scope of the IC is very wide as it is anticipated that this document will be used by interested organisations to address their own training needs (e.g. to organise 1-2 day training, a week or even for one semester), depending on their training needs and requirements. The potential users of the curriculum can select, mix and match the sections/modules/sub-topics of the current document to tailor their own courses.

Target audience and their pre-requisites

The *target audience* of EHSTP are the European FRs. However any other interested stakeholders (e.g. policy-/decision-makers, site operators, industry representatives, scholars, academics, and members of the public) will have access through the website to all the educational materials developed during the project. During three pilot sessions FRs will be taught and trained practically how to deal with incidents and/or accidents involving FCH systems and infrastructure. There are no special pre-requisites necessary to understand the teaching materials - the educational materials will be tailored and presented in a format suitable for an easy comprehension by a wide audience and by the different categories of FRs.

Table of the International Curriculum contents

The teaching materials will consist of three core sections: Basics of Hydrogen Safety for FRs; Regulations, Codes and Standards for FRs; Intervention Strategies and Tactics for FRs. The first section on Basics of Hydrogen Safety includes the following themes: overview of FCH applications, infrastructure and uses; specific safety issues related to hydrogen storage; overview of incidents/accidents involving hydrogen; basic properties and behaviour of hydrogen (including combustion); comparison of hydrogen behaviour to that of other common fuels; compatibility and interactions of hydrogen with different substances; hazards and risks associated with hydrogen; hydrogen releases; ignition of hydrogen-oxidizer mixtures; hydrogen flames; hydrogen releases indoors; explosions and blast waves; prevention, mitigation and fire-fighting techniques. The table of the IC content is shown in Table 1 below.

Table 1. The content of the IC

SECTION "BASICS OF HYDROGEN SAFETY FOR FIRST RESPONDERS"
Module "Introduction to hydrogen safety for First Responders" Overview of hydrogen production, storage, industrial and hydrogen energy usage. Storage of gaseous hydrogen. Liquefied hydrogen storage. Fire resistance rating of hydrogen tanks. Consequences of catastrophic failure of on-board storage (blast waves, fireballs etc). Solid storage of hydrogen. FCH vehicles. Hydrogen refuelling stations. Hydrogen transportation. Stationary FC applications. Hydrogen-based energy storage systems. Overview of incidents and accidents involving hydrogen. Introduction to hydrogen safety engineering framework.
Module "Properties of hydrogen relevant to safety" Physical properties of hydrogen. Combustion characteristics including flammability and detonability limits. Comparison of hydrogen characteristics with those for other fuels.
Module "Compatibility of hydrogen with different materials" Interaction of hydrogen with metals. Interaction of hydrogen with non-metallic, polymeric materials and gases. Mitigation measures for hydrogen embrittlement and good practices.
Module "Harm criteria for people and property" Health hazards of hydrogen. Thermal effects of fires on humans, structures and environments. Pressure effects from explosions. Comparison of harm criteria for unprotected and protected people (firemen).
Module "Unignited hydrogen releases outdoors and their mitigation" Compressed hydrogen leaks. Cryogenic leaks. How to decrease a separation distance from a hydrogen release? Mitigation measures for unignited releases.
Module "Ignition sources and prevention of ignition" Ignition sources. Hydrogen ignition mechanisms. Spontaneous ignition of sudden releases. Prevention of ignition.
Module "Separation from hydrogen flames and fire fighting" Microflames. Jet fires and three separation distances. Effect of buoyancy on separation distances. Radiation heat fluxes from jet fires and fireballs. Liquefied hydrogen fires.

Detection, mitigation and fire fighting of hydrogen flames. Module "Dealing with hydrogen explosions" Deflagrations and blast waves. Detonations and blast waves. Physical explosions and blast waves. Super-high overpressures during rapid phase transition (RPT) phenomenon. Possible mitigation measures for explosions. Module "Hazards of hydrogen use indoors and relevant mitigation techniques" Hazards and associated risks for the use of hydrogen in enclosures. Permeation leaks. Indoor hydrogen releases and dispersion. Natural and forced ventilation. Pressure peaking phenomenon. Venting of hydrogen-air deflagrations. Regimes of indoor jet fires including phenomena of self-extinction and external flame. Hydrogen sensors and hydrogen fire detectors.
SECTION "REGULATIONS, CODES AND STANDARDS (RCS) FOR FIRST RESPONDERS" Module "Regulations, Codes and Standards (RCS) for First Responders"
SECTION "INTERVENTION STRATEGIES AND TACTIC FOR FIRST RESPONDERS" Module "Intervention strategies and tactic for First Responders".
References Essential reading list. Further reading.
Glossary
Appendix 1. A schedule of one week course on hydrogen safety training for First Responders (an example)
Appendix 2. International and European RCS list relevant to HyResponse.

The expected duration of delivery of each section during the pilot sessions

Three training sessions will be organised and delivered during the face-to-face pilot training of a group of FRs from Europe. Each pilot training session will last 5 working days (i.e. 1 week). The educational training in basics of hydrogen safety, in RCS, and in intervention strategies and tactics will be delivered in advance of the operational and virtual exercises each day. It will mostly take place during morning classes and will last up to 16 hours in total for the entire week to cover all three sections. An example of the training programme for the first training session is shown in the Appendix 1 of this document (this could be re-formatted for the second and third training sessions following a feedback from the trainees of the first session). The first section, basics of hydrogen safety for Frs, consists of nine modules and the expected delivery time during the pilot training will be 8.5-9.0 hours. The second section containing one module is devoted to the RCS and requirements to FCH systems relevant to FRs. It is estimated that between 1.0 and 1.5 hours will be needed to deliver the envisaged content of the second section. The third section consists of one module and

covers the typical accident scenarios for selected FCH applications; relevant emergency response strategies and tactics; rescue operations. The expected duration of this section during the pilot training is between 5.0 and 5.5 hours. The content and structure of teaching materials for pilot sessions could differ from the content of the IC proposed in this document. This is due to a limited time assigned to the delivery of the teaching materials during only one week of face-to-face training (see Appendix 1). In addition, the feedback received from the trainees after each pilot session will be taken into account and both the IC and the educational materials could be modified afterwards.

The envisaged content of sections and modules

The envisaged content of the IC sections and modules as well as the list of references is shown below in the present document.

SECTION "BASICS OF HYDROGEN SAFETY FOR FIRST RESPONDERS"

Module "Introduction to hydrogen safety for First Responders"

Overview of hydrogen production, storage, industrial and hydrogen energy usage

Natural occurrence of hydrogen [BRHS, 2007]. Main methods of hydrogen production [Horwitz, 2009a]. Electrolysis of water [Grigoriev, 2010; Janssen et al, 2004]. Complex metal hydrides for production and storage of hydrogen [Klebanoff, 2012]. Reforming technologies [Sørensen, 2005]. Nuclear methods of hydrogen production [Klebanoff, 2012]. Hydrogen production methods using renewable energy: photochemical, biological and microbiological routes [Klebanoff, 2012]. Overview of hydrogen storage technologies [Klebanoff, 2012; Horwitz, 2009b; DoE targets, 2009; Risø Energy Report 3, 2004]. Volumetric and gravimetric capacities: targets [Ross, 2006; DoE targets, 2009]. Typical compressed hydrogen storage systems [GTR, 2013]. Gaseous hydrogen storage in racks [HyResponse Deliverable D2.1, 2014]. Liquid hydrogen storage systems [GTR, 2013]. Cryo-compressed hydrogen storage [Aceves et al, 2013]. Safety features of hydrogen storage options [Vieira et al, 2007; Klebanoff, 2012; DoE targets, 2009]. Uses of hydrogen in: petroleum and chemical industries; aerospace applications; manufacturing of pharmaceutical products; production of ammonia; semiconductor industry; welding [Klebanoof, 2012; Ogden, 2004]. Hydrogen as a reducing agent (recovery of metals from ores; organic synthesis) and as a coolant in power generation. Hydrogen as an energy carrier [FCIR, 2012, 2012; CFCP, 2014; FCIR, 2012; Ogden, 2004]. Hydrogen for heat and power in buildings [Ogden, 2004]. Inherently safer design of hydrogen and fuel cell systems [Rygas and Amiotte, 2013].

Storage of gaseous hydrogen

Compressed gaseous hydrogen (CGH2) storage [Klebanoff, 2012; Reijerkerk, 2009; BRHS, 2007; Barthelemy, 2011b]. Types of tanks for CGH2 storage [Horwitz, 2009b; Barthelemy, 2009; Barthelemy, 2011b]. Type I and II vessels [Horwitz, 2009b; Barthelemy, 2009]. Design and main characteristics of type III and IV vessels for on-board CGH2 storage [BRHS, 2007; Horwitz, 2009b; Gaseous and liquid hydrogen storage, US DoE]. Nominal Working Pressure (NWP) [Klebanoff, 2012; GTR, 2013]. Materials used for on-board hydrogen storage tanks [Horwitz, 2009b; BRHS, 2007]. Carbon reinforced epoxy resin [Klebanoff, 2012]. Testing of hydrogen tanks [GTR, 2013]. Behaviour of tanks in fire conditions [GTR, 2013]. Thermally and pressure activated pressure release devices (TPRD and PRD) [Malek, 2006; GTR, 2013]. Types of PRDs [Malek, 2006]. Safety issues of gaseous storage [Suzuki et al, 2006]. 'Blistering' of polymeric liner [Sunderland, 2010b]. Heating effects during filling [Sunderland, 2010b; SAE J2601, 2010; Galassi et al, 2011]. Effect of filling orientation on a vessel failure [Faudou et al, 2005; Barral et al, 2004].

Liquefied hydrogen storage

Storage for liquefied hydrogen (LH2) [Woods, 2008; Verfondern, 2007; Verfondern and Dienhart, 2007; Pritchard and Rattigan, 2010]. Tanks for LH2 storage [Horwitz, 2009b; Gaseous and liquid hydrogen storage, US DoE]. Boil-off phenomenon [Aceves et al, 1998; Sherif et al, 1997]. Enriched oxygen atmosphere formation at failure of external tank wall [Rybin et al, 2005]. Safety issues of LH2 storage: evaporation due to conversion heat release [NASA, 1997]. Potential hazard due to naturally occurring deuterium [NASA, 1997]. Spills of LH2 [Verfondern and Dienhart, 2007; Verfondern et al, 2004; Chitose et al, 2002; Chirivella and Witcofsky, 1986; Royle and Willoughby,

2012]. Cryogenic capable pressure vessels [Aceves et al, 1998; Aceves et al, 2006; Aceves et al, 2010; Aceves, 2011; US DOE, 2006; Aceves et al, 2013]. Effect of ortho- to para-hydrogen conversion heat on the reduction of boil-off phenomenon [Lanz et al, 2001; Aceves, 2011].

Fire resistance rating of hydrogen tanks

Effects of fire on high-pressure full composite hydrogen storage tanks. Vehicle bonfire tests [Stephenson, 2005; GTR, 2013; Ruban et al, 2011; Ruban et al, 2012]. Bonfire test with a diffusion box [Hirose et al, 2010]. Fire resistance of CGH2 and LH2 storage vessels [Stephenson, 2005; Ruban et al, 2011; Rybin et al, 2005; GTR, 2013]. Safety of hydrogen storage vessels in fire conditions [GTR, 2013]. Fire protection of hydrogen storage tanks [Gambone and Wong, 2007; Klebanoff, 2012; EPSRC project, 2013; PCT application, 2011].

Consequences of catastrophic failure of on-board storage (blast waves, fireballs etc)

Catastrophic failure of a hydrogen storage tank [Weyandt, 2005; Weyandt, 2006; Weyandt, 2007; Zalosh and Weyandt, 2005; Zalosh, 2007]. Generation of blast waves and fireballs [Zalosh, 2007].

Solid storage of hydrogen

Storage of hydrogen in advanced materials [Klebanoff, 2012; Hydrogen Storage Materials Database; Risø Energy Report 3, 2004]. Chemical and metal hydrides [Risø Energy Report 3, 2004; McPhy Energy, 2014]. Pyrophoric materials [Tanaka et al, 2009; Hydrogen Storage Materials Database]. Risk of explosion [Tanaka et al, 2009]. Heat management [Risø Energy Report 3, 2004]. Toxicity [Sakintuna et al, 2007; Khalil, 2011]. Sorbents [Horwits, 2009]. Carbon-based structures: carbon nanotubes, buckyballs; charred chicken feathers [Carbon-based materials; Hydrogen Storage Materials Database; The nanotube site]. Physical storage of hydrogen in capillary systems [Kohli et al, 2008; Zhevago et al, 2010; Ryazantcev and Chabak, 2006]. Multi-component hydrogen storage systems [Walker, 2008].

FCH vehicles

Hydrogen-powered passenger vehicles [FCIR, 2012]. Internal combustion engine (ICE) vehicles [Rigas and Amyotte, 2013]. Vehicles powered by alternative fuel: electric; hybrid and FCH vehicles [CFCP, 2014]. Hydrogen combustion engine [CEP, 2014]. Fuel Cell (FC)/Electric propulsion vehicles [CEP, 2014; CFCP 2014]. Comparison of FCH vehicle with conventional and electric vehicles [CEP, 2014; Rigas and Amyotte, 2013; CFCP, 2014]. Key elements of a typical FCH vehicle [GTR, 2013; EU No 406/2010]. Hydrogen fuelling systems [GTR, 2013]. On-board hydrogen storage [GTR, 2013]. Hydrogen delivery systems [GTR, 2013]. Components of a Fuel Cell (FC) system [GTR, 2013; FCTO, 2014]. Definition of a Fuel Cell (FC) [CEP, 2014; FCTO, 2014]. Proton Exchange Membrane (PEM) [CEP, 2014; FCTO, 2014]. Main principle of electricity production by FC [CEP, 2014; FCTO, 2014]. FC stacks [FCTO, 2014]. Electric propulsion and power management systems [GTR, 2013]. Main hazards associated with FCH vehicles [Rigas and Amyotte, 2013; Perrette et al, 2007; Gentilhomme et al, 2011]. Possible failure modes in FCH vehicles [Rigas and Amyotte, 2013]. FCH speciality vehicles: forklifts and pallet tracks [FCIR, 2012; HyResponse Deliverable D2.1, 2014]. Hydrogen-powered buses [HyFLEET: CUTE, 2014; AC Transit, 2014]. Two- and three-wheeled vehicles [FCIR, 2012]. Other types of FCH transport (trains, trams, ferries, boats, planes etc) [FCIR, 2012].

Hydrogen refuelling stations

Refuelling infrastructure [CFCP, 2014; FCIR, 2012]. Refuelling stations for buses and cars [AirProducts, 2014a; HyResponse Deliverable D2.1, 2014]. Refuelling stations for forklifts [Air

Liquide]. Safe filling procedures [Faudou et al, 2005; McDougal and Horacek, 2007; Schneider et al, 2007]. Safety of hydrogen refuelling stations [Shirvill et al, 2006; Shirvill et al, 2007; Tanaka et al, 2007; Makarov et al, 2009].

Hydrogen transportation

Distribution and transportation of hydrogen [HyResponse Deliverable D2.1, 2014; BRHS, 2009; CEP, 2014; FCTO, 2014; AC Transit, 2014; Reijerkerk, 2009]. Gaseous and liquefied hydrogen trailers/trucks [BRHS, 2009; Reijerkerk, 2009; Barthelemy, 2008; Hake et al, 2006]. Pipelines [Gillette and Kolpa, 2007; Airliquide, 2014; Gupta, 2010; Hake at al, 2006].

Stationary FC applications

Combined Heat and Power (CHP) generation [HyResponse Deliverable D2.1, 2014; Ogden, 2004; Stolten, 2010; FCIR, 2012; Maeda et al, 2010]. Uninterruptible power systems (UPS) [FCIR, 2012]. Primary power units [FCIR, 2012]. Back-up systems [AirProducts, 2014b]. Auxiliary Power Units (APU) [Ogden, 2004; FCIR, 2012].

Hydrogen-based energy storage systems

Greenenergy Box as an example of hydrogen energy storage system [HyResponse Deliverable D2.1, 2014]. MYRTE platform [HyResponse Deliverable D2.1, 2014]. Example of intervention map for fire and rescue services [HyResponse Deliverable D2.1, 2014].

Overview of incidents and accidents involving hydrogen

Databases of incidents and accidents involving hydrogen; lessons learned [H2 Incidents; HIAD]. Statistics of incidents for hydrogen releases and ignitions [Astbury and Hawksworth, 2007]. Selected case studies [H2 Incidents]. Hydrogen leak from on-board storage system of a FC lift track [H2 Incidents]. Ball of fire from HFC forklift flashes and quickly extinguishes [H2 Incidents]. HFC vehicle traffic accident [H2 Incidents]. Liquid hydrogen delivery track on fire [H2 Incidents]. Liquid hydrogen delivery track off-loading valve failure [H2 Incidents]. Near accident in a hydrogen compressor room [H2 Incidents]. Pressure relief device fails on a high-pressure storage tank [H2 Incidents]. Combustible hydrogen gas vapour ignites in a battery plant [H2 Incidents]. Liquid hydrogen tank incident causes the second incident [H2 Incidents]. Hydrogen cylinder leak at a fuelling station [H2 Incidents]. Burst of a fuelling hose [H2 Incidents]. Gasket failure in a PEM FC [H2 Incidents]. Explosion of hydrogen gas caused due to breakage of an external gas duct [JST database]. Pipe failure at a hydrogen production plant [H2 Incidents].

Introduction to hydrogen safety engineering framework

Hydrogen safety engineering framework [Molkov, 2012; Molkov and Saffers, 2013].

Module “Properties of hydrogen relevant to safety”

Physical properties of hydrogen

Atomic hydrogen [Molkov, 2012]. Hydrogen isotopes: protium, deuterium and tritium [Molkov, 2012]. Molecular hydrogen [Molkov, 2012; ISO/TR 15916, 2004]. Ortho- and para-hydrogen [NASA, 1997]. Equilibrium between ortho- and para-hydrogen [NASA, 1997]. Normal hydrogen [NASA, 1997]. Heat effect of the ortho-to para-hydrogen conversion [NASA, 1997]. Safety issues associated with the storage of liquefied hydrogen [Molkov, 2012; ISO/TR 15916, 2004; NASA, 1997]. Gaseous, liquefied and slush forms of hydrogen [Molkov, 2012]. Phase diagram of hydrogen [Molkov, 2012]. Sublimation curve, fusion curve, vaporisation curve [Molkov, 2012]. Triple point [NASA, 1997].

Critical point [Molkov, 2012]. Critical properties [Molkov, 2012]. Cryo-compressed gas [Molkov, 2012]. Normal boiling point and normal melting point of hydrogen [Molkov, 2012]. Safety issues associated with low boiling point of hydrogen [Molkov, 2012]. Liquid para-hydrogen [Molkov, 2012; ISO/TR 15916, 2004; NASA, 1997]. Safety issues associated with high density of saturated hydrogen vapour at low temperatures [Molkov, 2012; ISO/TR 15916, 2004; NASA, 1997]. Organoleptic properties of hydrogen: odour, colour, taste [Molkov, 2012; ISO/TR 15916, 2004; NASA, 1997]. Density of hydrogen [Molkov, 2012]. Buoyancy of hydrogen [Molkov, 2012; BRHS, 2009]. Heat of vaporization (condensation); heat of melting (fusion); heat of sublimation [Molkov, 2012]. Hydrogen expansion ratio [Molkov, 2012; ISO/TR 15916, 2004]. Diffusivity of hydrogen [Alcock et al, 2001; Baratov et al, 1990; Yang et al, 2011]. Viscosity of hydrogen [BRHS, 2009]. Specific heat and specific heat ratio [Molkov, 2012; ISO/TR 15916, 2004; BRHS, 2009]. Thermal conductivity [Molkov, 2012]. Joule-Thompson inversion temperature [Molkov, 2012]. Ideal and real gas equations [Molkov, 2012]. The Abel-Noble equation of state [Molkov, 2012; Chenoweth, 1983]. Speed of sound in gaseous and liquid hydrogen [Molkov, 2012; BRHS, 2009]. Solubility of hydrogen in metallic materials [Molkov, 2012; Barthelemy, 2006; Cotton and Wilkinson, 1999]. Hydrogen embrittlement [NASA, 1997; Barthelemy and Allidieres, 2005; Rogante et al, 2006].

Combustion characteristics including flammability and detonability limits

Combustion process definition [Warnatz et al, 2006]. Combustion (fire) triangle [Crowl, 2003]. Diffusion and turbulent non-premixed flames [Hottel and Hawthorne, 1949; Hawthorne et al, 1949; Turns, 2000; Kuo, 2005]. Premixed and partially premixed flames [Turns, 2000; Peters, 2000; Warnatz et al, 2006]. Flash fires [Law, 2006a]. Jet fires [Molkov, 2012; Law, 2006b]. Pre-mixed combustion modes: deflagration and detonation [Molkov, 2012]. Hydrogen flame emissivity [ADL, 1960]. Adiabatic flame temperature [BRHS, 2009; Williams, 1985; Law, 2006b]. Stoichiometric mixture and equivalence ratio [Molkov, 2012]. Heat of combustion: lower and upper heats of combustion [Molkov, 2012]. Flammability diagram [BRHS, 2007]. Lower and upper flammability limits (LFL and UFL) [Molkov, 2012]. Flammability ranges for hydrogen-air and for hydrogen-oxygen mixtures [Molkov, 2012; Schroeder and Holtappels, 2005; Schroeder et al, 2005]. Effect of pressure on the flammability range [Schroeder and Holtappels, 2005; Schroeder et al, 2004]. Effect of flame propagation direction on UFL and LFLs [Benz et al, 1988; Houf and Schefer, 2007]. Dependence of flammability limits on the presence of diluents (including steam) [NASA, 1997; Coward and Jones, 1952; Lee and Berman, 1997; Kumar et al, 1983; Kumar, 1985; Marshall, 1985]. Effect of temperature on UFL and LFLs [Zabetakis, 1967; Lee and Berman, 1997; Eichert, 1992]. Flammability limits for hydrogen and other common fuels [Molkov, 2012; Kuchta, 1985]. Flammability limits of mixtures of hydrogen with hydrocarbons [Karim et al, 1985; Wierzba et al, 1986; Wierzba and Kilchyk, 2001; Wierzba and Wang, 2006; Wierzba and Ale, 2000]. Flash point, auto-ignition temperature and maximum experimental safe gap [Molkov, 2012; Baratov et al, 1990]. Minimum ignition temperature of hydrogen [Lee and Berman, 1997; Hayashi and Tsuboi, 2008]. Critical ignition kernel [Glassman and Yetter, 2008]. Minimum ignition energy of hydrogen [Molkov, 2012; Kuchta, 1985]. Ignition energy as a function of hydrogen concentration; pressure and temperature [Lee and Berman, 1997; BRHS, 2007; Lewis and von Elbe, 1987]. Limiting oxygen index (LOI) [Molkov, 2012; NASA, 1997]. Laminar burning velocity of hydrogen-air mixtures [Molkov, 2012; BRHS, 2009; Law, 2006a; Lamoureux et al, 2003]. Expansion coefficient of combustion products and flame propagation speed [Molkov, 2012; BRHS, 2009; Law, 2006a; Lamoureux et al, 2003]. Laminar burning velocity as a function of hydrogen concentration [Molkov, 2012; BRHS, 2009; Lamoureux et al, 2003; Zimont and

Lipatnikov, 1995; Tse et al, 2000; Ronney, 1990]. Hydrogen flames quenching [Molkov, 2012]. Quenching gap/distance [Molkov, 2012; ISO/TR 15916, 2004; Wionsky, 1972]. Detonability limits [Molkov, 2012; ISO/TR 15916, 2004; NASA, 1997; Alcock et al, 2001; Tieszen et al, 1986].

Comparison of hydrogen characteristics with those for other fuels

Comparison of the main physical parameters for hydrogen and other substances [Molkov, 2012; Weast and Astle, 1979; Butler et al, 2009]. Ignition properties and combustion characteristics of hydrogen compared to those of other fuels [Molkov, 2012; Lee and Berman, 1997; Butler et al, 2009**;** Sunderland, 2010a; Swain and Swain, 1992; College of Desert (CoD), 2001, Dryer et al, 2007; Austin and Shepherd, 2003; Griffiths and Barnard, 1995; Lewis and von Elbe, 1987].

Module “Compatibility of hydrogen with different materials”

Interaction of hydrogen with metals

Degradation and material properties [BRHS, 2007]. Stress and strain [BRHS, 2007]. Fatigue and fracture mechanics [BRHS, 2007]. Effect of hydrogen on different materials [Chatterjee et al, 2001; Barthelemy, 2011a; Rogante et al, 2006]. Hydrogen damage processes [Barthelemy, 2011a; HySafe, 2006]. Dry and wet corrosions [Barthelemy, 2011a]. Corrosion caused by impurities [Barthelemy, 2009]. Hydrogen embrittlement [Barthelemy, 2011a]. Internal and environmental hydrogen embrittlement [San Marchi and Somerday, 2007]. Phenomenology of hydrogen embrittlement [BRHS, 2007; HySafe, 2006]. Hydrogen reaction embrittlement [HySafe, 2006]. Hydride embrittlement [BRHS, 2007]. Blistering [BRHS, 2007]. Hydrogen attack [BRHS, 2007]. Effect of temperature, pressure and composition of a material [Barthelemy, 2006]. Shatter cracks, flakes, fish-eyes and micro-perforations [BRHS, 2007]. Porosity [BRHS, 2007]. Mechanisms of metal degradation by hydrogen embrittlement [BRHS, 2007; HySafe, 2006]. Low temperature embrittlement [Barthelemy, 2011a; BRHS, 2007; HySafe, 2006]. Thermal contraction and thermal gradient [BRHS, 2007; HySafe, 2006]. Suitability of materials for hydrogen service [ISO/TR 15916, 2004]. Cold stretching for cryogenic storage of hydrogen [Barthelemy, 2011b]. Test methods for hydrogen embrittlement [Barthelemy, 2006; Nibur and Somerday, 2012]. Parameters affecting hydrogen embrittlement in steels [Barthelemy, 2006]. Environmental parameters or operating conditions: hydrogen purity; hydrogen partial pressure; temperature; stress and deformation; exposure time [Barthelemy, 2006]. Design and surface condition [Barthelemy, 2006]. Microstructure and chemical composition of materials [Barthelemy, 2006]. Heat treatment and mechanical properties [Barthelemy, 2006]. Welding [Barthelemy, 2006]. Cold working (strain hardening) [Barthelemy, 2006]. Non-metallic inclusions [Barthelemy, 2006].

Interaction of hydrogen with non-metallic, polymeric materials and gases

Polymeric materials suitable for hydrogen high pressure vessels [Barthelemy, 2011b]. Risk of explosion and fire [Barthelemy, 2009]. Swelling of polymers [Barthelemy, 2011b]. Presence of impurities in the gas [Barthelemy, 2011b]. Violent reactions involving hydrogen [Barthelemy, 2011a]. Formation of dangerous products through chemical reactions [Barthelemy, 2011a]. Reactions of hydrogen with halogens [Cotton and Wilkinson, 1999]. Reaction of hydrogen with oxygen [Cotton and Wilkinson, 1999]. Interaction of hydrogen with nitrogen (ammonia production) [Cotton and Wilkinson, 1999]. Formation of metal hydrides [Cotton and Wilkinson, 1999]. Reactions of hydrogen with metal oxides and non-metal oxides (hydrogen as a powerful reducing agent) [Cotton and Wilkinson, 1999].

Mitigation measures for hydrogen embrittlement and good practices

Accidents and incidents caused by hydrogen embrittlement [H2 Incident reporting]. Mitigation of hydrogen embrittlement by the addition of vanadium and rare earth elements to ferric steel, or, Ni, C, and Mn to austenitic stainless steels [Barthelemy, 2011b; Somerday and San Marchi, 2008]. Mitigation of hydrogen attack: addition of Cr, Mo, To, W; heat treatment (stress relief treatment), level of stress (elimination of residual stresses by heat treatment) [Barthelemy, 2006].

Module “Harm criteria for people and property”

Health hazards of hydrogen

Odour and toxicity of hydrogen [Molkov, 2012; US DoE, 2008; NIO, 2013]. Health effects [NASA, 1997]. Gaseous hydrogen: oxygen depletion and asphyxiation [NASA, 1997]. Liquefied hydrogen: cryogenic burns, frostbite, hypothermia, lung damage from inhalation of cold vapour [NASA, 1997; US DoE, 2008]. Invisibility of hydrogen flames in daylights [NASA, 1997]. Effects of possible ignition, combustion and explosions of hydrogen [NASA, 1997; Molkov, 2012; US DoE, 2008]. Cuts caused by high pressure jets [BRHS, 2007].

Thermal effects of fires on humans, structures and environments

Thermal effects of hydrogen fires on people: hyperthermia; respiratory tract burns, body surface burns [LaChance et al, 2011; US DoE, 2008; BRHS, 2007; TNO Green Book, 1992; LaChance, 2010a; World Bank, 1988; LaChance, 2010b; IFC, 2006; NFPA 2002]. Time to incapacitation [US DoE, 2008; BSI, 1997]. ‘Harm’ and ‘no harm’ criteria for people [LaChance, 2010b]. Damage criteria for buildings, vehicles and people [BRHS, 2007; NFPA 55, 2010; NIO 2013].

Pressure effects from explosions

Impact of overpressure on people [NASA, 1997; LaChance, 2010b; Barry, 2003; Baker et al, 1983; Dorofeev et al, 1995; NIO, 2013]. Pressure effects on buildings: combination of overpressure and impulse [BRHS, 2007; Mercx et al, 1991]. Fragmentation and missile effects [BRHS, 2007]. Primary and secondary fragments [Mannan, 2005]. Drag-type and lifting type fragments [Mannan, 2005]. Impact effects, trajectories and impact conditions [Mannan, 2005]. Jet effects on fragment surface and missile propulsion [Molkov et al, 2003].

Comparison of harm criteria for unprotected and protected people (firemen)

Effect of radiant heat flux on unprotected people and first responders [World Bank, 1988; Lees, 1996; BSI, 2004; Pasman, 2006]. Effect of radiant heat flux on structures and environment [Lees, 1996; WRC, 2008; Tromp et al, 2003].

Module “Unignited hydrogen releases outdoors and their mitigation”

Compressed hydrogen leaks

Jet releases of compressed gaseous hydrogen [Molkov, 2012]. Sub-sonic, sonic and supersonic jets [Anderson, 1990; Bülent Yüceil and Volkan Ötügen, 2002]. Expanded, under-expanded and over-expanded jets [Molkov, 2012]. The under-expanded jet scheme [Molkov, 2012]. Momentum-controlled jets, transitional jets and buoyancy-controlled jets [Molkov, 2012]. Concentration decay in momentum controlled jets [Molkov, 2012; Molkov, 2009]. Main safety requirement for unignited releases [Molkov, 2012; Chen and Rodi, 1980; NFPA 55, 2010; IFC, 2006]. The nomogram for calculation of a separation distance from unignited releases [Molkov, 2012]. Effect of the jet attachment on the separation distance [Hourri et al, 2009; Hourri et al, 2011; Royle and Willoughby,

2009]. Blow-down of compressed hydrogen storage tank [Roberts et al, 2006; Molkov et al, 2009; Schefer et al, 2007; Brennan and Molkov, 2011]. Behaviour of round and plane jets [Molkov et al, 2010; Makarov and Molkov, 2013; Pope, 2008].

Cryogenic leaks

The releases of liquid hydrogen [Witcofsky and Chirivella, 1984; Chitose et al, 2002; Molkov et al, 2005]. Formation of hydrogen cloud [Witcofsky and Chirivella, 1984; Chitose et al, 2002]. Releases from storage tanks and pool spreading [Fay, 2003; Verfondern and Dienhart, 1997; Verfondern and Dienhart, 2007]. Pool boiling [Verfondern and Dienhart, 2007; Gottfried et al, 1966].

How to decrease a separation distance from a hydrogen release?

Separation distance for vertical, horizontal and downward releases [Houf and Schefer, 2008; Shevyakov et al, 1980]. Reduction of separation distance by buoyancy [Molkov, 2012; Shevyakov et al, 1980; Shevyakov and Savelieva, 2004; Molkov et al, 2010]. 'Safe' PRD diameter [Molkov, 2012].

Mitigation measures for unignited releases

Prevention of hydrogen leaks and formation of flammable mixtures [BRHS, 2007]. Detection of hydrogen leaks [BRHS, 2007; ISO, 2004]. Differential pressure flow meters [BRHS, 2007]. Use of a flow restrictor in a pipeline for hydrogen supply [Molkov, 2012]. Inability to use odorants to detect hydrogen leaks [Hall, 2010].

Module "Ignition sources and prevention of ignition"

Ignition sources

Electric sparks (static charges, short circuiting, fuse tripping, contactors) [BRHS, 2007; Glassman and Yetter, 2008]. Mechanic sparks (grinding, impact) [Hawksworth et al, 2004; Hawksworth et al, 2005; Hawksworth, 2011]. Light (laser/flash) [Gelfand et al, 2008]. Hot surfaces [Lee and Berman, 1997; Stamps and Berman, 1991; Tamm et al, 1987]. Ignition by catalytic surface [Cho and Law, 1986; Verfondern et al, 2004; Brady et al, 2010]. Ignition by hot jets [Lee and Berman, 1997; Gelfand et al, 2008; Zabetakis, 1956; Shepherd, 1985]. Adiabatic compression (pressure increase) [Pan et al, 1995; Jiang et al, 1997]. Ignition by shock wave focusing [Gelfand et al, 2008]. Electrified particulates [Merilo, 2010].

Hydrogen ignition mechanisms

Ignition and reverse Joule-Thomson effect [Molkov, 2012]. Electrostatic charge generation [Astbury and Hawksworth, 2007]. Sparks from isolated conductors [Astbury and Hawksworth, 2007]. Brush discharges [Astbury and Hawksworth, 2007; Gibson and Harper, 1988; Ackroyd and Newton, 2003]. Corona discharges [Astbury and Hawksworth, 2007; Cross and Jean, 1987]. Diffusion mechanism of hydrogen ignition [Molkov, 2012; Wolanski and Wojcicki, 1972]. Sudden adiabatic compression [Astbury and Hawksworth, 2007; Pan et al, 1995; Cain, 1997].

Spontaneous ignition of sudden releases

Pressure limits of spontaneous ignition of hydrogen sudden releases into air [Molkov, 2012]. Dynamics of spontaneous hydrogen ignition – physical mechanism [Molkov, 2012; Bragin and Molkov, 2011; Bragin et al, 2011; Xu and Wen, 2011]. Effect of membrane or valve opening rate on the spontaneous ignition of high pressure hydrogen release [Xu et al, 2009; Bragin and Mokov, 2010]. Effect of burst disk shape on hydrogen ignition [Lee and Jeung, 2009]. Mechanism of flame separation by vortex [Molkov, 2012; Mogi et al, 2008; Bragin and Molkov, 2009; Bragin and Molkov,

2011]. Lower pressure limits for spontaneous ignition in a T-shape PRD [Bragin and Molkov, 2009; Bragin and Molkov, 2011; Bragin et al, 2011]. Dynamics of temperature and hydrogen mole fraction at an initial stage of hydrogen release into air [Molkov, 2012; Bragin et al, 2011]. Critical conditions for spontaneous ignition by the shock wave reflection [Molkov, 2012; Bragin et al, 2011]. Effect of storage pressure on a spontaneous ignition in a T-shape channel [Molkov, 2012; Golub et al, 2010].

Prevention of ignition

Prevention and control of ignition sources [HSE, 2012; Nolan, 1999; CoA, 2006; Daycock and Rew, 2004; Lees, 1996; Worsell, 1996; Leroux, 2012; CENELEC, 2003].

Module "Separation from hydrogen flames and fire fighting"

Microflames

Typical flow rates [Molkov, 2012; SAE J2579; Butler et al, 2009]. Quenching and blow-off limits [Molkov, 2012; Sunderland, 2010a; Lecoustre et al, 2010; Baker et al, 2002; Cheng et al, 2006]. Round burners [Butler et al, 2009; Lee et al, 2003]. Quenching limit and round burner type [Butler et al, 2009]. Pressure dependence of quenching diameters [Molkov, 2012]. Leaky fittings [Molkov, 2012; Sunderland, 2010a; Butler et al, 2009; Ge and Sutton, 2006].

Jet fires and three separation distances

Introduction to hydrogen fires and associated safety issues [Molkov, 2012]. Main terminology: jets; plumes; subsonic, sonic (choked) and supersonic jets; expanded and under-expanded jets [Molkov, 2012]. Dimensionless numbers: Froude number (Fr); Reynolds number (Re); Mach number (M) [Molkov, 2012]. Laminar diffusion flames [Molkov, 2012; Hottel and Hawthorne, 1949; Hawthorne et al, 1949; Turns, 2000; Mogi and Horiguchi, 2009]. Momentum-dominated and buoyancy-controlled jets [Molkov et al, 2010; Shevyakov and Savelieva, 2004]. Turbulent non-premixed flames [Molkov, 2012; Hottel and Hawthorne, 1949; Hawthorne et al, 1949; Turns, 2000]. Jet fire parameters: temperature, visibility, flame length, flame shape, radiation [Wen, 2006; Houf and Schefer, 2007]. Definition of flame length [Molkov et al, 2010; Molkov and Saffers, 2011; Molkov and Saffers, 2013]. Dependences of jet flame length on Reynolds and Froude numbers [Baev et al, 1974; Shevyakov and Komov, 1977; Becker and Liang, 1978; Delichatsios, 1993]. Infrared, visible and ultraviolet emissions and flame lengths [Schefer et al, 2004; Schefer et al, 2004]. Length to width ratio of jet fires [Houf and Schefer, 2007; Turns and Myhr, 1991]. Relationship between the flame length, the nozzle diameter and mass flow rate [Molkov, 2012; Lewis and von Elbe, 1987; Kalghatgi, 1984; Poinsot and Veynante, 2001]. Dimensional correlation for hydrogen jet flame length [Molkov, 2012]. The nomogram for graphical flame estimation [Molkov, 2012]. Universal dimensionless correlation for hydrogen jet flame length [Molkov and Saffers, 2013]. Flame blow-out and lift-off phenomena [Kalghatgi, 1981a; Kalghatgi, 1981b; Kalghatgi, 1984; Cheng and Chiou, 1998]. Dependence of lift-off height on flow velocity [Kalghatgi, 1981a; Annushkin and Sverdlov, 1979]. Independence of lift-off height on nozzle diameter [Kalghatgi, 1984]. A jet blow-off phenomenon [Molkov, 2012; Mogi and Horiguchi, 2008]. Flame blow-off pressure for different nozzle diameters [Mogi and Horiguchi, 2008; Okabayashi et al, 2007]. Separation distances for hydrogen jet fires [Molkov, 2012; HyIndoor WP 4 final report]. Jet fire hot current for momentum-dominated and buoyancy-controlled flows [Imamura et al, 2008; Saffers, 2010]. Effect of jet attachment on the separation distance [Willoughby and Royle, 2009]. Location of a hydrogen flame tip [Molkov, 2012; Saffers, 2010; Molkov et al, 2010]. Equivalent unignited hydrogen jet concentration and flame length [Molkov et al, 2010; Saffers,

2010]. Effect of ignition source location on the jet flame propagation upstream and downstream [Veser et al, 2009]. Effect of nozzle shape on a flame length [Molkov, 2012]. Jet flame elongation due to the wall/ground attachment phenomenon [Molkov, 2012; Willoughby and Royle, 2009]. Pressure effects of hydrogen jet fires [Molkov, 2012]. Ignition delay [Molkov, 2012; Royle and Willoughby, 2009; Takeno et al, 2007; Royle and Willoughby, 2009]. Delayed ignition of non-premixed turbulent jets [Takeno et al, 2007; Royle and Willoughby, 2009]. Effect of an ignition source location on the delay of ignition [Molkov, 2012]. Effect of an orifice diameter on overpressure [Molkov, 2012].

Effect of buoyancy on separation distances

Effect of buoyancy on reduction of the separation distance [Molkov, 2012; Shevyakov et al, 1980; Shevyakov and Savelieva, 2004; Molkov et al, 2010].

Radiation heat fluxes from jet fires and fireballs

Formation of a fireball [Zalosh, 2007; Zalosh and Weyandt, 2005; Rigas and Amyotte, 2013]. Boiling liquid expanding vapour explosion (BLEVE) [Rigas and Amyotte, 2013]. Fireball characteristics [Harstad and Bellan, 2006; Lowesmith and Hankinson, 2013; Venetsanos et al, 2003]. Radiation from hydrogen jet fires [Saffers, 2010]. Radiative heat flux [Schefer et al, 2006; Molina et al, 2007]. Air temperature rise due to jet fire [Saffers, 2010; LaChance, 2010b]. Effect of radiative heat fluxes on the separation distances [Houf and Schefer, 2007; NFPA 55, 2010; Schefer et al, 2006; Saffers, 2010; Molina et al, 2007; Sivathanu and Gore, 1993]. Distribution of radiative heat flux for hydrogen jet fires [Schefer et al, 2006; Saffers, 2010; Molina et al, 2007]. Effect of radiant heat flux on structures and environment [Lees, 1996; WRC, 2008; Tromp et al, 2003].

Liquefied hydrogen fires

Liquefied hydrogen fires [Verfondern, 2008; Verfondern and Dienhart, 1997; Verfondern and Dienhart, 2007; Gottfried et al, 1966; Kreith and Bohn, 2001]. Thermal radiation from liquefied hydrogen fires [Burgess et al, 1961; Burgess and Hertzberg, 1974; McGratten et al, 2000]. Data correlation of hydrocarbon and cryogenic pool fires [Zabetakis and Burgess, 1961].

Detection, mitigation and fire-fighting of hydrogen flames

Detection of hydrogen flames [BRHS, 2007]. UV detectors [BRHS, 2007]. IR detectors [BRHS, 2007]. Thermal detectors [BRHS, 2007]. Imaging systems [BRHS, 2007]. Limitation to use hydrogen sensors outdoors [BRHS, 2007]. Use of thermal imaging devices [DEMA, 2012; NIO, 2013]. Separation distances based on hydrogen flame length [Molkov, 2012; US DoE, 2008; BSI, 2004]. The use of walls (or barriers) in mitigation hydrogen jet fires [Schefer et al, 2011; Willoughby and Royle, 2009; Willoughby and Royle, 2011; Schefer et al, 2009; Houf et al, 2011]. Effect of barrier wall on the delayed ignition of hydrogen jet [Molkov, 2012; Houf et al, 2010; Schefer et al, 2009]. Extinction of diffusion flames [Molkov, 2012; Creitz, 1961]. Extinguishment of hydrogen fires [DEMA, 2012; NIO, 2013].

Module “Dealing with hydrogen explosions”

Deflagrations and blast waves

Terminology and definitions: physical explosions, gaseous deflagrations and detonations [Molkov, 2012]. General features of deflagrations [Molkov, 2012]. Laminar, cellular and turbulent flames [Gelfand et al, 2008; BRHS, 2007]. Hydrogen-air deflagrations in the open atmosphere [Molkov, 2012]. The largest hydrogen-air deflagration test in atmosphere [Pförtner and Schneider, 1983].

Flame propagation and flame acceleration [Molkov, 2012; Bradley et al, 2001]. Positive and negative phases of the pressure wave [BRHS, 2007; Molkov et al, 2006a]. Deflagrations in closed vessels [Molkov, 2012]. Relationship between explosion severity and flame propagation parameters [Bradley and Mitcheson, 1976]. Pressure and temperature dependence of explosion severity parameters [Bradley and Mitcheson, 1976]. Dynamics of flame front propagation [Grossel, 2002; Tse et al, 2000; Bradley et al, 2000; Law, 2006; Bradley, 1992; Bradley et al, 1994]. Flame induced flow [Grossel, 2002]. Flame instabilities and flame wrinkling [Tse et al, 2000; Bradley et al, 2000; Law, 2006]. Effect of turbulence on flame propagation [Law, 2006; Bradley, 1992; Bradley et al, 1994]. Prediction of pressure build-up in closed space [Molkov et al, 2004a]. Deflagrations in a system of connected vessels: pressure piling effect [Abdullin et al, 1988]. The Le Chatelier-Brown principle analogue for vented deflagrations [Molkov et al, 1993a; Molkov et al, 1999; Molkov, 2002]. Coherent deflagrations in a system enclosure-atmosphere [Molkov, 2012]. Role of external explosions [Molkov et al, 2006]. Hydrogen-air deflagrations in a tunnel [Molkov, 2012; Molkov et al, 2008a]. Lean hydrogen-air mixture combustion and non-uniform deflagrations [Molkov, 2012; Whitehouse et al, 1996; Verbecke et al, 2009]. Effect of water sprays on the dynamics of hydrogen-air deflagration [Shebeko et al, 1990; Gelfand et al, 2008]. Separation distances: pressure in a near field and pressure decay in a far field [BRHS, 2007; Molkov et al, 2008]. Separation distances: deflagration pressure amplitude versus flame propagation velocity and acceleration [Gorev and Bystrov, 1984; Dorofeev, 2002; Nishimura et al, 2011]. Separation distances: pressure effects of delayed ignition of hydrogen releases [Royle and Willoughby, 2009; Molkov, 2012; Houf et al, 2010; Schefer et al, 2009]. Flame acceleration criteria and fast deflagrations [Dorofeev et al, 2001]. Deflagration-to-detonation transition (DDT) [Molkov, 2012; Ciccarelli and Dorofeev, 2008; Lee, 2008]. Jump in velocity propagation at DDT [Lee, 2008]. DDT during venting of hydrogen deflagrations [Cooper, 1986; Dorofeev et al, 1995b; Alekseev et al, 2001]. Correlation between characteristic size of a turbulent jet developing DDT and detonation cell size [Gelfand et al, 2008]. Flame acceleration and DDT [Grossel, 2002; Teodorczyk, 2007]. Spontaneous flame induced by gradient of induction time [Zeldovich, 1980]. The SWACER mechanism [Molkov, 2012; Lee and Moen, 1980]. Run-up distance for deflagration to detonation transition (DDT) [Molkov, 2012; Kuznetsov et al, 2005]. Blast waves from deflagrations [Dorofeev et al, 1995b; Tang and Baker, 1999; BRHS, 2007; Dorofeev, 2007a; Dorofeev, 2007b]. Deflagration pressure wave decay in the open atmosphere [Dorofeev et al, 2001; Dorofeev, 1996; Dorofeev et al, 1996].

Detonations and blast waves

Initiation of detonation [Lee et al, 1982; Cassut, 1961; Molkov, 2012; BRHS, 2009; Grossel, 2002; Teodorczyk, 2007]. Minimum dimensions of hydrogen-air mixtures for detonation [Lee et al, 1982]. Galloping detonation, overdriven detonation, spin detonation, stable detonation [Lee, 2008; Grossel, 2002; Law, 2006]. Detonation waves [Law, 2006]. Parameters of detonation waves: velocity, pressure and temperature [Gelfand et al, 2008; Molkov, 2012; Kuznetsov et al, 2005]. Calculation of the Chapman-Jouget detonation wave velocity and comparison with experimental data [Law, 2006; BRHS, 2009]. Detonation products of hydrogen-air and hydrogen-oxygen mixtures [BRHS, 2007]. Parameters of reflected detonation waves [Gelfand et al, 2008]. The detonation wave structure [Law, 2006; Lee, 2008]. Detonability limits [Molkov, 2012; Ciccarelli, 2002; Ng et al, 2007; Stamps et al, 2006]. Detonability limits for initiation by high explosives [Gelfand et al, 2008]. Detonability limits of hydrogen-air mixtures diluted with carbon dioxide and water [Gelfad et al, 2008]. Detonability limits for mixtures hydrogen-oxygen-nitrogen [Cassut, 1961; Jost and Wagner, 1981; Gelfand et al,

2008]. Detonation area for mixtures H_2–CO–CO_2–air [Gelfand et al, 2008]. Detonation cell size [Molkov, 2012; Bull et al, 1982; Lee, 1984; Shepherd, 1986; Lee and Berman, 1997]. Effect of equivalence ration of detonation cell size [Gelfand et al, 2008]. Dependence of detonation cell size on initial pressure and temperature [Kuznetsov et al, 2005; Ciccarelli et al, 1994b; Gelfand et al, 2008; Lee and Berman, 1997; Ng et al, 2007; Stamps et al, 2006]. Effect of dilution by steam and CO_2 [Shepherd, 1986; Ciccarelli et al, 1994a; Ciccarelli et al, 1994b; Gelfand et al, 2008]. Comparison of detonation cell size with other fuels [Lee, 1984; Austin and Shepherd, 2003]. Relationship between detonation cell width and critical initiation energy for onset of detonation [Teodorczyk, 2006; Lee, 2008]. Critical tube diameter for onset of detonations [Lee, 1984; Lee, 2008; Dorofeev et al, 2000; Kuo, 2005; Ciccarelli, 2002]. Critical energy of direct initiation of spherical detonation [Law, 2006; Lee, 2008]. Modelling and simulation of hydrogen detonations [Molkov, 2012; Zbikowski, 2010; Zbikowski et al, 2008; Zbikowski et al, 2010]. Detonation of 30% hydrogen-air mixture in 5.23 m hemisphere [Molkov, 2012; Groethe et al, 2005]. Detonation of 29.05% hydrogen-air mixture in 2.95 m radius balloon [Molkov, 2012; Zbikowski, 2010]. Detonations in a system incombustible liquid-bubbles of flammable mixture [Gelfand et al, 2008]. Blast waves from detonations of hydrogen containing mixtures [Dorofeev et al, 1995b; Dorofeev, 2007a; Dorofeev, 2007b; Gelfand et al, 2008].

Physical explosions and blast waves

Classification of physical explosions [Crawl, 2003]. P-I diagram for structural damage [Baker et al, 1983; Dorofeev et al, 1995a]. Reflection of pressure and shock waves [Baker et al, 1983; Ben-Dor, 2007]. Blast waves generated due to failure of high pressure storage tank. Bursting spheres and cylinders [Zalosh, 2007; Adamczyk and Strehlow, 1977; Esparza and Baker, 1977; Baker et al, 1983].

Super-high overpressures during rapid phase transition (RPT) phenomenon

Phenomenon of combustion-induced rapid phase transition [Basco et al, 2013; Di Benedetto et al, 2012].

Possible mitigation measures for explosions

Hydrogen deflagration mitigation techniques [Grossel, 2002; Bradley and Mitcheson, 1978a; Bradley and Mitcheson, 1978b]. Pressure containment [Grossel, 2002]. Deflagration venting [Molkov, 2012;]. Vent sizing technique for low strength equipment and buildings [Molkov and Bragin, 2013; Molkov, 2012]. Suppressant barriers [Grossel, 2002]. Suppressant injections [Grossel, 2002]. Suppression of turbulent combustion in systems hydrogen-air-steam-mist [Gelfand et al, 2008]. Fast acting valves [Grossel, 2002]. Flame front diverters [Grossel, 2002]. Deflagration flame arresters [Grossel, 2002; Korzhavin et al, 2004]. Deflagration flame arresters design and operation [Grossel, 2002]. Dependence of the quenching distance on pressure and equivalence ratio [Grossel, 2002; Gelfand et al, 2008]. Minimum safety experimental gap (MSEG) [NASA, 1997; BRHS, 2007]. Correlation between MSEG and MIA [Gelfand et al, 2008]. Flame arresters for hydrogen service [Grossel, 2002]. Detonation arresters for hydrogen-air mixtures [Grossel, 2002]. Measures for reducing the potential of detonation wave generation [Teodorczyk, A, 2006].

Module “Hazards of hydrogen use indoors and relevant mitigation techniques”

Hazards and associated risks for the use of hydrogen in enclosures

Effect of temperature and heat flux [LaChance, 2010b; NIO, 2013; HyIndoor]. Oxygen depletion and asphyxiation caused by unignited release into confined space [NASA, 1997]. Effects from overpressure [LaChance, 2010b; Baker et al, 1983; Dorofeev et al, 1995; NIO, 2013]. Pressure

peaking phenomenon [Brennan and Molkov, 2013]. Structural collapse and life safety [BRHS, 2007; LaChance, 2010b].

Permeation leaks

The sources and types of hydrogen leaks [EIGA, 2007]. Typical flow rates of hydrogen during accidental releases [Molkov, 2012; EU No 406/2010, 2010]. Permeation leaks [SAE J2578; Schefer et al, 2006]. Permeability of hydrogen for a particular material and a permeation rate [Molkov, 2012; San Marchi et al, 2007; Schultheiss, 2007]. Uniformity of permeated hydrogen concentration distribution [Molkov, 2012]. Dispersion of permeated hydrogen in a garage [Molkov, 2012; Saffers et al, 2011]. Effect of testing conditions (pressure, temperature and age of a container) on hydrogen permeation rate [Molkov, 2012; Adams et al, 2011; SAE J2579, 2009; Mitlitsky et al, 2000; Rothe, 2009; Mitlitsky et al, 1999]. Safe permeation rate of hydrogen [Molkov, 2012; Adams et al, 2011; SAE J2579, 2009; EU No 406/2010, 2010].

Indoor hydrogen releases and dispersion

Hydrogen releases and dispersions in an enclosure [Molkov, 2012; SAE J2578, 2009; Schefer et al, 2006; San Marchi et al, 2007; Schultheiss, 2007; Saffers et al, 2011; Adams et al, 2011; SAE J2579]. A scheme for hydrogen dispersion in a closed space [HyIndoor; Zalosh, 2006]. Dispersion of hydrogen in a vented enclosure [HyIndoor]. Steady state plume, puff and starting plume [Zalosh, 2006]. Plume formation distance and concentration profile [Zalosh, 2006; Hunt and Kaye, 2001]. Examples of gaseous hydrogen releases in a confined space [Swain et al, 2003; Swain and Swain, 1996]. Unintended release of hydrogen from FCH forklift in a warehouse [Ekoto et al, 2011; Houf et al, 2011]. Potential scenarios and consequences of the indoor leak: accumulation, jet fire, deflagration [HyIndoor].

Natural and forced ventilation

Passive (natural) and forced (active/mechanical) ventilation [Molkov et al, 2014]. Ventilation effects on the buoyant plume in an enclosure [HyIndoor; Zalosh, 2006; Hunt and Kaye, 2001; Baines and Turner, 1969; Hunt and Linden, 2001; Tamura et al, 2013]. Ideal well-mixed and displacement regimes of enclosure ventilation [HyIndoor]. The nomogram for calculation of hydrogen concentration in an enclosure with one vent [HyIndoor, WP2 final report; Molkov et al, 2014].

Pressure peaking phenomenon

Pressure effects in enclosures [Brennan and Molkov, 2013; Brennan et al, 2010]. Pressure loads at constant mass flow rates [Molkov, 2012; Brennan and Molkov, 2013; Brennan et al, 2010]. Overpressure in a garage [Brennan and Molkov, 2013; Brennan et al, 2010]. Pressure peaking phenomenon for hydrogen unignited release in a vented enclosure [Brennan and Molkov, 2011; Brennan and Molkov, 2013; Brennan et al, 2010]. Air changes per hour and natural ventilation vent sizing [Molkov, 2012]. The nomograms to determine ‘safe’ PRD diameter and subsequent blow-down time [Molkov, 2012; Brennan and Molkov, 2011; Molkov et al, 2009].

Venting of hydrogen-air deflagrations

Vented deflagrations [Molkov, 2012]. Pressure peak structure [Molkov, 2012; Dragosavic, 1973; Cooper et al, 1986]. Turbulence generated by venting process [Molkov et al, 1999; Molkov et al, 2006c]. Vented deflagrations with inertial vent covers [Molkov, 2012]. Inertial vent cover jet effect [Molkov et al, 1993b; Molkov et al, 2004].

Regimes of indoor jet fires including phenomena of self-extinction and external flame

Fires in the enclosures [Molkov et al, 2013; Molkov et al, 2014]. Factors affecting hydrogen fires indoors [Karlsson and Quintiere, 2000; HyIndoor]. Releases along the walls and surfaces [Brennan et al, 2011; Hourri et al, 2011; Royle and Willoughby, 2009]. Self-extinguishing flames [Molkov et al, 2013; Molkov et al, 2014]. Triple flames [Matalon, 2007].

Hydrogen sensors and hydrogen fire detectors

Types of hydrogen sensors [NASA, 1997; HyIndoor]. General characteristic of commercially available hydrogen sensors [HyIndoor]. Response factors [HyFacts]. Hydrogen fire detectors [HyIndoor]. The choice of hydrogen fire detectors [HyIndoor].

SECTION "REGULATIONS, CODES AND STANDARDS (RCS) FOR FIRST RESPONDERS"

Module "Regulations, Codes and Standards (RCS) for First Responders"

RCS for hydrogen production applications and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS for hydrogen distribution and transportation applications and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS for FC vehicles and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS for hydrogen refuelling stations and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS for stationary FC applications and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS for hydrogen-based energy storage applications and relevance to FRs [Appendix 2; Hydrogen/Fuel Cells Codes and Standards]. RCS specific to fire service intervention [BSI, 2004]. RCS on ignition prevention and electrical safety [CENELEC, 2003]. Electrical safety of FCs [BS EN62282-3-1, 2007]. Prescriptive and performance-based approach to hydrogen safety [LaChance et al, 2009].

SECTION "INTERVENTION STRATEGIES AND TACTIC FOR FIRST RESPONDERS"

Module "Intervention strategies and tactic for First Responders"

Typical accident scenarios involving hydrogen production applications and relevant emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accident scenarios involving hydrogen storage applications and relevant emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accident scenarios involving hydrogen distribution and transportation applications and relevant emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accidental scenarios related to FC vehicles and emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accidental scenarios related to hydrogen refuelling stations and emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accident scenarios involving stationary FC applications and relevant emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Typical accident scenarios involving hydrogen-based energy storage

systems and relevant emergency response strategies and tactics [HyResponse Deliverable D2.2, 2014; NIO, 2013; DEMA, 2012]. Rescue operations [NIO, 2013; DEMA, 2012; SAE J2990, 2012].

References and sources

Essential reading list

Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II. Available from: www.bookboon.com, free download e-book [accessed 13.05.14].

Rigas, F and Amyotte, P (2013). Hydrogen safety. Boca Raton: CRC press. Taylor and Francis Group.

Klebanoff, L (Ed) (2012). Hydrogen storage technology: Materials and applications. Boca Raton: CRC Press. Taylor&Francis.

GTR, Proposal for a global technical regulation (gtr) on hydrogen fuelled vehicles, 2013. ECE/TRANS/WP.29/GRSP/2013/41. United Nations. Economic Commission for Europe. Inland Transport Committee. World Forum for Harmonization of Vehicle Regulations, 160th Session, Geneva, 25-28 June 2013.

EU No 406/2010, Commission Regulation of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles. Official Journal of the European Union. Vol. 53, 18 May 2010. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:FULL:EN:PDF [accessed on 13.02.14].

H2 Incidents, H2 Incident Reporting and Lessons Learned (database). Available from: http://www.h2incidents.org/ [accessed on 01.05.14].

NIO Note D'Information Operationnelle (2013). 'Intervention sur les installations d'hydrogène et Les risques lies. In French. Available from: http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CC4QFjAA&url=http%3A%2F%2Fwww.interieur.gouv.fr%2Fcontent%2Fdownload%2F64227%2F463800%2Ffile%2FNIO%2520Risque%2520hydrog%25C3%25A8ne_18%2520juin%25202013.pdf&ei=_kp_U8StBYHm7AbyzYG4Bw&usg=AFQjCNGc-br8_Bi2CrfvL_6VWHXA7txq4A&bvm=bv.67720277,d.ZGU [accessed 23.05.14].

Hydrogen/Fuel Cell Codes and Standards. Available from: http://www.fuelcellstandards.com/ [accessed 30.05.14].

HyResponse Deliverable D2.1-Description of selected FCH systems and infrastructure, relevant safety features and concepts (2014). Available from: http://www.hyresponse.eu [accessed 10.06.14].

HyResponse Deliverable D2.2- Detailed scenarios of typical accident for selected FCH systems and infrastructure (2014). Available from: http://www.hyresponse.eu [accessed 10.06.14].

Further reading

Abdullin, RK, Babkin, VS, Senachin, PK (1988). Combustion of gas in connected vessels. Combustion, Explosion and Shock Waves. Vol. 24, pp. 123-132.

AC Transit, 2014. Available from: http://www.actransit.org/environment/the-hyroad/ [accessed on 01.05.14].

Aceves, SM (2011). Compact (L)H2 storage with extended dormancy in cryogenic pressure vessels. International Conference on Sustainable Energy Storage. Belfast, UK, February 2011.

Aceves, SM, Berry, GD and Rambach, GD (1998). Insulated pressure vessels for hydrogen storage on vehicles. International Journal of Hydrogen Energy. Vol. 23, pp. 583-591.

Aceves, SM, Berry, GD, Martinez-Frias, J and Espinosa-Loza, F (2006). Vehicular storage of hydrogen in insulated pressure vessels. International Journal of Hydrogen Energy. Vol. 31, pp. 2274-2283.

Aceves, SM, Espinosa-Loza, F, Ledesma-Orozco, E, Ross, TO et al. (2010). High-density automotive

hydrogen storage with cryogenic capable pressure vessels. International Journal of Hydrogen Energy. Vol. 35, pp. 1219-1226.

Aceves, SM, Petitpas, G, Espinosa-Loza, F, Matthews, MJ and Ledesma-Orozco, E (2013). Safe, long range, inexpensive and rapidly refueable hydrogen vehicles with cryogenic pressure vessels. International Journal of Hydrogen Energy. Vol. 38, pp. 2480-2489.

Ackroyd, GP and Newton, SG (2003). An investigation of the electrostatic ignition risks associated with a plastic coated metal. Journal Electrostatics. Vol. 59, pp. 143-151.

Adamczyk, AA and Strehlow, RA (1977). Terminal energy distribution of blast waves from bursting spheres. Technical Report NASA CR-2903, NASA, Washington D.C.

Adams, P, Bengaouer, A, Cariteau, B, Molkov, V and Venetsanos, AG (2011). Allowable hydrogen permeation rate from road vehicles. International Journal of Hydrogen Energy. Vol. 36, pp. 2742-2749.

ADL. Arthur D. Little Inc (1960). Final report on an investigation of hazards associated with the storage and handling of liquid hydrogen. Report C-61092, Cambridge, USA.

AirLiquide. Hydrogen Refuelling Stations. Available from: http://www.airliquideadvancedbusiness.com/file/otherelement/pj/b7/59/cd/7e/al_plaquette_hydrogene_uk434602932671885752.pdf [accessed on 16.05.14].

AirLiquide: packaging and transporting gases. (2014). Available from: http://www.airliquide.com/en/company/our-businesses-our-products/packaging-and-transporting-gases/gas-pipes.html [accessed on 01.05.14].

AirProducts (2014a). Hydrogen Fuelling Stations for Transportation Fleets. Available from: http://www.airproducts.co.uk/~/media/downloads/h/hydrogen-fueling-stations/data-sheets/en-hydrogen-fueling-stations-datasheet.pdf?industryItem=industries&subIndustryItem=Energy&segment=Hydrogen-Energy&applicationChildItem=Transportation&productLevel3=Hydrogen-Fueling-Stations [accessed on 16.05.14].

AirProducts (2014b). PRISM® Hydrogen Generation Systems. Available from: http://www.airproducts.co.uk/~/media/Files/PDF/products/supply-options/gas-generation/en-GB-prism-hydrogen-generation-systems-datasheet.pdf?industryItem=industries&subIndustryItem=Energy&segment=Hydrogen-Energy&applicationChildItem=Transportation&productLevel3=Onsite-Generators [accessed on 16.05.14].

Alcock, JL, Shirvill, LC and Cracknell, RF (2001). Comparison of existing safety data on hydrogen and comparative fuels. Deliverable report of European FP5 project EIHP2, May 2001. Available from: http://www.eihp.org/public/documents/CompilationExistingSafetyData_on_H2_and_ComparativeFuels_S..pdf [accessed on 13.05.14].

Alekseev, VI, Kuznetsov, MS, Yankin, YG and Dorofeev, SB (2001). Experimental study of flame acceleration and DDT under conditions of transverse venting. Journal of Loss Prevention in the Processes Industries. Vol. 14, pp. 591-596.

Anderson, JD (1990). Modern compressible flow. 2nd edition. Singapore: McGraw-Hill.

Annushkin, MY and Sverdlov, ED (1979). Stability of submerged diffusion flames in subsonic and underexpanded supersonic gas-fuel streams. Combustion, Explosion and Shock Waves. Vol. 14(5), pp. 597-605.

Astbury, GR and Hawksworth, SJ (2007). Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms. International Journal of Hydrogen Energy. Vol. 32, pp. 2178-2185.

Austin, JM and Shepherd, JE (2003). Detonations in hydrocarbon fuel blends. Combustion and Flame. Vol. 132, pp. 73-90.

Austin, JM and Shepherd, JE (2003). Detonations of hydrocarbon fuel blends. Combustion and Flame. Vol. 132, pp. 73-90.

Baev, VK, Kuznetsov, PP, Mogil'nyi, IA, Tret'yakov, PK and Yasakov, VA (1974). Length of diffusion flames. Combustion, Explosion and Shock Waves. Vol. 10, pp. 420-426.

Baines, WD and Turner, JS (1969). Turbulent buoyant convection from a source in confined region. Journal of Fluid Mechanics. Vol. 37, pp. 51-80.

Baker, J, Calvert, ME and Murphy, DW (2002). Structure and dynamics of laminar jet micro-slot diffusion flames. Journal of Heat Transfer. Vol. 124, pp. 783-790.

Baker, WE, Cox, PA, Westine, PS, Kulesz, JJ and Strehlow, RA (1983). Explosion hazards and evaluation. Amsterdam: Elsevier Scientific Publishing Co, The Netherlands.

Baratov, AN, Korolchenko, AY and Kravchuk, GN (Eds.) (1990). Fire and explosion hazards of substances and materials. Moscow: Khimia. 496 p., ISBN 5-7245-0603-3 part 1, ISBN 5-7245-0408-1 part 2 (in Russian).

Barral, K, Pregassame, S, and Renault, P (2004). Thermal effects of fast filling hydrogen compression in refuelling stations. 15th World Hydrogen Energy Conference. Yokohama, Japan.

Barry, TF (2003). Fire exposure profile modelling: some threshold damage limit (TDL) data. A whitepaper by TFBarry Publications, September 2003.

Barthelemy, H (2006). Compatibility of metallic materials with hydrogen. Teaching Materials of the 1st European Summer School on Hydrogen Safety, 15-24 August 2006.

Barthelemy, H (2007). Safety of hydrogen cylinders and pressure vessels. Teaching materials of the 2nd European Summer School on Hydrogen Safety, 30 July-8 August 2007, Belfast, UK.

Barthelemy, H (2009). Hydrogen storage technologies: compatibility of materials with hydrogen. Teaching materials of the 4th ISCARW, Corsica, June 2009.

Barthelemy, H (2011a). Hydrogen storage technologies, compatibility of materials with hydrogen. Teaching materials of Joint European Summer School for fuel cell and hydrogen technology. August 2011, Viterbo, Italy.

Barthelemy, H (2011b). Hydrogen storage - industrial prospectives. 4th International Conference on Hydrogen Safety. San Francisco, USA.

Barthelemy, H and Allidieres, L (2005). Gaseous hydrogen refuelling stations: Selection of materials for hydrogen high pressure fuelling connectors. First International Conference on Hydrogen Safety, Pisa, Italy, 8-10 September, 2005.

Basco, A, Cammarota, F, Di Benedetto, A, Di Sarli, V, Salzano, E and Russo, G (2013). The effect of hydrogen presence on combustion-induced rapid-phase transition of $CO/O_2/N_2$ mixtures. International Journal of Hydrogen Energy. Vol. 38, pp. 16463-16470.

Becker, HA and Liang, D (1978). Visible length of vertical free turbulent diffusion flames. Combustion and Flame. Vol. 32, pp. 115-137.

Ben-Dor, G (2007). Shock wave reflection phenomena. 2nd edition. Berlin: Springer.

Benz, FJ, Bishop, CV and Pedley, MD (1988). Ignition and thermal hazards of selected aerospace fluids: overview, data, and procedures. NASA White Sands Test Facility, Lac Cruces, NM, USA.

Bradley, D (1992). How fast can we burn? Proceedings of the 24th Symposium (International) on Combustion, Pittsburgh, 1992. The Combustion Institute, pp. 247-262.

Bradley, D and Mitcheson, A (1976). Mathematical solutions for explosions in spherical vessels. Combustion and Flame. Vol. 26, pp. 201-217.

Bradley, D and Mitcheson, A (1978a). The venting of gaseous explosions in spherical vessels. I – Theory. Combustion and Flame. Vol. 32, pp. 221-236.

Bradley, D and Mitcheson, A (1978b). The venting of gaseous explosions in spherical vessels. II – Theory and experiment. Combustion and Flame. Vol. 32, pp. 237-255.

Bradley, D, Cresswell, TM and Puttock, JS (2001). Flame acceleration due to flame-induced instabilities in large-scale explosions. Combustion and Flame. Vol. 124, pp. 551-559.

Bradley, D, Lawes, M, Scott, MJ and Mushi, EMJ (1994). Afterburning in spherical premixed turbulent explosions. Combustion and Flame. Vol. 99, pp. 581-590.

Bradley, D, Sheppard, CGW, Woolley, R, Greenhalgh, DA and Lockett, RD (2000). The development and structure of flame instabilities and cellularity at low Markstein numbers in explosions. Combustion and Flame. Vol. 122, pp. 195-209.

Brady, K, Sung, C-J and T'ien, J (2010). Ignition propensity of hydrogen/air mixtures impinging on a

platinum stagnation surface. International Journal of Hydrogen Energy. Vol. 35, pp. 11412-11423.
Bragin, M and Molkov, V (2009). Physics of spontaneous ignition of high-pressure hydrogen release and transition to jet fire. Proceedings of the 3rd International Conference on Hydrogen Safety, 16-18 September 2009, Ajaccio, France.
Bragin, MV and Molkov, VV (2010). The effect of burst disk opening on combustible mixture formation preceding hydrogen spontaneous ignition. Paper at the XXV International Conference Equation of State for Matter, Elbrus, Russia.
Bragin, MV and Molkov, VV (2011). Physics of spontaneous ignition of high-pressure hydrogen release and transition to jet fire. International Journal of Hydrogen Energy. Vol. 36(3), pp. 2589-2596.
Bragin, MV, Makarov, DV and Molkov, VV (2011). Pressure limit of hydrogen spontaneous ignition in a T-shaped channel. Proceedings of the 4th International Conference on Hydrogen Safety, 12-14 September 2011, San Francisco, USA.
Brennan, S and Molkov, V (2011). Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation. Proceedings of the 4th International Conference on Hydrogen Safety, 12-14 September 2011, San Francisco, USA.
Brennan, S and Molkov, V (2013). Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation. International Journal of Hydrogen Energy. Vol. 38, pp. 8159-8166.
Brennan, S, Bengaouer, A, Carcassi, M, Cerchiara, G, Evans, G, Friedrich, A, Gentilhomme, O, Houf, W, Kotchourko, A, Kotchourko, N, Kudriakov, S, Makarov, D, Molkov, V, Papanikolaou, E, Pitre, C, Royle, M, Schefer, R, Stern, G, Venetsanos, AG, Veser, A et al. (2011). Hydrogen and fuel cell stationary applications: Key findings of modelling and experimental work in the HYPER project. International Journal of Hydrogen Energy, Vol. 36 (3), pp. 2711-2720.
Brennan, S, Makarov, D and Molkov, V (2010). Dynamics of flammable hydrogen-air mixture formation in an enclosure with a single vent. Proceedings of the 6th International Seminar on Fire and Explosion Hazards, Leeds, April 2010.
BRHS, Biennal Report on Hydrogen Safety (2007). Network of Excellence HySAFE. Available from: http://www.hysafe.org/BRHS [accessed on 12.02.14].
BRHS, Biennial Report on Hydrogen Safety (2009). The European network of excellence "Safety of hydrogen as an energy carrier" (NoE HySafe). Available from: www.hysafe.org [accessed on 13.05.14].
BS EN62282-3-1 (2007). Fuel cell technologies — Part 3-1: Stationary fuel cell power systems - Safety.
BSI (1997). British Standard 7899-2:1997. Code of practice for assessment of hazard to life and health from fire. Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires. British Standards Institution.
BSI (2004). Published Document PD 7974-6:2004. The application of fire safety engineering principles to fire safety design of buildings - Part 6: Human factors: Life safety strategies - Occupants evacuation, behaviour and condition (Sub-system 6). British Standards Institution.
Bülent Yüceil, K and Volkan Ötügen, M (2002). Scaling parameters for under-expanded supersonic jets. Physics of Fluids. Vol. 14, pp. 4206-4215.
Bull, DC, Ellworth, JE and Shiff, PJ (1982). Detonation cell structures in fuel/air mixtures. Combustion and Flame. Vol. 45(1), pp. 7-22.
Burgess, DS and Hertzberg, M (1974). Radiation from pool flames. In Afgan, NH and Beer, JM, editors, Heat transfer in flames, chapter 27. Washington, DC: Scripta Book Co.
Burgess, DS, Strasser, A and Grumer, J (1961). Diffusive burning of liquid fuels in open trays. Fire Research Abstracts and Reviews. Vol. 3, p. 177.
Butler, MS, Moran, CW, Suderland, PB and Axelbaum, RL (2009). Limits for hydrogen leaks that can support stable flames. International Journal of Hydrogen Energy. Vol. 34, pp. 5174-5182.
Cain, TM (1997). Autoignition of hydrogen at high pressure. Combustion and Flame. Vol. 111, pp.

124–132.

Carbon-based materials. Published on US DoE website. Available from: http://energy.gov/eere/fuelcells/carbon-based-materials-high-surface-area-sorbents-and-new-materials-and-concepts [accessed 04.05.14].

Cassut, LH (1961). Experimental investigation of detonation in unconfined gaseous hydrogen-oxygen-nitrogen mixtures. ARS Journal. Vol. 31, p. 7.

CENELEC (2003). Electrostatics – Code of practice for the avoidance of hazards due to static electricity, PD CLC/TR 50404:2003.

CEP, Clean Energy Partnership, 2014. Available from: http://www.cleanenergypartnership.de/tech/site.php?l=en [accessed on 01.05.14].

CFCP, California Fuel Cells Partnership, 2014. Available from: http://cafcp.org/ [accessed on 01.05.14].

Chatterjee, UK, Bose, SK and, Roy SK (2001). Environmental Degradation of Metals. New York: Marcel Dekker. 509p.

Chen, CJ and Rodi, W (1980). Vertical turbulent buoyant jets - a review of experimental data, The Science Applications of Heat and Mass Transfer series, Vol. 4, Ed. by Chen C.J. 1980, Pergamon Press: Oxford, 83p.

Cheng, TS and Chiou, CR (1998). Experimental investigation on the characteristics of turbulent hydrogen jet flames. Combustion Science and Technology. Vol. 136, pp. 81-94.

Cheng, TS, Chen, CP, Chen, CS, Li, YH, Wu, CY and Chao, YC (2006). Characteristics of microjet methane diffusion flames. Combustion Theory and Modelling. Vol. 10, pp. 861-881.

Chenoweth, DR (1983). Gas-transfer analysis. Section H – Real gas results via the van der Waals equation of state and virial-expansion extensions of its limiting Abel-Nobel form. Livermore, CA, Sandia National Laboratories.

Chirivella, JE and Witcofsky, RD (1986). Experimental results from fast 1500-gallon LH2 spills. AIChE Symposium Series: cryogenic properties, processes and applications. Vol. 82, pp. 120-141.

Chitose, K, Okamto, M, Takeno, K, Hayashi, K and Hishida, M (2002). Analysis of a large scale liquid hydrogen dispersion using the multi-phase hydrodynamics analysis code (CHAMPAGNE). Journal of Energy Resources Technology. Vol. 124, pp. 283-289.

Cho, P and Law, CK (1986). Catalytic ignition of fuel/oxygen/nitrogen mixtures over platinum. Combustion and Flame. Vol. 66(2), pp. 159-170.

Ciccarelli, G (2002). Critical tube measurements at elevated initial mixture temperatures. Combustion Science and Technology. Vol. 174, pp. 173-183.

Ciccarelli, G, Ginsberg, T, Boccio, J, Econonmos, C, Finfrock, C, Gerlach, L, et al. (1994a). High temperature hydrogen-air-steam detonation experiments in the BNL small-scale development apparatus. Technical Report NUREG/CR-6213, Brookhaven National Laboratory, Upton, New York.

Ciccarelli, G, Ginsberg, T, Boccio, J, Econonmos, C, Sato, K and Kinoshita, M (1994b). Hydrogen-air-steam mixtures at elevated temperatures. Combustion and Flame. Vol. 99, pp. 212-220.

CoA, Commonwealth of Australia (2006). Draft national code of practice for the control of workplace hazardous chemicals. Available: http://www2.unitar.org/cwm/publications/cbl/ghs/Documents_2ed/D_National_Documents_and_Legislation/267_Australia_ASCC_Code.pdf [accessed on 18.02.2014]

CoD, College of the Desert (2001). Hydrogen Fuel Cell Engines and Related Technologies, Module 1: Hydrogen Properties. Energy Technology Training Center, College of the Desert. Available from: http://www.hydrogensafety.info/resources/courseManual.asp [accessed on 29.12.11].

Cooper, MG, Fairweather, M and Tite, JP (1986). On the mechanisms of pressure generation in vented explosions. Combustion and Flame. Vol. 65, pp. 1-14.

Cotton, FA and Wilkinson, G (1999). Advanced inorganic chemistry: A comprehensive text. 6th edition. John Wiley and Sons Ltd, United States.

Coward, HF and Jones, GW (1952). Limits of flammability of gases and vapors, Bulletin 503, Bureau of Mines, p. 155.

Creitz, EC (1961). Inhibition of diffusion flames by methyl bromide and trifluoromethyl-bromide applied to the fuel and oxygen sides of the reaction zone. Journal of Research for Applied Physics and Chemistry. Vol. 65A, pp. 389-396.

Cross, S and Jean, A (1987). Electrostatics principles, problems and applications. Bristol: Adam Hilger.

Crowl, DA (2003). Understanding explosions. New York: Center for Chemical Process Safety, American Institute of Chemical Engineers, USA.

Daycock, JH and Rew, PJ (2004). Development of a method for the determination of on-site ignition probabilities. Health and Safety Executive Research Report No. RR226.

Delichatsios, M (1993). Transition from momentum to buoyancy-controlled turbulent jet diffusion flames and flame height relationships. Combustion and Flame. Vol. 92, pp. 349-364.

DEMA, Danish Emergency Management Agency (2012). Guidance: Emergency service operations at hydrogen service tank facilities.

Di Benedetto, A, Cammarota, F, Di Sarli, V, Salzano, E and Russo, G (2012). Combustion-induced rapid-phase transition cRPT in CH_4/CO_2/O_2-enriched mixtures. Energy & Fuels, Vol.26, pp. 4799-4803.

DNV Technica (2001). Human resistance against thermal effects, explosion effects, toxic effects and obscuration of vision. DNV Technica, Scandpower A/S, Det Norske Veritas, Oslo, Norway.

DoE targets for on-board hydrogen storage systems for light-duty vehicles (2009). Published on DOE/EERE website. Available from: http://energy.gov/sites/prod/files/2014/03/f12/targets_onboard_hydro_storage.pdf [accessed on 16.05.14].

Dorofeev, SB (1996). Blast effect of confined and unconfined explosions. In: Sturtevant, B, Shepherd, J and Hornung, H, editors. 20th International Symposium on Shock Waves. Singapore: World Scientific Publishing Co, volume 1, pp. 77-86.

Dorofeev, SB (2002). Flame acceleration and DDT in gas explosions. Journal de Physique de France IV. Vol. 12(7), pp. 3-10.

Dorofeev, SB (2007a). Evaluation of safety distances related to unconfined hydrogen explosions. International Journal of Hydrogen Energy. Vol. 32, pp. 2118-2124.

Dorofeev, SB (2007b). A flame speed correlation for unconfined gaseous explosions. Process Safety Progress. Vol. 26(2), pp. 140-149.

Dorofeev, SB, Bezmelnitsin, AV and Sidorov, VP (1995a). Transition to detonation in vented hydrogen-air explosions. Combustion and Flame. Vol. 103(3), pp. 243-246.

Dorofeev, SB, Kuznetsov, MS, Alekseev, VI, Efimenko, AA and Breitung, W (2001). Evaluation of limits for effective flame acceleration in hydrogen mixtures. Journal of Loss Prevention in the Process Industries. Vol. 14, pp. 583-589.

Dorofeev, SB, Sidorov, VP and Dvoinishnikov, AE (1995b). Blast parameters from unconfined gaseous detonations. Proceedings of 20th Symposium (Int.) on Shock Waves (Pasadena, CA, USA, July 1995) pp. 673-678.

Dorofeev, SB, Sidorov, VP and Dvoinishnikov, AE (1996). Blast parameters from unconfined gaseous detonations. In: Sturtevant, B, Shepherd, J and Hornung, H editors. 20th International Symposium on Shock Waves. Singapore: World Scientific Publishing Co, volume 1, pp. 673-678

Dorofeev, SB, Sidorov, VP, Kuznetsov, MS, Matsukov, ID and Alekseev, VI (2000). Effect of scale on the onset of detonations. Shock Waves. Vol. 10, pp. 137-149.

Dragosavic, M (1973). Structural measures against natural-gas explosions in high-rise blocks of flats. Heron. Vol. 19, pp. 1-50.

Dryer, FL, Chaos, M, Zhao, Z, Stein, JN, Alpert JY and Homer, CJ (2007). Spontaneous ignition of pressurized releases of hydrogen and natural gas into air. Combustion Science and Technology. Vol. 179, pp. 663-694.

Eichert, H (1992). *Gefaehrdungspotential bei einem verstaerkten Wasserstoffeinsatz*. Deutsche Forschungsanstalt fuer Luft- und Raumfahrt (DLR), Stuttgart, Germany.

EIGA, European Industrial Gases Association (2007). Determination of safety distances. IGC Doc 75/07/E.

Ekoto, IW, Merilo, EG, Houf, EG, Evans, GH and Groethe, MA (2011). Experimental investigation of hydrogen release and ignition from fuel cell powered forklifts in enclosed spaces. International Conference on Hydrogen Safety, San Francisco, September 2011.

EPSRC project (2013). Integrated safety strategies for onboard hydrogen storage systems.

Esparza, ED and Baker, WE (1977). Measurement of blast waves from bursting pressurized frangible spheres. Technical Report NASA-CR-2843, NASA, Washington D.C.

Faudou, J-Y, Lehman, J-Y and Pregassame, S (2005). Hydrogen refuelling stations: safe filling procedures. Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 safety. Pisa, Italy, September 2005.

Fay, JA (2003). Model of spills and fires from LNG and oil tankers. Journal of Hazardous Materials. Vol. B96, pp. 171-188.

FCIR, The Fuel Cell Industry Review (2012). Available from: http://www.fuelcelltoday.com/media/1713685/fct_review_2012.pdf [accessed on 29.04.14]

FCTO, Fuel Cell Technologies Office (2014). Available from: http://energy.gov/eere/fuelcells/fuel-cell-technologies-office [accessed on 01.05.14].

Friedrich, A, Veser, A, Stern, G and Kotchourko, N (2011). Hyper experiments on catastrophic hydrogen releases inside a fuel cell enclosure. International Journal of Hydrogen Energy. Vol. 36, pp. 2678-2687.

Galassi, MC, Papanikolaou, E, Heitsch, M, Baraldi, D et al (2011). Validation of CFD models for hydrogen fast filling simulations. 4th International Conference on Hydrogen Safety. San Francisco, USA, September 2011.

Gambone, LR and Wong, JY (2007). Fire protection strategy for compressed hydrogen-powered vehicles. 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007.

Gaseous and liquid hydrogen storage. Published on DoE website. Available from: http://energy.gov/eere/fuelcells/gaseous-and-liquid-hydrogen-storage [accessed on 16.05.14].

Ge, X and Sutton, WH (2006). Analysis and test of compressed hydrogen interface leakage by commercial stainless steel (NPT) fittings. SAE International, pp. 35-47.

Gelfand, BE, Popov, OE and Chaivanov, BB (2008). Hydrogen: parameters of combustion and explosion. Moscow: Fizmatlit, 288 p. ISBN 978-5-9221-0898-0 (in Russian).

Gentilhomme, O, Proust, C, Jamois, D, Tkatschenko, Cariteau, B et al. (2011). Data for the evaluation of hydrogen risks onboard vehicles: outcomes from the French project DRIVE. International Conference on Hydrogen Safety (ICHS 2011), San Francisco, USA 2011.

Gibson, N and Harper, DJ (1988). Parameters for assessing electrostatic risk from non-conductors - a discussion. Journal Electrostatics. Vol. 21, pp. 27–36.

Gillette, JL and Kolpa, RL (2007). Overview of interstate hydrogen pipeline systems. Argonn National Laboratory. ANL/EVS/TM/08-2.

Glassman, I and Yetter, RA (2008). Combustion. 4th edition. Elsevier.

Golub, VV, Volodin, VV, Baklanov, DI, Golovastov, SV and Lenkevich, DA (2010). Experimental investigation of hydrogen ignition at the discharge into channel filled with air. In: Physics of Extreme States of Matter, ISBN 978-5-901675-96-0, Chernogolovka, 2010, pp.110-113.

Gorev, VA and Bystrov, SA (1984). Explosion waves generated by deflagration combustion. Combustion, Explosion and Shock Waves. Vol. 20(6), pp. 614-620.

Gottfried, BS, Lee, CJ and Bell, KJ (1966). The Leidenfrost phenomenon: film boiling of liquid droplets on a flat plate. International Journal of Heat and Mass Transfer. Vol. 9, pp. 1167-1187. De aquae communis nonullis qualitatibus tractatus-On the fixation of water in divers fire. A tract about some qualities of common water (translated from Latin into English by C. Wares),

Griffiths, JF and Barnard, JA (1995). Flame and combustion. 3rd edition. London: Chapman & Hall.

Grigoriev, S (2010). Hydrogen safety aspects of water electrolysers. 7th ISCARW "Progress in Hydrogen Safety, April 2010, University of Ulster, Belfast, UK.

Grossel, SS (2002). Deflagration and detonation flame arresters. American Institute of Chemical

Engineers. New York: Center for Chemical Process Safety, pp. 60-63.

Gupta, RB (Ed) (2009). Hydrogen fuel; production, transport and storage. B. Raton: CRC Press. Taylor& Francis Group), USA.

Hake, J-F, Linssen, J and Walbeck, M (2006). Prospects for hydrogen in the German energy system. Energy Policy. Vol. 34, pp.1271-1283.

Hall, K (2010). RCS experiences from industry in deploying hydrogen technologies in the UK, 6th ISCARW, Hydrogen regulations, codes and standards, Belfast, January 2010

Harstad, K and Bellan, J (2006). Global analysis and parametric dependencies for the potential unintended hydrogen-fuel releases. Combustion and flame. Vol. 144, pp. 89-102.

Hawksworth, S (2011). Hydrogen RCS. Presentation at the 10th International Short Course Progress in Hydrogen Safety and Advanced Research Workshop, Belfast, UK, January 2011.

Hawksworth, S, Rogers, R, Beyer, M, Proust, C, Lakic, D, Gummer, J and Raveau, D (2005). MECHEX - Criteria for assessing the likelihood of ignition by mechanical sources. International European Safety Management Group Symposium 2005 - Process Safety and Industrial Explosion Protection. Numberg, Germany.

Hawksworth, S, Rogers, R, Proust, C, Beyer, M and Schenk, S (2004). Mechanical ignition hazards in potentially explosive atmospheres - EC project MECHEX. International European Safety Management Group Symposium 2004 - Process Safety and Industrial Explosion Protection. Numberg, Germany.

Hawthorne, WR, Weddell, DS and Hottel, HC (1949). Mixing and combustion in turbulent gas jets. Proceedings of the Combustion Institute. Vol. 3, pp. 266-288.

Hayashi, AK and Tsuboi, N (2008). Fundamentals of hydrogen ignition and high pressure hydrogen jet auto-ignition. Teaching materials of Third European Summer School on Hydrogen Safety, 21-31 July 2008. With contributions from Chihiro Kamei, Shingo Ida, Keisuke Aizawa, Delphine Pinto, Yun-Feng Liu, Hiroyuki Sato, Satoru Watanabe, Takuya Negami, Satoru Watanabe, Eisuke Yamada, Fumio Higashino, Youhi Mori, Mitsuo Koshi, Toshio Mogi, Dongjoon Kim, Hiroumi Shiina, and, Sadashige Horiguchi.

HIAD, Hydrogen Incidents and Accidents Database. Available from: https://odin.jrc.ec.europa.eu/odin/controller?query=Login&target=/Hiad4/index.hiad [accessed 19.05.14].

Hirose, T, Matsushima, K, Narusawa, K and Taniguchi, T (2010). Studies of the release of high-pressure hydrogen gas in the case of vehicle fire. SAE International, 14603066. 24/08/10.

Horwitz J (2009a). Next-generation hydrogen production. Pira International Ltd: Surrey. ISBN 9781905189137.

Horwitz, J (2009b). Developments in hydrogen storage. Surrey: Pira International Ltd. ISBN 9781905189120.

Hottel, HC and Hawthorne, WR (1949). Diffusion in laminar flame jets. Proceedings of the Combustion Institute. Vol. 3, pp. 254-266.

Houf, W and Schefer, R (2008). Analytical and experimental investigation of small-scale unintended releases of hydrogen. International Journal of Hydrogen Energy. Vol. 33(4), pp. 1435-1444.

Houf, W, Schefer, R, Evans, G, Merilo, E and Groethe, M (2010). Evaluation of barrier walls for mitigation of unintended releases of hydrogen. International Journal of Hydrogen Energy. Vol. 35, pp. 4758-4775.

Houf, WG and Schefer, RW (2007). Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen. International Journal of Hydrogen Energy. Vol. 32, pp. 136-151.

Houf, WG, Evans, GH, Ekoto, IW and Merilo, EG (2011). Hydrogen fuel-cell forklift vehicle releases in enclosed spaces. International Conference on Hydrogen Safety, San Francisco, September 2011. Available from: http://conference.ing.unipi.it/ichs2011/papers-presentations.htm [accessed on 18.05.14].

Hourri, A, Angers, B and Bénard, P (2009). Surface effects on flammable extent of hydrogen and methane jets. International Journal of Hydrogen Energy. Vol. 34(3), pp. 1569-1577.

Hourri, A, Angers, B, Bénard, P, Tchouvelev, A and Agranat, V (2011). Numerical investigation of the

flammable extent of semi-confined hydrogen and methane jets. International Journal of Hydrogen Energy. Vol. 36(3), pp. 2567-2572.

HSE, Health and Safety Executive (2012). Hazardous area classification and control of ignition sources. Available from: http://www.hse.gov.uk/comah/sragtech/techmeasareaclas.htm [accessed on 18.02.14].

Hunt, GR and Kaye, NG (2001). Virtual origin correction for lazy turbulent plumes. Journal of Fluid Mechanics. Vol. 435, pp. 377-396.

Hunt, GR and Linden, PF (2001). Steady-state flows in an enclosure ventilated buoyancy forces assisted by wind. Journal of Fluid Mechanics. Vol. 426, pp. 355-386.

Hydrogen Storage Materials Database. US DoE. Available from: http://www.hydrogenmaterialssearch.govtools.us/ [accessed on 16.05.14].

HyFacts Project. Available from: http://www.hyfacts.eu/ [accessed on 16.05.14].

HyFLEETE CUTE (2014). Available from: http://www.global-hydrogen-bus-platform.com/Technology/Buses [accessed on 01.05.14].

HyIndoor project. Available form http://www.hyindoor.eu/

HySafe (2006). Deliverable D76 - Report on existing know-how in the field of material compatibility.

IFC, International Fire Code (2006). International Code Council.

Imamura, T, Hamada, S, Mogi, T, Wada, Y, Horiguchi, S, Miyake, A, and Ogawa, T (2008). Experimental investigation on the thermal properties of hydrogen jet flame and hot currents in the downstream region. International Journal of Hydrogen Energy. Vol. 33, pp. 3426-3435.

ISO/TR 15916 (2004). Basic considerations for the safety of hydrogen systems. International Organization for Standardization. ISO Technical Committee 197 Hydrogen Technologies. International Organization for Standardization, Geneva.

Janssen, H, Bringmann, JC, Emonts, B and Schroeder, V (2004). Safety-related studies on hydrogen production in high-pressure electrolysers. International Journal of Hydrogen Energy. Vol. 29,pp.759-770.

Jeary, B (2001). Fast filling of compressed hydrogen fuels storage containers, Proceedings of 11th Canadian Hydrogen Conference, Victoria, Canada, 17-20 June 2001.

Jiang, Z, Takayama, K, Babinsky, H and Meguro, T (1997). Transient shock wave flows in tubes with a sudden change in cross section. Shock Waves. Vol. 7, pp. 151-162.

Jost, W and Wagner, HG (1981). Influence of various parameters on initiation, stability and limits of detonation. AFOSR 78-3587. 1979; AFOSR 79-0117A. 1981; AFOSR 73-2541, 1978.

JST database, The Japan Science and Technology Agency. JST failure knowledge database. Available from: http://www.sozogaku.com/fkd/en/index.html [accessed 21.05.14].

Kalghatgi GT (1981b). Blow-out stability of gaseous jet diffusion flames. Part II: Effect of cross-wind. Combustion Science and Technology. Vol. 26(5), pp. 241-244.

Kalghatgi, GT (1981a). Blow-out stability of gaseous jet diffusion flames. Part I: in still air. Combustion Science and Technology. Vol. 26(5), pp. 233-239.

Kalghatgi, GT (1984). Lift-off heights and visible lengths of vertical turbulent jet diffusion flames in still air. Combustion Science and Technology. Vol. 41, pp. 17-29.

Karim, GA, Wierzba, I and Boon, S (1985). Some considerations of the lean flammability limits of mixture involving hydrogen. International Journal of Hydrogen Energy. Vol. 10, pp. 117-123.

Karlsson, B and Quintiere, J (2000). Enclosure fire dynamics. CRC Press.

Khalil, YF (2011). Hydrogen storage materials safety and screening criteria. Presentation at the Task 31 Hydrogen Safety of International Energy Agency meeting, Karlsruhe Institute of Technology, Germany, 11-13 April, 2011.

Kluger, Y (2003). Bomb explosions in acts of terrorism. Israeli Medical Association, IMAJ 5, pp. 235-240.

Kohli, DK, Khardekr, RK, Singh, R and Gupta, PK (2008). Glass micro-container based hydrogen storage scheme. International Journal of Hydrogen Energy. Vol. 33, pp. 417-422.

Korzhavin, AA, Klimenko, AS, and Babkin, VS (2004). Inert porous media as an effective tool for explosion-proofing of closed technological equipment. In Bradley, D, Drysdale, D and Molkov, V. editors. Fire and Explosion Hazards, Proceedings of the 4th International Seminar, Newtownabbey, UK: University of Ulster, pp. 893-904.

Kreith, F and Bohn, MS (2001). Principles of heat transfer. 6th edition. Brooks/Cole Publishers, Pacific Grove, CA, pp. 627-661.

Kuchta, JM (1985). Investigation of fire and explosion accidents in the chemical, mining and fuel-related industries - A manual. United States Department of the Interior, Bureau of Mines, Bulletin 680.

Kumar, RK (1985). Flammability limits of hydrogen-oxygen-diluent mixtures. Journal of Fire Sciences. Vol. 3, pp. 245-262.

Kumar, RK, Tamm, H and Harrison, WC (1983). Combustion of hydrogen-steam-air mixtures near lower flammability limits. Combustion Science and Technology. Vol. 33, pp. 167-178.

Kuo, KK (2005). Principles of combustion. 2nd edition. New York: John Wiley & Sons.

Kuznetsov, M, Alexseev, V, Matsukov, I and Dorofeev, S (2005). DDT in a smooth tube filled with a hydrogen-oxygen mixture. Shock Waves. Vol. 14(3), pp. 205-215.

LaChance, J (2010a). Analyses to support development of risk-informed separation distances for hydrogen codes and standards, 6th ISCARW, January 2010, Belfast.

LaChance, J (2010b). Progress in risk assessment methodologies for emerging hydrogen applications, 6th ISCARW, January 2010, Belfast.

LaChance, J, Tchouvelev, A and Engebo, A (2011). Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. Vol. 36 pp. 2381-2388.

LaChance, J, Tchouvelev, A and Ohi, J (2009). Risk-informed process and tools for permitting hydrogen refuelling stations. International Journal of Hydrogen Energy. Vol. 34, pp. 5855.

Lamoureux, N, Djebaili-Chaumeix, N and Paillard, C-E (2003). Laminar flame velocity determination for H2-air-He-CO2 mixtures using the spherical bomb. Experimental Thermal and Fluid Science. Vol. 27, pp. 385-393.

Lanz, A, Heffel, J and Messer, C (2001). Hydrogen fuel cell engines and related technologies. College of the Desert, USA Energy Technology Training Center, 43-500 Monterey Avenue, Palm Desert, CA 92260, United States of America.

Law, CK (2006a). Propagation, structure, and limit phenomena of laminar flames at elevated pressures. Combustion Science and Technology. Vol. 178, pp. 335-360.

Law, CK (2006b). Combustion Physics. New York: Cambridge University Press.

Lecoustre, VR, Sunderland, PB, Chao, BH and Axelbaum, RL (2010). Extremely weak hydrogen flames, Combustion and Flame. Vol. 157, pp. 2209-2210.

Lee, BJ and Jeung, I-S (2009). Numerical study of spontaneous ignition of pressurized hydrogen release by the failure of a rupture disk into a tube. International Journal of Hydrogen Energy. Vol. 34, pp. 8763-8769.

Lee, ID, Smith, OI and Karagozian, AR (2003). Hydrogen and helium leak rates from micromachined orifices. AIAA Journal. Vol. 41, pp. 457-463.

Lee, JH, Kynstantus, RC, Guirao, M, Benedick, WA and Shepherd, JE (1982). Hydrogen-air detonations. Proceedings of the 2nd International Workshop on the Impact of Hydrogen on Water Reactor Safety. M. Berman, Ed., SAND82-2456, Sandia National Laboratories, Albuquerque, NM, October.

Lee, JHS (1984). Dynamic parameters of gaseous detonations. Annual Reviews of Fluid Mechanics. Vol. 16, pp. 311-336.

Lee, JHS (2008). The detonation phenomenon. Cambridge: Cambridge University Press, UK.

Lee, JHS and Berman, M (1997). Hydrogen combustion and its application to nuclear reactor safety. In Greene, GA, Hartnett, JP, Irvine, TF Jr and Cho, YI, editors. Heat Transfer in Nuclear Reactor Safety, volume 29 of Advances in Heat Transfer, chapter 2, pp. 59-123. New York: Academic Press.

Lee, JHS and Moen, IO (1980). The mechanism of transition from deflagration to detonation in vapor cloud explosions. Progress in Energy Combustion Science. Vol. 16, pp. 359-389.

Lees, FP (1996). Loss prevention in the process industries. Vol. 2, 2nd edition. Oxford: Butterworth-Heinemann, Oxforshire, UK.

Leroux, P (2012). Area Classification. Why? Where? How? Who? When? Available from: http://www.iecex.com/dubai/speakers/Day%202_0830-0915_IECEx_Dubai_Area_Classif_final_Leroux_P.pdf [accessed on 18.02.2014].

Lewis, B and von Elbe, G (1987). Combustion, flames and explosions of gases. 3rd edition. Academic, Press.

Lowesmith, BJ and Hankinson, G (2013). Large scale experiments to study fires following the rupture of high pressure pipelines conveying natural gas and natural gas/hydrogen mixtures. Process safety and environment protection. Vol. 91, pp. 101-111.

Maeda, K, Masumoto, K and Hayano, A (2010). A study on energy saving in residential PEFC cogeneration systems. Journal of Power Sources. Vol. 195, pp. 3779-3784.

Makarov, D and Molkov, V. (2013). Plane hydrogen jets. International Journal of Hydrogen Energy. Vol. 38 (19), pp. 8068–8083,

Makarov, D, Verbecke, F, Molkov, V, Roe, O et al. (2009). An inter-comparison exercise on CFD model capabilities to predict a hydrogen explosion in a simulated vehicle refuelling environment. International Journal for Hydrogen Energy. Vol. 34, pp. 2800-2814.

Malek, MA (2006). Pressure relief devices ASME and API code simplified. New York: McGraw Hill.

Mannan, S (Ed) (2005). Lees' loss prevention in the process industries. Hazard identification, assessment and control. 3rd edition. Oxford: Elsevier.

Marshall, BW Jr (1986). Hydrogen:air:steam flammability limits and combustion characteristics in the FITS vessel. NUREG/GR-3468, SAND84-0383.

Matalon, M (2007). Intrinsic flame instabilities in premixed and non-premixed combustion. Annual Review of Fluid Mechanics 39, pp. 163-191.

McDougall, M and Horacek, P (2007). Temperature limitations during refuelling of on-board 70 MPa hydrogen storage. NHA Annual Hydrogen Conference. March 19-22, 2007.

McGratten, KB, Baum, HR and Hamins, A (2000). Thermal radiation from large pool fires. Technical Report NISIR 6546, National Institute of Standards and Technology.

Mercx, WPM, Weerheijm, J and Verhagen, TLA (1991). Some considerations on the damage criteria and safety distances for industrial explosions. 11th Symposium on New Directions in Process Safety - Hazards. 124, pp. 255-275.

Merilo, EG (2010). Experimental investigation of entrained electrified particulates as a source of spontaneous ignition on hydrogen jet fires. MSc Thesis. University of Ulster.

Mitlitsky, F, Weisberg, AH and Blake, M (1999). Vehicular hydrogen storage using lightweight tanks (regenerative fuel cell systems), prepared for U.S. DOE Hydrogen program 1999. Annual review meeting, CO, USA, 4-6 May 1999.

Mitlitsky, F, Weisberg, AH and Blake, M (2000). Vehicular hydrogen storage using lightweight tanks. Lawrence Livermore National Laboratory. Proceedings of the 2000 U.S. DOE Hydrogen program review, NREL/CP-570e28890, USA.

Mogi, T and Horiguchi, S (2009). Experimental study on the hazards of high-pressure hydrogen jet diffusion flames. Journal of Loss Prevention in the Process Industries. Vol. 22, pp. 45-51.

Mogi, T, Kim, D, Shiina, H and Horiguchi, S (2008). Self-ignition and explosion during discharge of high-pressure hydrogen. Journal of Loss Prevention in the Process Industries. Vol. 21(2), pp. 199-204.

Mokov, V and Bragin, M (2013). Hydrogen-air deflagrations: vent sizing correlation for low-strength equipment and buildings. International Conference on Hydrogen Safety, Brussels, Belgium, 9-11 September 2013.

Molina, A, Schefer, RW and Houf, WG (2007). Radiative fraction and optical thickness in large-scale hydrogen-jet fires. Proceedings of the Combustion Institute. Vol. 31, pp. 2565-2572.

Molkov, V (2009). Hydrogen non-reacting and reacting jets in stagnant air: overview and state-of-

the-art, Proceedings of the 10th International Conference on Fluid Control, Measurements, and Visualization (FLUCOM 2009), Moscow, Russia.

Molkov, V and Saffers, J-B (2011). The correlation for non-premixed hydrogen jet flame length in still air. Proceedings of the 10th International Symposium on Fire Safety Science, June 2011, University of Maryland, USA.

Molkov, V and Saffers, J-B (2013). Hydrogen jet flames. International Journal of Hydrogen Energy. Vol. 38, pp. 8141-8158.

Molkov, V, Bragin, M, Brennan, S, Makarov, D and Saffers, J-B (2010). Hydrogen safety engineering: overview of recent progress and unresolved issues. Proceedings of the International Congress on Combustion and Fire Dynamics. 20-23 October 2010, Santander, Spain.

Molkov, V, Grigorash, A, Eber, R, Tamanini, F and Dobashi, R (2004b). Vented gaseous deflagrations with inertial vent covers: State-of-the-art and progress. Process Safety Progress. Vol. 23(1), pp. 29-36.

Molkov, V, Makarov, D and Bragin, M (2009). Physics and modelling of under-expanded jets and hydrogen dispersion in atmosphere, In Fortov, VE et al. (eds). Physics of Extreme State of Matter 2009. Chernogolovka, Russia, pp.143-145.

Molkov, V, Shentsov, V and Quintiere, J (2014). Passive ventilation of a sustained gaseous release in an enclosure with one vent. International Journal of Hydrogen Energy, in press.

Molkov, V, Shentsov, V, Brennan, S and Makarov, D (2013). Hydrogen non-premixed combustion in enclosure with one vent and sustained release: numerical experiments. Proceedings of ICHS 2013, Brussels, Belgium, 2013.

Molkov, V, Shentsov, V, Brennan, S and Makarov, D (2014). Hydrogen non-premixed combustion in enclosure with one vent and sustained release: numerical experiments. International Journal of Hydrogen Energy, in press.

Molkov, V, Verbecke, F and Makarov, D (2008a). LES of hydrogen-air deflagrations in a 78.5m tunnel. Combustion Science and Technology. Vol. 180, pp. 796-808.

Molkov, VV (2002). Accidental gaseous deflagrations: modelling, scaling and mitigation. Journal de Physique IV. Vol. 12 (7), pp. 19-30.

Molkov, VV, Baratov, AN and Korolchenko, AY (1993a). Dynamics of gas explosions in vented vessels: a critical review and progress. Progress in Astronautics and Aeronautics. Vol. 154, pp. 117-131.

Molkov, VV, Dobashi, R, Suzuki, M and Hirano, T (1999). Modeling of vented hydrogen-air deflagrations and correlations for vent sizing. Journal of Loss Prevention in the Process Industries. Vol. 12, pp. 147-156.

Molkov, VV, Eber, RM and Grigorash, AV (2003). Vented gaseous deflagrations: modelling of translating inertial vent covers. Journal of Loss Prevention in the Process Industries. Vol. 16(5), pp. 395-402.

Molkov, VV, Makarov, D and Grigorash, A (2004a). Cellular structure of explosion flames: modelling and large-eddy simulation. Combustion Science and Technology. Vol. 176, pp. 851-865.

Molkov, VV, Makarov, DV and Prost, E (2005). On numerical simulation of liquefied and gaseous hydrogen releases at large scales. 1st International Conference on Hydrogen Safety. Pisa, Italy.

Molkov, VV, Makarov, DV and Puttock, J (2006). The nature and large eddy simulation of coherent deflagrations in a vented enclosure-atmosphere system. Journal of Loss Prevention in the Process Industries. Vol. 19, pp. 121-129.

Molkov, VV, Nikitenko, VM, Filippov, AV and Korolchenko, AY (1993b). Dynamics of gas explosion in a vented vessel with inertial vent covers. Proceedings of Joint Meeting of the Russian and Japanese Sections of the Combustion Institute, Russia, pp. 183-185.

NASA (1997). Safety standard for hydrogen and hydrogen systems. Guidelines for hydrogen system design, materials selection, operations, storage, and transportation. Technical report NSS 1740.16, Office of safety and mission assurance, Washington. Available from: http://www.hq.nasa.gov/office/codeq/doctree/canceled/871916.pdf NSS 1740.16 was cancelled on July 25 2005 [accessed 13.05.14].

NFPA 55, National Fire Protection Association (2010). Standard for the storage, use, and handling of compressed gases and cryogenic fluids in portable and stationary containers, cylinders, and tanks. Quincy, MA, 2010.

NFPA, National Fire Protection Association (2002). Society of Fire Protection Engineers Handbook, 3rd edition.

Ng, HD, Ju, Y and Lee, JHS (2007). Assessment of detonation hazards in high-pressure hydrogen storage from chemical sensitivity analysis. International Journal of Hydrogen Energy. Vol. 32, pp. 93-99.

Nibur, K and Somerday, B (2012). Mechanical test methods for gaseous hydrogen embrittlement," in Gaseous Hydrogen Embrittlement of Materials in Energy Technologies, R. Gangloff and B. Somerday, eds., Woodhead Publishing, Cambridge, UK.

Nishimura, I, Mogi, T and Dobashi, R (2013). Simple method for predicting pressure behaviour during gas explosions in confined spaces considering flame instabilities. Journal of Loss Prevention in the Process Industries. Vol. 26, pp. 351-354.

Nolan, DP (1999). Handbook of fire and explosion protection engineering principles for oil, gas, chemical, and related facilities. New York: William Andrew Publishing, USA.

Ogden J (2004). Hydrogen as an energy carrier: outlook for 2010, 2030 and 2050. Reprint from workshop proceedings. The 10-50 Solution: Technologies and Policies for a Low-Carbon Future. The Pew Center on Global Climate Change and the National Commission on Energy Policy, March 2004 UCD-ITS-RP-04-24, Institute of Transportation Studies University of California, Davis, 2004

Okabayashi, K, Hirashima, H, Nonaka, T, Takeno, K, Chitose, K and Hashiguchi, K (2007). Introduction of Technology for Assessment on Hydrogen Safety. Mitsubishi Heavy Industries Ltd. Technical Review. Vol. 44(1), pp. 1-3.

Pan, L, Fisher, SA, Jayanti, S and Hewitt, GF (1995). Measurement and prediction of temperature rise following sudden compression in a high-pressure pipeline. Transactions of the Institution of Chemical Engineers. Vol. 73 (Part B), pp. 18–20.

Pasman, HJ (2006). The challenge of risk control in a hydrogen based economy, Teaching Materials of 1st European Summer School on Hydrogen Safety. Belfast, UK, 15-24 August 2006.

PCT application (2011). Dual storage tank and PRD with variable aperture. Priority 21.04.2011 from GB 1106812.9, and 04.10.2011 from GB 111723.0.

Perrette, L, Paillere, H and Joncquet, G (2007). Presentation of the French National Project DRIVE: Experimental data for the evaluation of hydrogen risks onboard vehicles, the validation of numerical tools and the edition of guidelines. 2007 SAE World Congress and Exhibition (SP-2097).

Peters, N (2000). Turbulent combustion. Cambridge: Cambridge University Press.

Pförtner, H and Schneider, H (1983). Fraunhofer-institut fur treib-und explosivstoffe. ICT-Projektforschung 19/83. Forschungsprogramm "Prozeßgasfreisetzung - Explosion in der Gasfabrik und Auswirkungen von Druckwellen auf das Containment". Ballonversuche zur Untersuchung der Deflagration von Wasserstoff/Luft-Gemischen (Abschlußbericht). Dezember 1983.

Poinsot, T and Veynante, D (2001). Theoretical and numerical combustion. Edwards, Philadelphia.

Pope, SB (2000). Turbulent flows. Cambridge: Cambridge University Press.

Pritchard, DK and Rattigan, WM (2010). Hazards of liquid hydrogen. Buxton: Health and Safety Executive, Research report RR769.

Proust, C, Jamois, D and Studer, E (2011). International Journal of Hydrogen Energy. Vol. 36, pp. 2367-2373.

Reijerkerk, J (2009a). Hydrogen applications – Industrial Gas Industry. 5th ISCARW, Belfast, UK.

Reijerkerk, J (2009b). Hydrogen production, logistics and storage. Teaching materials of the 5th International Short Course and Advanced Research Workshop (ISCARW), 19-23 October 2009, Belfast, UK.

Risø Energy Report 3: Hydrogen and its competitors (2004). Edited by Larsen, H, Feidenhans, R and Petersen, LS. Risø National Laboratory. ISBN 87-550-3349-0.

Roberts, PT, Shirvill, LC, Roberts, TA, Butler, CJ and Royle, M (2006). Dispersion of hydrogen from

high-pressure sources. Proceedings of Hazards XIX Symposium. Manchester, UK.

Rogante, M, Battistella, P and Cesari, F (2006). Hydrogen interaction and stress-corrosion in hydrocarbon storage vessel and pipeline weldings. International Journal of Hydrogen Energy. Vol. 31, p. 597-601.

Ronney, PD (1990). Near-Limit flame structures at Low Lewis Number. Combustion and Flame. Vol. 82, pp. 1-14.

Ross, DK (2006). Hydrogen storage: the major technological barrier to the development of hydrogen fuel cell cars. Process Safety and Environmental Protection.

Rothe, V (2009). GM Permeation, delivered for presentation to the EC Hydrogen Working Group meeting on 10 March 2009, GM Powertrain Germany.

Royle, M and Willoughby, D (2012). Releases of unignited liquid hydrogen. HSL Report XS/11/70. Available from HSL: Buxton.

Royle, M and Willoughby, DB (2009). Consequences of catastrophic releases of ignited and unignited hydrogen jet releases. 3rd International Conference on Hydrogen Safety, Ajaccio, France.

Ruban, S, Heudier, L, Jamois, D, Proust, C, Boughy-Weber C et al. (2011). Fire risk of high-pressure full composite cylinders for automotive applications. 4th International Conference on Hydrogen Safety. San Francisco, USA.

Ruban, S, Heudier, L, Jamois, D, Proust, C, Bustamante-Valencia, L, Jallais, S, Kremer-Knobloch, K et al (2012). Fire risk on high-pressure full composite cylinders for automotive applications. International Journal of Hydrogen Energy, Vol. 37, pp. 17630-17638.

Ryazantcev, EP and Chabak, AF (2006). Hydrogen production, storage, and use at nuclear power plants. Atomic Energy. Vol. 101, pp. 876-881.

Rybin, H, Krainz, G, Bartlok, G and Kratzer, E (2005). Safety demands for automotive hydrogen storage systems. 1st International Conference on Hydrogen Safety. Pisa, Italy.

SAE J2578 (2009). Recommended practice for general fuel cell vehicle safety, a surface vehicle recommended practice, SAE International, Detroit, Michigan, USA, January, 2009.

SAE J2579 (2009). Technical information report for fuel systems in fuel cell and other hydrogen vehicles, SAE International, Detroit, Michigan, USA, January, 2009.

SAE J2601 (2010). Fuelling protocols for light duty gaseous hydrogen surface vehicles. A Surface Vehicle Technical Information Report, SAE International, Detroit, Michigan, USA.

SAE J2990 (2012). Hybrid and EV First and Second Responder Recommended Practice. USA

Saffers, JB (2010). Principles of hydrogen safety engineering. PhD thesis. University of Ulster.

Saffers, JB, Makarov, DV and Molkov, VV (2011). Modelling and numerical simulation of permeated hydrogen dispersion in a garage with adiabatic walls and still air. International Journal of Hydrogen Energy. Vol. 36(3), pp. 2582-2588.

Sakintuna, B, Lamari-Darkrim, F and Hirscher, M (2007). Metal hydride materials for solid hydrogen storage: A review. International Journal of Hydrogen Energy. Vol. 32, pp. 1121-1240.

San Marchi, C and Somerday, BP (2007). Effect of high-pressure gaseous hydrogen on structural metals. SAE 2007 Transactions Journal of Materials and Manufacturing. Vol. 116, pp. 94-109.

San Marchi, C, Somerday, BP and Robinson, SL (2007). Permeability, solubility and diffusivity of hydrogen isotopes in stainless steels at high gas pressures. International Journal of Hydrogen Energy. Vol. 32, pp. 100- 116.

Schefer, R, Groethe, M, Houf, W and Evans, G (2009). Experimental evaluation of barrier walls for risk reduction of unintended hydrogen releases. International Journal of Hydrogen Energy. Vol. 34, pp. 1590-1606.

Schefer, R, Houf, W, and Colton, J (2004). Experimental measurements to characterize the thermal and radiation properties of open flame hydrogen plume. 15th Annual Hydrogen Conference and Hydrogen Expo. Los Angeles, USA.

Schefer, RW, Houf, WG, Bourne, B and Colton, J (2006a). Spatial and radiative properties of an open flame hydrogen plume. International Journal of Hydrogen Energy. Vol. 31(10), pp. 1332-1340.

Schefer, RW, Houf, WG, San Marchi, C, Chernicoff, WP and Englom, L (2006b). Characterization of

leaks from compressed hydrogen dispensing systems and related components. International Journal of Hydrogen Energy. Vol. 31, pp. 1247-1260.

Schefer, RW, Houf, WG, Williams, TC, Bourne, B and Colton, J (2007). Characterization of high-pressure, underexpanded hydrogen-jet flames. International Journal of Hydrogen Energy. Vol. 32, pp. 2081-2093.

Schefer, RW, Merilo, EG, Groethe, MA and Houf, WG (2011). Experimental investigation of hydrogen jet fire mitigation by barriers. International Journal of Hydrogen Energy. Vol. 36, pp. 2530-2537.

Schneider, J, Gambone, L, McDougal, M, Dudgeon, M et al (2007). 70 MPa gaseous hydrogen storage fuelling testing. World Hydrogen Technologies Convention (WHTC 2007).

Schroeder, V and Holtappels, K (2005). Explosion characteristics of hydrogen-air and hydrogen-oxygen mixtures at elevated pressures. 1st International Conference on Hydrogen Safety, Pisa, Italy.

Schroeder, V, Emonts, B, Janssen, H and Schultze, HP (2004). Explosion limits of hydrogen/oxygen mixtures at initial pressures up to 200 bar. Chemical Engineering and Technology. Vol. 27, pp. 847-851.

Schultheiss, D (2007). Permeation barrier for lightweight liquid hydrogen tanks. PhD thesis. Augsburg University.

Shebeko, YN, Tsarichenko, SG, Eremenko, OY, Keller, VD and Trunev, AV (1990). Combustion of lean hydrogen-air mixtures in an atomized water stream. Combustion, Explosion and Shock Waves. Vol. 26, pp. 426-428.

Shepherd, J (1986). Chemical kinetics of hydrogen-air-diluent detonations. Progress in Aeronautics and Astronautics. Vol. 106, pp. 263-293.

Shepherd, JE (1985). Hydrogen steam jet flame facility and experiments. Technical Report NUREG/CR-3638, SAND84-0060, Sandia National Laboratories, Albuquerque, New Mexico.

Sherif, SA, Zeytinoglu, N and Veziroglu, TN (1997). Liquid hydrogen: potential, problems, and a proposed research program. International Journal of Hydrogen Energy. Vol. 22, pp. 683-688.

Shevyakov, GG and Komov, VF (1977). Effect of non-combustible admixtures on length of an axisymmetric on-port turbulent diffusion flame. Combustion, Explosion and Shock Waves. Vol. 13, pp. 563-566.

Shevyakov, GG and Savelieva, NI (2004). Dispersion and combustion of hydrogen jet in the open atmosphere. International Scientific Journal for Alternative Energy and Ecology. Vol. 1(9), pp. 23-27 (in Russian).

Shevyakov, GG, Tomilin, VP and Kondrashkov, YuA (1980). Engineering Physical Journal. deposit with VINITI, N3671-80 (in Russian).

Shirvill, LC and Roberts, TA (2006). Designing for safe operations: understanding the hazards posed by high-pressure leaks from hydrogen vehicle refuelling systems. National Hydrogen Association Annual Hydrogen Conference.

Shirvill, LC, Royle, M and Roberts, TA (2007). Hydrogen releases ignited in a simulated vehicle refuelling environment. 2nd International Conference for Hydrogen Safety, San-Sebastian, Spain.

Sivathanu, YR and Gore, JP (1993). Total radiative heat loss in jet flames from single point radiative flux measurements. Combustion and Flame. Vol. 94(3), pp. 265-270.

Somerday, BP and San Marchi, C (2008). Effects of hydrogen gas on steel vessels and pipelines. In: Jones RH, Thomas GJ, editors. Materials for the Hydrogen Economy. Boca Ranton: Taylor & Francis Group, USA, pp. 157-179.

Sørensen, B (2005). Hydrogen and fuel cells. Emerging technologies and applications. Elsevier Academic Press. ISBN-13:978-0-12-655281-2.

Stamps, DW and Berman, M (1991). High-temperature hydrogen combustion in reactor safety applications. Nuclear Science and Engineering. Vol. 109, pp. 39-48.

Stamps, DW, Slezak, SE and Tiezen, SR (2006). Observations of cellular structure of fuel-air detonations. Combustion and Flame. Vol. 144, pp. 289-298.

Stephenson, RR (2005). Fire safety of hydrogen-fuelled vehicles: system-level bonfire test. International Conference on Hydrogen Safety, Pisa, Italy.

Stolten, D (Ed) (2010). Hydrogen and Fuel Cells: Fundamentals, Technologies and Applications. Weinheim: Wiley-VCH.

Sunderland, P (2010b). Hydrogen vehicles and safety regulations in the U.S. Teaching materials of the 8th ISCARW, Belfast, UK, June 2010.

Sunderland, PB (2010a). Hydrogen microflame hazards, Proceedings of the 8th International Short Course and Advanced Research Workshop in the series "Progress in Hydrogen Safety", Hydrogen and Fuel Cell Early Market Applications, 11 - 15 October 2010, University of Ulster, Belfast.

Suzuki, J, Tamura, Y, Watanabe, S and Takabayashi, M (2006). Fire safety evaluation of a vehicle equipped with hydrogen fuel cylinders; comparison with gasoline and CNG vehicles. SAE World Congress & Exhibition. April 2006.

Swain, MR and Swain, MN (1992). A comparison of H_2, CH_4, and C_3H_8 fuel leakage in residential settings. International Journal of Hydrogen Energy. Vol. 17, pp. 807-815.

Swain, MR and Swain, MN (1996). Passive ventilation systems for the safe use of hydrogen. International Journal of Hydrogen Energy. Vol. 21, pp. 823-835.

Swain, MR, Filoso, P, Grilliot, ES and Swain, MN (2003). Hydrogen leakage into simple geometric enclosures. International Journal of Hydrogen Energy. Vol. 28, pp. 229-248.

Takeno, K, Okabayashi, K, Kouchi, A, Nonaka, T, Hashiguchi, K and Chitose, K (2007). Dispersion and explosion field tests for 40MPa pressurized hydrogen. International Journal of Hydrogen Energy. Vol. 32, pp. 2144-2153.

Tamm, H, Ungurian, M and Kumar, RK (1987). Effectiveness of thermal ignition devices in rich hydrogen -air-steam mixtures. Technical Report EPRI NP-5254, Electric Power Research Institute, Palo Alto, California.

Tamura, Y, Masayuki, T and Sato, K (2013). Validity of low ventilation for accident processing with hydrogen leakage from hydrogen-fuelled vehicles. SAE Technical paper 2013-01-0211.

Tanaka, H, Tokoyoda, K, Matsumoto. M, Suzuki, Y, Kiyobayashi, T and Kuriyama, N (2009). Hazard assessment of complex hydrides as hydrogen storage materials. International Journal of Hydrogen Energy. Vol. 34, pp. 3210-3218.

Tanaka, T, Azuma, T, Evans, JA, Cronin, PM, Johnson, DM and Cleaver, RP (2007). Experimental study on hydrogen explosions in a full-scale hydrogen filling station model. International Journal of Hydrogen Energy. Vol. 32, pp. 2162-2170.

Tang, MJ and Baker, QA (1999). A new set of blast curves from vapor cloud explosion. Process Safety Progress. Vol. 18(4), pp. 235-240.

Teodorczyk, A (2006). Fast deflagrationa, deflagration to detonation transition (DDT) and direct detonation of hydrogen-air mixtures. Teaching Materials of European Summer School on Hydrogen Safety, 2006.

Teodorczyk, A (2007). Limits of steady propagation of hydrogen deflagrations and detonations. Teaching Materials of 2nd European Summer School on Hydrogen Safety, Belfast, UK.

The McPhy Energy (2014). Available from: http://www.mcphy.com/en/technologies/solid-hydrogen-storage/mcphy-technology/ [accessed 04.05.14].

The nanotube site. Available from: http://www.pa.msu.edu/cmp/csc/nanotube.html [accessed 04.05.14].

Tieszen, SR, Sherman, MP, Benedick, WB, Shepherd, JE, Knystautas, R and Lee, JHS (1986). Detonation cell size measurements in hydrogen-air-steam mixtures. Progress in Astronautics Aeronautics. Vol. 106, pp. 205–219.

TNO Green Book (1992). Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials, Report CPR 16E, Voorburg, The Netherlands.

Tromp, TK, Shia, R-L, Allen, M, Eiler, JM and Yung, YL (2003). Potential environmental impact of a hydrogen economy on the stratosphere. Science. Vol. 300, pp. 1740-1742.

Tse, SD, Zhu, DL and Law, CK (2000). Morphology and burning rates of expanding spherical flames in H2/O2/inert mixtures up to 60 atmospheres. Proceedings of the 28th Symposium (International) on Combustion, Pittsburgh, PA: The Combustion Institute, pp. 1793-1800.

Turns, SR (2000). An introduction to combustion: Concepts and applications. Singapore: McGraw-Hill. 2nd Ed. 676p.

Turns, SR and Myhr, FH (1991). Oxides of nitrogen emissions from turbulent jet flames: Part I-Fuel effects and flame radiation. Combustion and Flame. Vol. 87, pp. 319-335.

US DoE US Department of Energy (2006). Technical assessment: Cryo-compressed hydrogen storage for vehicular applications. Available from: http://www.hydrogen.energy.gov/pdfs/cryocomp_report.pdf [accessed 04.05.14].

US DoE, US Department of Energy (2008). Hydrogen safety training for first responders. Available from: http://hydrogen.pnl.gov/FirstResponders/ [accessed on 13.05.14].

Venetsanos, AG, Huld, T, Adams, P and Bartzis, JG (2003). Source, dispersion and combustion modelling of an accidental release of hydrogen in an urban area. Journal of hazardous materials. Vol. A105, pp. 1-25.

Verbecke, F, Makarov, D and Molkov, V (2009). VLES of lean hydrogen-air deflagrations in a closed 5.7m height vessel. 6th Mediterranean Combustion Symposium, Ajaccio, France.

Verfondern, K (1997). Considerations of hydrogen as a future energy carrier and its production by nuclear power. Forschhungszentrum Juelich, FZJ-ISR-IB-/9-97.

Verfondern, K (2008). Safety considerations of liquid hydrogen. Forschungszentrum Jülich, GmbH, Jülich, 178 p., ISBN 978-3-89336-530-2.

Verfondern, K (Ed) (2007). Nuclear energy for hydrogen production. Energy Technology. Vol. 58. Jülich: Forschungszentrum Jülich GmbH, 199 p.

Verfondern, K and Dienhart, B (1997). Experimental and theoretical investigation of hydrogen pool spreading and vaporization. International Journal of Hydrogen Energy. Vol. 22, pp. 649-660.

Verfondern, K and Dienhart, B (2007). Pool spreading and vaporization of liquid hydrogen. International Journal of Hydrogen Energy. Vol. 32, pp. 256-267.

Verfondern, K, Jahn, W, Reinecke, E-A and Tragsdorf, IM (2004). Experimental investigations and numerical modelling on hydrogen recombining devices in closed areas. 15th World Hydrogen Energy Conference. Yokohama, Japan.

Veser, A, Kuznetsov, M, Fast, G, Friedrich, A, Kotchourko, N, Stern, G, et al. (2009). The structure and flame propagation regimes in turbulent hydrogen jets. 3rd International Conference on Hydrogen Safety, Ajaccio, France.

Vieira, A, Faria, H, de Oliveira, R, Correia, N and Marques, AT (2007). H2 high pressure on-board storage considering safety issues. 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007.

Walker, G (Ed) (2008). Solid-state hydrogen storage. Materials and chemistry. Boca Raton: Woodhead Publishing Ltd, USA.

Warnatz, J, Maas, U and Dibble, RW (2006). Combustion. Physical and chemical fundamentals, modeling and simulations, experiments, pollutants formation. 4th edition. Berlin: Springer-Verlag.

Weast, RC and Astle, MJ (1979). CRC Handbook of Chemistry and Physics. 59th edition. West Palm Beach: CRC Press, Inc.

Wen, JX. Hydrogen fires (2006). Teaching Materials of the First European Summer School on Hydrogen Safety, 15-24 August 2006.

Weyandt, N (2005). Analysis of induced catastrophic failure of a 5000 psig type IV hydrogen cylinder. Motor Vehicle Fire Research Institute. Report. February, 2005. Available from: www.mvfri.org [accessed 04.05.14].

Weyandt, N (2006). Vehicle bonfire to induce catastrophic failure of a 5000-psig hydrogen cylinder installed on a typical SUV, Motor Vehicle Fire Research Institute. Report. December, 2006. Available from: www.mvfri.org [accessed 04.05.14].

Weyandt, N (2007). Intentional failure of a 5000 psig hydrogen cylinder installed in a SUV without standard required safety devices: 2007-01-0431. SAE World Congress & Exhibition. April 2007.

Whitehouse, DR, Greig, DR and Koroll, GW (1996). Combustion of stratified hydrogen-air mixtures in the 10.7 m3 combustion test facility cylinder. Nuclear Engineering and Design. Vol. 166, 453-462.

Wierzba, I and Ale, BB (2000). Rich flammability limits of fuel mixtures involving hydrogen at elevated temperature. International Journal of Hydrogen Energy. Vol. 25, pp. 75-80.

Wierzba, I and Kilchyk, V (2001). Flammability limits of hydrogen-carbon monoxide mixtures at moderately elevated temperatures. International Journal of Hydrogen Energy. Vol. 26, pp. 639-643.

Wierzba, I and Wang, Q (2006). The flammability limits of H2-CO-CH4 mixtures in air at elevated temperatures. International Journal of Hydrogen Energy. Vol. 31, pp. 485-489.

Wierzba, I, Karim, GA, Cheng, H (1986). The rich flammability limits of fuel mixtures containing hydrogen. American Institute of Chemical Engineers. Vol. 81, p. 251.

Williams, FA (1985). Combustion theory. 2nd edition. Menlo Park, California: The Benjamin/Cummings Publishing Company.

Willoughby, DB and Royle, M (2009). The interaction of hydrogen jet releases with walls and barriers. 3rd International Conference on Hydrogen Safety, Ajaccio, France.

Willoughby, DB and Royle, M (2011). The interaction of hydrogen jet releases with walls and Barriers. International Journal of Hydrogen Energy. Vol. 36, pp. 2455-2461.

Wionsky, SG (1972). Predicting Flammable Material Classifications. Chemical Engineering. Vol. 79, no. 26, pp. 81-86.

Witcofsky, RD and Chirivella, JE. (1984). Experimental and analytical analysis of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills. International Journal of Hydrogen Energy. Vol. 9, pp. 425-435.

Wolanski, P and Wojcicki, S (1972). Investigation into the mechanism of the diffusion ignition of a combustible gas flowing into an oxidizing atmosphere. Proceedings of the Combustion Institute. Vol. 14, pp. 1217-1223.

Woods, SS (2008). Aerospace hydrogen hazard assessment. Teaching materials of the 3rd European Summer School on Hydrogen Safety, Belfast, UK, July 2008.

World Bank, Techniques for assessing industrial hazards (1988). World Bank Technical Paper Number 55.

Worsell, N (1996). Risk of Ignition of Explosive Atmospheres. Health and Safety Laboratory Report No. RAS/96/13.

WRC, World Radiation Centre (2008). Solar constant. Available from: http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant [accessed 15.05.14].

Xu, BP and Wen, JX (2011). Numerical study of spontaneous ignition of pressurized hydrogen release through a length of tube with local contraction. 4th International Conference on Hydrogen Safety, San Francisco, USA.

Xu, BP, Wen, JX, Dembele, S, Tam, VHY and Hawksworth, SJ (2009). The effect of pressure boundary rupture rate on spontaneous ignition of pressurized hydrogen release. Journal of Loss Prevention in the Process Industries. Vol. 22(3), pp. 279-287.

Yang, JC, Pitts, WM, Fernandez, M and Kuldeep, P (2011). Measurements of effective diffusion coefficients of helium and hydrogen through gypsum. Proceedings of the Fourth International Conference on Hydrogen Safety, paper ID 144, 12-14 September 2011, San Francisco, USA.

Zabetakis, MG (1956). Research on the combustion and explosion hazards of hydrogen-water vapor-air mixtures. Technical Report AECU-3327, U.S. Atomic Energy Commission Report.

Zabetakis, MG (1967). Safety with cryogenic fluids. New York: Plenum Press.

Zabetakis, MG and Burgess, DS (1961). Research on the hazards associated with the production and handling of liquid hydrogen. Bureau of Mines Report of Investigation RI 5707, US Department of Interior.

Zalosh, R (2006). Hydrogen mixing in large enclosures. Teaching Materials of the First European Summer School on Hydrogen Safety, Belfast, 15-24 August, 2006.

Zalosh, R (2007). Blast waves and fireballs generated by hydrogen fuel tank rupture during fire exposure. Proceedings on the 5th Seminar on Fire and Explosion Hazard, Edinburgh, UK, 23-27 April 2007, pp. 2154-2161.

Zalosh, R and Weyandt, N (2005). Hydrogen fuel tank fire exposure burst test. SAE Paper No. 2005-

01-1886.

Zbikowski, M (2010). Hydrolssongen deflagration-to-detonation transition and its mitigation technologies. PhD thesis, University of Ulster, September 2010.

Zbikowski, M, Makarov, D and Molkov, V (2008). LES model of large scale hydrogen–air planar detonations: Verification by the ZND theory. International Journal of Hydrogen Energy. Vol. 33, pp. 4884-4892.

Zbikowski, M, Makarov, D and Molkov, V (2010). Numerical simulations of large-scale detonation tests in the RUT facility by the LES model. Journal of Hazardous Materials. Vol. 181(1-3), pp. 949-956.

Zeldovich, YB (1980). Regime classification of an exothermic reaction with non-uniform initial conditions. Combustion and Flame. Vol. 39, pp. 211-214.

Zhevago, NK, Denisov, EI and Glebov, VI (2010). Experimental investigation of hydrogen storage in capillary arrays. International Journal of Hydrogen Energy. Vol. 35, pp. 169-175.

Zimont, VL and Lipatnikov, AN (1995). A numerical model of premixed turbulent combustion of gases. Chemical Physics Reports. Vol. 14, no. 7, pp. 993-1025.

Glossary

Accident is an unforeseen and unplanned event or circumstance causing loss or injury.

Auto-ignition temperature is the minimum temperature required to initiate combustion reaction of fuel-oxidiser mixture in the absence of an external source of ignition.

Boiling point is the temperature to which a fuel must be cooled in order to store and use it as a liquid. The *normal boiling point* (NBP) of a liquid is the case in which the vapour pressure of the liquid equals the defined atmospheric pressure at sea level (1 atmosphere or 101,325 Pa). The *standard boiling point* (SBP) is defined as the temperature at which boiling occurs under a pressure of 1 bar (100,000 Pa).

Consequences are expected effects from the realization of hazard severity usually measured in terms of life safety exposure, property damage and environmental impact.

Deflagration and **detonation** are propagation of a combustion zone at a velocity that is respectively less than and greater than the speed of sound in the unreacted mixture.

Equivalence ratio is the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio.

Fire-resistance rating is a measure of time for which a passive fire protection system can withstand a standard fire resistance test.

Flammability range is the range of concentrations between the lower and the upper flammability limits.

Flashpoint is the lowest temperature at which the fuel produces enough vapours to form a flammable mixture with air at its surface.

Fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electrical energy, heat and reaction products

Hazard is a chemical or physical condition that has the potential for causing damage to people, property and the environment.

Hydrogen safety engineering is an application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen.

Incident is something that occurs casually in connection with something else.

Laminar burning velocity is the rate of flame propagation relative to the velocity of the unburned gas that is ahead of it, under stated conditions of composition, temperature, and pressure of the unburned gas.

Limiting oxygen index is the minimum concentration of oxygen that will support flame propagation in a mixture of fuel, air, and nitrogen.

Lower flammability limit (LFL) is the lowest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame.

Mach disk is a strong shock normal to the under-expanded jet flow direction.

Maximum experimental safe gap (MESG) of flammable gases and vapours is the lowest value of the safe gap measured according to IEC 60079-1-1 (2002) by varying the composition of the mixture. The safe gap is the gap width (determined with a gap length of 25 mm) at which in the case of a given mixture composition, a flashback just fails to occur.

Minimum ignition energy (MIE) of flammable gases and vapours is the minimum value of the electric energy, stored in the discharge circuit with as small a loss in the leads as possible, which

(upon discharge across a spark gap) just ignites the quiescent mixture in the most ignitable composition. For a given mixture composition the following parameters of the discharge circuit must be varied to get the optimum conditions: capacitance, inductivity, charging voltage, as well as shape and dimensions of the electrodes and the distance between electrodes.

Normal Temperature and Pressure (NTP) conditions are: temperature 293.15 K and pressure 101.325 kPa.

Quenching distance is the maximum distance between two parallel plates that will extinguish a flame passing between the plates.

Quenching gap is the spark gap between two flat parallel-plate electrodes at which ignition of combustible fuel-air mixtures is suppressed. The quenching gap is the passage gap dimension requirement to prevent propagation of an open flame through a flammable fuel-air mixture that fills the passage.

Permeation is the movement of atoms, molecules, or ions into or through a porous or permeable substance.

Scenario is the set of circumstances, chosen as an example that defines the development of incident/accident involving hydrogen

Separation distance is the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident.

Severity is qualitative or quantitative estimate of the hazard intensity in terms of source intensity, time and distance.

Specific gravity is the ratio of the density of a substance to the density of a reference substance, both at the same temperature and pressure.

Sublimation is the change directly from solid to vapour or vice versa without going through the liquid phase.

Reynolds number is a dimensionless number that gives a measure of the ratio of inertial to viscous forces.

Risk is the combination of the probability of an event and its consequence.

Under-expanded jet is a jet with a pressure at the nozzle exit which is above atmospheric pressure.

Upper flammability limit (UFL) is the highest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame.

Appendix 1. A schedule of a one week course on hydrogen safety training for First Responders (an example)

Morning sessions

First session program

	Monday	Tuesday	Wednesday	Thursday	Friday
08h00-08h30	**Welcome**	**CyberLaboratory** Lecturer: STM	**CyberLaboratory** Lecturer: STM	**CyberLaboratory** Lecturer: STM	**CyberLaboratory** Lecturer: STM
8h30-9h15	**Educational training. Lecture 1.** Introduction to FCH applications and hydrogen safety. Lecturers: STM, AZ, FV, SB	**Educational training. Lecture 3.** Safety of compressed hydrogen storage. Lecturers: STM, VM	**Educational training. Lecture 6.** Harm criteria for people and environment, damage criteria for structures. Lecturers: STM,VM	**Educational training. Lecture 12.** Hazards of hydrogen use indoors. Lecturers: STM,VM	**Educational training. Lecture 9.** Ignition sources and prevention of ignition. Lecturers: STM,VM
9h15-10h00	**Educational training. Lecture 4.** Hydrogen properties relevant to safety. Lecturers: STM, VM	**Strategies and intervention** Methodology and response guide Instructors: FL	**Educational training. Lecture 8.** Unignited hydrogen releases and their mitigation. Lecturers: STM,VM	**Educational training. Lecture 11.** Dealing with hydrogen explosions. Lecturers: STM,VM	**Virtual Reality Training** Exercise: Multi vehicle accident - dismantled storage - H2 jet fire from H2 trailer - extrication r conventional car - hazmat trailer involved-motorway. Animator: EM Instructors: 2 officers advisors
	Break 30 min				
10h30-11h15	**Educational training. Lecture 10.** Hydrogen fires. Lecturers: STM,VM	**Strategies and intervention – class exercises.** **FC vehicles accidents (car, bus, forklift)** - Applications description - Safety features and related RCS -Typical scenarios - Intervention strategy and tactics Instructors: AZ, FV, STM, FL, SB	**Strategies and intervention – class exercises.** **Refuelling stations, storage and FC system accidents.** - Applications description - Safety features and related RCS -Typical scenarios - Intervention strategy and tactics Instructors: AZ, FV, STM, SB, FL, FH	**Strategies and intervention – Class exercises.** **Stationary and mobility applications** - Applications description - Safety features and related RCS -Typical scenarios - Intervention strategy and tactics Instructors: AZ, FV, STM, SB, FL, FH	
11h15-12h00	**Educational training. Lecture 2.** RCS for First Responders. Lecturer: RD, AZ				**Synthesis of training** **all Partners**
	Break 2 h				

European Hydrogen Emergency Response training programme for First Responders

Afternoon sessions

	Discovery level			Advanced level			Expert level	
14h00-14h45	**VR Platform Presentation** Using virtual reality safety procedure, etc. Animator: EM Instructors: FV, FL, SB		**Operational Training** Exercise: Single FC car accident - FC car in a fire - no extrication - small road (FC_Car_D_F2) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: FC bus in a fire on a small road (FC_Bus_D_F1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: H2 leak at a refuelling station (H2_Refuelling_A_L1) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: FC car in fire at a refuelling station (H2_Refuelling_E_E1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: Multi-vehicle accident - dismantled storage - H2 jet fire from H2 trailer - extrication conventional car - motorway (FCT_E_F6) 3 Instructors ENSOSP: exercise director safety officer	**Virtual Reality Training** Exercise: Multi-vehicle accident - FC bus in a fire - extrication conventional car - urban environment (FC_Bus_E_F3) Animator: EM Instructors: 2 officers advisors
	Outfit change (fire suits)		Break 15 min					
15h00-15h45	**Operational Platform demonstration** Instructors: FL, SB, FV, AZ Jet fires, delayed ignition, gas sensors efficiency for H2,CNG,LPG		**Operational Training** Exercise: Multi-vehicle accident - FC car in a fire - no extrication - motorway (FC_Car_A_E2) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: Forklift in a fire inside a warehouse. (FC_Forklift_A_F1) Animator: EM Instructors: 2 officers 2 advisors	**Operational Training** Exercise: FC system default - H2 leak - urban environment (FC_System_E_L1) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: H2 storage - H2 jet fire - industrial environment (H2_Storage_E_F1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: H2 storage default – H2 leak – Refuelling station – urban environment (FC_System_E_L1) 3 Instructors ENSOSP: exercise director safety officer	**Virtual Reality Training** Exercise: Fire in an industrial environment - FC system in the environment (FCSY_E_E1) Animator: EM Instructors: 2 officers advisors
	Operational Platform exercices H2 jet fires 3 Instructors ENSOSP: exercise director safety officier field officer +advisors	**Explosion demonstrations** 2 Instructors ENSOSP: safety officier field officer +advisors (CNG and H2 explosions at various concentrations)	Break 30 min					
16h15-17h00			**Virtual Reality Training** Exercise: FC bus in a fire on a small road (FC_Bus_D_F1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: Single FC car accident - FC car in a fire - no extrication - small road (FC_Car_D_F2) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: FC car in a fire at a refuelling station (H2_Refuelling_E_E1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: H2 leak at a refuelling station (H2_Refuelling_A_L1) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: Multi vehicle accident - FC bus in a fire - extrication conventional car - urban environment (FC_Bus_E_F3) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: Multi vehicle accident - dismantled storage - H2 jet fire from H2 trailer - extrication conventional car - motorway (H2_Trailer_E_F6) 3 Instructors ENSOSP: exercise director safety officer
17h00-17h45	**Explosion demonstrations** 3Instructors ENSOSP: safety officer field officer +advisors (CNG and H2 explosions at various concentrations)	**Operational Platform exercices** H2 jet fires 2 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: Forklift in a fire inside a warehouse. (FC_Forklift_A_F1) Animator: EM Instructors: 2 officers 2 advisors	**Operational Training** Exercise: Multi-vehicle accident - FC car in a fire - no extrication - motorway (FC_Car_A_E2) 3Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: H2 storage - H2 jet fire - industrial environment (H2_Storage_E_F1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: FC system default - H2 leak - urban environment (FC_System_E_L1) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors	**Virtual Reality Training** Exercise: Fire in an industrial environment - FC system in the environment (FC_System_E_E1) Animator: EM Instructors: 2 officers advisors	**Operational Training** Exercise: H2 storage default – H2 leak – Refuelling station – urbanenvironment (H2_Trailer_E_L1) 3 Instructors ENSOSP: exercise director safety officer field officer +advisors
17h45-18h15	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**	**Debriefing in classroom**

Legend:
- Lecture
- Strategies and intervention
- Operational platform
- Virtual reality training

2 groups -> 12 people per group max

Teachers:
FV - Franck Verbecke
STM - Svetlana Tretsiakova-McNally
AZ - Adrien Zanoto
VM - Vladimir Molkov
RD - Randy Dey
EM - Eric Maranne
FL - Francois Laumanne

Appendix 2. International and European RCS list relevant to HyResponse

International and European Regulations – Operation			
EC Directive	**Scope**	**Description**	**Covered applications - examples**
1999/92/EC	Improving the safety and health protection of workers potentially at risk from explosive atmospheres	This Directive deals with the minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres. It sets out the responsibilities of employers and not manufacturers.	- For all applications with flammable and explosive substances
98/24/EC	Protection of the health and safety of workers from the risks related to chemical agents at work	This Directive aim is to protect people and the environment against substance-related damage by means of regulations on the classification, labelling and packaging of dangerous substances and preparations, measures to protect workers and other persons during activities involving hazardous substances and restrictions on the manufacture and use of specific hazardous substances, preparations and articles.	- For all applications with chemical substances
2003/105/EC (amending of 86/82/EC)	Control of major-accident hazards involving dangerous substances (Seweso II)	This Directive is aimed at the prevention of major accidents which involve dangerous substances, and the limitation of their consequences for man and the environment, with a view to ensuring high levels of protection throughout the Community in a consistent and effective manner.	- For establishments where dangerous substances are present in large quantities

International and European Regulations – Manufacturing			
EC Directive	**Subject**	**Description**	**Covered applications - examples**
Orange book	UN Model Regulations UN Recommendations on the Transport of Dangerous Goods - Model Regulations	1. These Recommendations have been developed by the United Nations Economic and Social Council's Committee of Experts on the Transport of Dangerous Goods in the light of technical progress, the advent of new substances and materials, the exigencies of modern transport systems and, above all, the requirement to ensure the safety of people, property and the environment. They are addressed to governments and international organizations concerned with the regulation of the transport of dangerous goods. They do not apply to the bulk transport of dangerous goods in sea-going or inland navigation bulk carriers or tank-vessels, which is subject to special international or national regulations.	- Trailers - Cylinders (type I-IV) - Pressure receptacles, their valves and other accessories - tanks, battery vehicles/wagons, multiple-element gas containers (MEGCs), their valves and other accessories
2008/68/EC	Transport of dangerous goods ➔ ADR/RID	This Directive shall apply to the transport of dangerous goods by road, by rail or by inland waterway within or between Member States, including the activities of loading and unloading, the transfer to or from another mode of transport and the stops necessitated by the circumstances of the transport. ➔ See ADR/RID 2013 as well	- Trailers - Cylinders (type I-IV) - Pressure receptacles, their valves and other accessories - tanks, battery vehicles/wagons, multiple-element gas containers (MEGCs), their valves and other accessories
Draft Global technical regulation No. xx Hydrogen Fueled Vehicle	Hydrogen Fueled Vehicle	This regulation specifies safety-related performance requirements for hydrogen-fueled vehicles. The purpose of this regulation is to minimize human harm that may occur as a result of fire, burst or explosion related to the vehicle fuel system and/or from electric shock caused by the vehicle's high voltage system. This regulation applies to all hydrogen fueled vehicles of Category 1-1 and 1-2, with a gross vehicle mass (GVM) of 4,536 kilograms or less.	- Hydrogen fuelled vehicles
EU 79/2009 **(Regulation)**	Approval of Hydrogen-Powered Motor Vehicles	This Regulation shall apply to: 1. hydrogen-powered vehicles of categories M and N, as defined in Section A of Annex II to Directive 2007/46/EC, including impact protection and the electric safety of such vehicles; 2. hydrogen components designed for motor vehicles of categories M and N; 3. hydrogen systems designed for motor vehicles of categories M and N, including	- FCHV - Storage cylinders for hydrogen vehicles - Components for hydrogen vehicles

International and European Regulations – Manufacturing			
EC Directive	**Subject**	**Description**	**Covered applications - examples**
		new forms of hydrogen storage or usage.	
EU 406/2010 **(Regulation)**	Approval of hydrogen-powered motor vehicles	See EU 79/2009	- FCHV - Storage cylinders for hydrogen vehicles - Components for hydrogen vehicles
97/23/EC	Pressure Equipment Directive (PED)	This Directive applies to the design, manufacture and conformity assessment of pressure equipment and assemblies with a maximum allowable pressure PS greater than 0,5 bar (0,05 MPa). Pressure equipment means vessels, piping, safety accessories and pressure accessories. For a complete list of harmonized standards: http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/pressure-equipment/index_en.htm	- For gases (GH2) and liquids (LH2) - Stationary storage - Compressor - HRS - Fuel cell applications - Piping - Assemblies - Components and equipment
2006/95/EC	Low Voltage Directive (LVD)	For the purposes of this Directive, 'electrical equipment' means any equipment designed for use with a voltage rating of between 50 and 1 000 V for alternating current and between 75 and 1 500 V for direct current. For a complete list of harmonized standards: http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/low-voltage/index_en.htm	- Fuel cell applications - Electrical and control equipment
2004/108/EC	Electromagnetic Compatibility (EMC)	Regulates the electromagnetic compatibility of equipment. Aims to ensure the functioning of the internal market by requiring equipment to comply with an adequate level of electromagnetic compatibility. For a complete list of harmonized standards: http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/electromagnetic-compatibility/index_en.htm	- Fuel cell applications - Electrical and control equipment - Equipment with electrical components in general
2010/35/EU	Transportable Pressure Equipment (TPED)	This Directive sets out detailed rules concerning transportable pressure equipment to enhance safety and ensure free movement of such equipment within the Union.	- Pressure receptacles, their valves and other accessories - tanks, battery vehicles/wagons, multiple-element gas containers (MEGCs), their valves and other accessories
2009/105/EC	Simple Pressure Vessels	Simple pressure vessels are welded vessels produced in series with an internal	- Air compressor

International and European Regulations – Manufacturing			
EC Directive	**Subject**	**Description**	**Covered applications - examples**
	(SPVD)	overpressure of more than 0,5 bar which are used for air or nitrogen and are not expose fire exposure. Excluded are vessels specifically designed for nuclear use, failure of which may cause an emission of radioactivity, vessels specifically intended for installation in or the propulsion of ships and aircraft and fire extinguishers. For a complete list of harmonized standards: http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/simple-pressure-vessels/index_en.htm	
2006/42/EC	Machinery Directive (MD)	This Directive applies to products like machinery, interchangeable equipment, safety components, lifting accessories, chains, ropes and webbing, removable mechanical transmission devices and partly completed machinery. Machinery means an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application. Safety component' means a component which serves to fulfil a safety function, is independently placed on the market, the failure and/or malfunction of which endangers the safety of persons, and is not necessary in order for the machinery to function, or for which normal components may be substituted in order for the machinery to function. For a complete list of harmonized standards: http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/machinery/index_en.htm	- Drive of pumps, compressors etc. - Safety components

1. EN/ISO/IEC and other RCS for hydrogen applications

RCS	Scope	Description	Covered applications - examples
ISO 15916	Basic considerations for the safety of hydrogen systems	This Technical Report provides guidelines for the use of hydrogen in its gaseous and liquid forms. It identifies the basic safety concerns and risks, and describes the properties of hydrogen that are relevant to safety.	- Storage - Compressor - HRS - Assemblies - CHP - Fuel cell systems - Production
ISO 16110-1	Hydrogen generators using fuel processing technologies — Part 1: Safety	This part of ISO 16110 applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than 400 m3/h at 0 °C and 101,325 kPa, herein referred to as hydrogen generators, that convert an input fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen (e.g. a fuel cell power system or a hydrogen compression, storage and delivery system). It applies to hydrogen generators using one or a combination of the following input fuels: • natural gas and other methane-rich gases derived from renewable (biomass) or fossil fuel sources, e.g. landfill gas, digester gas, coal mine gas; • fuels derived from oil refining, e.g. diesel, gasoline, kerosene, liquefied petroleum gases such as propane and butane; • alcohols, esters, ethers, aldehydes, ketones, Fischer-Tropsch liquids and other suitable hydrogen-rich organic compounds derived from renewable (biomass) or fossil fuel sources, e.g. methanol, ethanol, di-methyl ether, biodiesel; • gaseous mixtures containing hydrogen gas, e.g. synthesis gas, town gas. This part of ISO 16110 is applicable to stationary hydrogen generators intended for indoor and outdoor commercial, industrial, light industrial and residential use. It aims to cover all significant hazards, hazardous situations and events relevant	- Hydrogen generation - Reforming

RCS	Scope	Description	Covered applications - examples
		to hydrogen generators, with the exception of those associated with environmental compatibility (installation conditions), when they are used as intended and under the conditions foreseen by the manufacturer. NOTE A list of significant hazards and hazardous situations dealt with in this part of ISO 16110 is found in Annex A. This part of ISO 16110 is a product safety standard suitable for conformity assessment as stated in IEC Guide 104, ISO/IEC Guide 51 and ISO/IEC Guide 7.	
ISO 22734-1	Hydrogen generators using water electrolysis process — Part 1: Industrial and commercial applications	This International Standard defines the construction, safety and performance requirements of packaged or factory matched hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water to produce hydrogen and oxygen gas. This International Standard is applicable to hydrogen generators that use the following types of ion transport medium: • Group of aqueous bases; • Solid polymeric materials with acidic function group additions such as acid proton exchange membrane (PEM). This part of ISO 22734 is applicable to hydrogen generators intended for indoor and outdoor commercial and industrial use (non-residential use). Hydrogen generators that can also be used to generate electricity such as reversible fuel cells are excluded from the scope of this International Standard. This International Standard is intended to be used for certification purposes.	- Hydrogen generation - Electrolyser
ISO 22734-2	Hydrogen generators using water electrolysis process — Part 2: Residential applications	This standard defines the construction, safety and performance requirements of packaged hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water. This standard is applicable to hydrogen generators that use the following types of ion transport medium: • group of aqueous bases; • solid polymeric materials with acidic function group additions such as acid proton exchange membrane (PEM). This standard is applicable to hydrogen generators intended for indoor and outdoor residential use (non-commercial and non-industrial use) in sheltered areas such as car-ports, garages, utility rooms and similar areas of a residence. This standard	- Hydrogen generation - Electrolyser

RCS	Scope	Description	Covered applications - examples
		includes cord-connected equipment for outdoor and garage use only. Hydrogen generators that can also be used to generate electricity such as reversible fuel cells are excluded from the scope of this standard. This standard does not include portable hydrogen generators. Hydrogen generators that also supply oxygen as a product are excluded from the scope of this standard. This standard is intended to be used for certification purposes.	
ISO/TS 20100	Gaseous hydrogen fuelling stations	This Technical Specification specifies the characteristics of outdoor public and non-public fuelling stations that dispense gaseous hydrogen used as fuel onboard land vehicles of all types.	- HRS
ISO 15399	Gaseous Hydrogen — Cylinders and tubes for stationary storage	The standard covers cylinders and tubes intended for the stationary storage of gaseous hydrogen of up to a maximum volume of 10 000 l and a maximum pressure of 110 MPa, of seamless metallic construction or of composite construction.	- Storage cylinders and tubes
ISO 17268	Compressed hydrogen surface vehicle refuelling connection devices	This International Standard applies to design, safety and operation verification of Compressed Hydrogen Surface Vehicle (CHSV) refuelling connection devices hereinafter referred to as nozzle and receptacle. CHSV Refuelling nozzles and receptacles consist of the following components, as applicable	- FCHV - HRS
ISO 26142	Hydrogen detection apparatus — Stationary applications	This International Standard defines the performance requirements and test methods of hydrogen detection apparatus that is designed to measure and monitor hydrogen concentrations in stationary applications. The provisions in this International Standard cover the hydrogen detection apparatus used to achieve the single and/or multilevel safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration. The requirements applicable to the overall safety system, as well as the installation requirements of such apparatus, are excluded. This International Standard sets out only the requirements applicable to a product standard for hydrogen detection apparatus, such as precision, response time, stability, measuring range, selectivity and poisoning. This International Standard is intended to be used for certification purposes.	- Hydrogen detectors
IEC 60079-10-1	Explosive atmospheres - Part 10-1:	IEC 60079-10-1 is concerned with the classification of areas where flammable gas	- Classification of areas - Explosive gas

RCS	Scope	Description	Covered applications - examples
	Classification of areas - Explosive gas atmospheres	or vapour or mist hazards may arise and may then be used as a basis to support the proper selection and installation of equipment for use in a hazardous area. It is intended to be applied where there may be an ignition hazard due to the presence of flammable gas or vapour, mixed with air under normal atmospheric conditions, but it does not apply to a) mines susceptible to firedamp; b) the processing and manufacture of explosives; c) areas where a hazard may arise due to the presence of combustible dusts or fibres; d) catastrophic failures which are beyond the concept of abnormality; e) rommos used for medial purposes; f) domestic premises. This first edition of IEC 60079-10-1 cancels and replaces the fourth edition of IEC 60079-10, published in 2002, and constitutes a technical revision. The significant technical changes with respect to the previous edition are: - introduction of Annex D which deals with explosion hazard from flammable mists generated by the release under pressure of high flash point liquids; - introduction of Clause A.3 (release rate) which gives thermodynamic equations for release rate with a number of examples for estimating release rate of fluids and gases.	atmospheres
ISO/TS 15869	Gaseous hydrogen and hydrogen blends —Land vehicle fuel tanks	This International Standard specifies the requirements for lightweight refillable fuel tanks intended for the onboard storage of high-pressure compressed gaseous hydrogen or hydrogen blends on land vehicles. This International Standard is not intended as a specification for fuel tanks used for solid, liquid hydrogen or hybrid cryogenic high-pressure hydrogen storage applications. This International Standard is applicable for fuel tanks of steel, stainless steel, aluminium or non-metallic construction material, using any design or method of manufacture suitable for its specified service conditions. This International Standard applies to the following types of fuel tank designs: — Type 1: metal fuel tanks; — Type 2: hoop-wrapped composite fuel tanks with a metal liner; — Type 3: fully wrapped composite fuel tanks with a metal liner;	- FCHV

RCS	Scope	Description	Covered applications - examples
		— Type 4: fully wrapped composite fuel tanks with no metal liner.	
ISO 23273-1	Fuel cell road vehicles -- Safety specifications -- Part 1: Vehicle functional safety	Specifies the essential requirements for the functional safety of fuel cell (FCV) with respect to hazards to persons and the environment inside and outside of the vehicles caused by the operational characteristics of the fuel cell power system.	- FCHV
ISO 23273-2	Fuel cell road vehicles -- Safety specifications -- Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen	Specifies the essential requirements for fuel cell vehicles (FCV) with respect to the protection of persons and the environment inside and outside the vehicle against hydrogen related hazards.	- FCHV
ISO 23273-3	Fuel cell road vehicles -- Safety specifications -- Part 3: Protection of persons against electric shock	Specifies the essential requirements of fuel cell vehicles (FCV) for the protection of persons and the environment inside and outside the vehicles against electric shock.	- FCHV
ISO 11114-1	Transportable gas cylinders -- Compatibility of cylinder and valve materials with gas contents - Part 1: Metallic material	This standard gives guidance in the selection and evaluation of compatibility between metallic gas cylinder and valve materials, and the gas content.	- Cylinders - Valves - Components in contact with gases
ISO 11114-2	Transportable gas cylinders -- Compatibility of cylinder and valve materials with gas contents - Part 2: Non-metallic material	This Standard gives guidance in the selection and evaluation of compatibility between non-metallic materials for gas cylinders and valves and the cylinders gas contents. This standard also covers bundles, tubes and pressure drums.	- Cylinders - Valves - Components in contact with gases
ISO 17519	Gas cylinders – Refillable permanently mounted composite tubes for transportation	This International Standard defines minimum requirements for serially produced light-weight transportable tubes of composite construction permanently mounted in a transport frame intended for the bulk transport of pressurized gases. These tubes are from 450 liters to 10 000 liters water capacity. The service conditions do not cover external loadings on the transport frame which may arise in transport. Those requirements are specifically provided in standards for the transport frame of which the composite tube is an integral part. The tube is required to meet any and all additional applied loads that are imposed by the specific frame design while in conformance to this International Standard. These tubes may also be suitable for ground storage. This International Standard covers tubes of filament-wound composite construction, using any design or method of manufacture suitable for the	- Tubes

RCS	Scope	Description	Covered applications - examples
		specified service conditions. Note: These composite cylinders are classified as “tubes” in many regulations and standards due their size (internal volume). The use of the term “cylinder” in this International Standard is intended as a generic term that can be used in place of “tube”. Cylinders covered by this International Standard are designated as follows1): Type IV[1] - a Fully Wrapped Cylinder with a non-load sharing liner and composite reinforcement on both the cylindrical part and the dome ends	
ISO 11515	Gas cylinders -- Refillable composite reinforced tubes of water capacity between 450 L and 3000 L -- Design, construction and testing	This International Standard specifies minimum requirements for the design, construction and performance testing of composite reinforced tubes between 450 l and 3 000 l water capacity, for the storage and conveyance of compressed or liquefied gases with test pressures up to and including 1600 bar with a design life of between 15 and 30 years. The expected service temperatures are between – 40 C and + 65 C. The tubes in this standard are defined as one of three Types": Type 2 - a Hoop Wrapped Tube with a load sharing metal liner and composite reinforcement on the cylindrical portion only. Type 3 - a Fully Wrapped Tube with a load sharing metal liner and composite reinforcement on both the cylindrical portion and the dome ends. Type 4 - a Fully Wrapped Tube with a non-load sharing liner and composite reinforcement on both the cylindrical portion and the dome ends. Type 4 tubes manufactured and tested to this standard are not intended to contain toxic, oxidizing or corrosive gases. This standard is limited to tubes with composite reinforcement of carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix. Composite tubes can be used alone or in batteries to equip trailers or skids (ISO modules) or MEGCs for the transportation and distribution of gases. This International Standard does not include consideration of any additional stresses that can occur during service or transport, e.g. torsional / bending stresses, etc. However it is important that the stresses associated with mounting the tube are considered by the assembly manufacturer and the tube manufacturer.	- Tubes

[1] Consideration will be given to including Type 2 and Type 3 tubes of this size if issues related to acceptance of welds in structural liners can be resolved.

RCS	Scope	Description	Covered applications - examples
ISO 11119-1	Gas cylinders -- Refillable composite gas cylinders and tubes -- Design, construction and testing -- Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l	This part of ISO 11119 specifies requirements for composite gas cylinders between 0.5 l and 150 l water capacity, for the storage and conveyance of compressed or liquefied gases. This International Standard is applicable to: Hoop wrapped composite cylinders with a seamless metallic liner and a design life from 10 years to non-limited life. The cylinders are constructed in the form of a liner over-wrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix, or steel wire to provide circumferential reinforcement. NOTE Hoop wrapped composite cylinders are frequently referred to as "Type 2" composite cylinders. This part of ISO 11119 does not address the design, fitting and performance of removable protective sleeves. Where these are fitted they should be considered separately. NOTE ISO 11439 applies to cylinders intended for use as fuel containers on natural gas vehicles and ISO 11623 covers periodic inspection and re-testing of composite cylinders.	- Cylinders
ISO 11119-2	Gas cylinders -- Refillable composite gas cylinders and tubes -- Design, construction and testing -- Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners	This part of ISO 11119 specifies requirements for composite gas cylinders between 0.5 l and 150 l water capacity, for the storage and conveyance of compressed or liquefied gases. This International Standard is applicable to: Fully wrapped composite cylinders with a load-sharing liner (i.e. a liner that shares the load of the overall cylinder design) and a design life from 10 years to non-limited life. The cylinders are constructed in the form of a seamless liner over-wrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix to provide longitudinal and circumferential reinforcement. NOTE Fully-wrapped composite cylinders with a load sharing liners are frequently referred to as 'Type 3' composite cylinders. This part of ISO 11119 does not address the design, fitting and performance of removable protective sleeves. Where these are fitted they should be considered separately.	Cylinders

RCS	Scope	Description	Covered applications - examples
		NOTE ISO 11439 applies to cylinders intended for use as fuel containers on natural gas vehicles and ISO 11623 covers periodic inspection and re-testing of composite cylinders.	
ISO 11119-3	Gas cylinders of composite construction -- Specification and test methods – Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450L with non-load-sharing metallic or non-metallic liners	This part of ISO 11119 specifies requirements for composite gas cylinders between 0.5 l and 150 l water capacity, for the storage and conveyance of compressed or liquefied gases This International Standard is applicable to: Fully wrapped composite cylinders with a non-load-sharing metallic or non-metallic liner (i.e. a liner that does not share the load of the overall cylinder design) and a design life from 10 years to non-limited life. The cylinders are constructed in the form of a liner over-wrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix to provide longitudinal and circumferential reinforcement. NOTE Fully wrapped composite cylinders with non-load-sharing liners are frequently referred to as “Type 4” composite cylinders. Composite cylinders without liners (including cylinders without liners manufactured from two parts joined together) and with a test pressure of less than 60 bar. The cylinders are constructed: 1) in the form of a disposable mandrel overwrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix to provide longitudinal and circumferential reinforcement; 2) in the form of two filament wound shells joined together. This part of ISO 11119 does not address the design, fitting and performance of removable protective sleeves. Where these are fitted they should be considered separately. NOTE ISO 11439 applies to cylinders intended for use as fuel containers on natural gas vehicles and ISO 11623 covers periodic inspection and re-testing of composite cylinders	Cylinders
ISO 11119-4	Gas cylinders of composite construction — Specification and test methods — Part 4: Fully-	This part of ISO 11119 specifies requirements for composite gas cylinders and tubes between 0.5 l and 450 l water capacity, for the storage and conveyance of compressed or liquefied gases. This International Standard is applicable to: Fully wrapped composite cylinders with a load-sharing welded liner (i.e. a liner that	Cylinders

RCS	Scope	Description	Covered applications - examples
	wrapped fibre reinforced composite gas cylinders with load-sharing welded metal liners	shares the load of the overall cylinder design) and a design life from 10 years to non-limited life. The cylinders are constructed in the form of a welded stainless steel liner or welded ferritic steel liner or friction stirred welded aluminium liner or welded titanium liner over-wrapped with carbon fibre or aramid fibre or glass fibre (or a mixture thereof) in a matrix to provide longitudinal and circumferential reinforcement. This part of ISO 11119 specifies requirements for composite gas cylinders between 0.5 l and 150 l water capacity, for the storage and conveyance of compressed or liquefied gases. NOTE Fully-wrapped composite cylinders with a load sharing liners are frequently referred to as 'Type 3' composite cylinders. This part of ISO 11119 does not address the design, fitting and performance of removable protective sleeves. Where these are fitted they should be considered separately. NOTE ISO 11439 applies to cylinders intended for use as fuel containers on natural gas vehicles and ISO 11623 covers periodic inspection and re-testing of composite cylinders.	
IEC 62282-3-100	Fuel cell technologies - Part 3-100: Stationary fuel cell power systems – Safety	Applies to stationary packaged, self-contained fuel cell power systems or fuel cell power systems comprised of factory matched packages of integrated systems which generate electricity through electrochemical reactions. Is a product safety standard suitable for conformity assessment.	- Stationary fuel cell systems - UPS
IEC 62282-3-200	Fuel cell technologies - Part 3-200: Stationary fuel cell power systems – Performance test methods	Covers operational and environmental aspects of the stationary fuel cell power systems performance. The test methods apply to power output under specified operating and transient conditions; electrical and thermal efficiency under specified operating conditions; environmental characteristics under specified operating and transient conditions.	- Stationary fuel cell systems - UPS
IEC 62282-3-201	Fuel cell technologies - Part 3-201: Stationary fuel cell power systems - Performance test methods for small fuel cell power systems	Provides the test methods for the electrical/thermal and environmental performance of small stationary power systems that meet the following criteria: • Output: nominal electrical power output of less than 10 kW; • Output mode: grid-connected/independent operation or stand-alone operation with single-phase AC output or 3-phase AC output not exceeding 1000 V, or DC output not exceeding 1500V; • Operating pressure: maximum allowable working pressure of less than 0.1 MPa (G) for the fuel and oxidant passages; • Fuel: gaseous fuel (natural gas, liquefied petroleum gas, propane, butane,	- small fuel cell power system

RCS	Scope	Description	Covered applications - examples
		hydrogen, etc.) or liquid fuel (kerosene, methanol, etc.); and, • Oxidant: air.	
IEC 62282-3-300	Fuel cell technologies - Part 3-300: Stationary fuel cell power systems – Installation	Provides minimum safety requirements for the installation of indoor and outdoor stationary fuel cell power systems in compliance with IEC 62282-3-1; applies to the installation of systems intended for electrical connection to mains directly or with a transfer switch, or intended for a stand-alone power distribution system, or intended to provide AC or DC power.	- Stationary fuel cell systems - UPS
IEC 62282-4-100:	Fuel cell technologies – Part 4-100: Fuel cell systems for forklift applications – Safety requirements, environmental aspects and test procedures	This part of IEC 62282-4 will cover safety, performance, construction, marking and test requirements and interchangeability of fuel cell systems onboard specialty vehicles other than road vehicles and auxiliary power units (APUs). However, the first edition of this document will include items applicable to forklifts. The future editions of this document will include items applicable to onboard vehicles other than road vehicles and APUs	- Fuel cell systems for forklift applications
IEC 62282-4-200	Fuel cell technologies – Part 4-200: Fuel cell systems for forklift applications: Performance requirements and test procedures	This part of IEC 62282-4 will cover safety, performance, construction, marking and test requirements and interchangeability of fuel cell systems onboard specialty vehicles other than road vehicles and auxiliary power units (APUs). However, the first edition of this document will include items applicable to forklifts. The future editions of this document will include items applicable to onboard vehicles other than road vehicles and APUs	- Fuel cell systems for forklift applications
EN 60079	Explosive atmospheres	e.g. Part 25: Intrinsically safe electrical systems Part 29: Gas detectors Harmonized standard acc. to ATEX – but not all parts	- General for all substances which can build up a potential explosive atmosphere, e.g.: - For gases (GH2) and liquids (LH2) - Stationary storage - Compressor - HRS - Fuel cell applications - Piping - Assemblies - Components and equipment

RCS	Scope	Description	Covered applications - examples
			- CHP
EN 60079-10	Explosive atmospheres	Classification of areas - Explosive gas atmospheres NOT harmonized with ATEX	- General for all substances which can build up a potential explosive atmosphere, e.g.: - For gases (GH2) and liquids (LH2) - Stationary storage - Compressor - HRS - Fuel cell applications - Piping - Assemblies - Components and equipment - CHP