# CLEAN HYDROGEN JOINT UNDERTAKING (CLEAN HYDROGEN JU)

# EHSP Guidance on Hydrogen Safety Engineering – Guidance Document

## 01 May 2023

NOTICE

**Document history**

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| 1 | 12/12/2022 | 1st draft |
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| 3 | 01/05/2023 | 3rd (final) by EHSP TF3 |
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**List of Acronyms**

| TERM | DEFINITION |
|---|---|
| BST | Baker-Strehlow-Tang |
| CFD | Computational fluid dynamics |
| CGH2 | Compressed Gaseous Hydrogen |
| DDT | Deflagration to Detonation Transition |
| EHSP | European Hydrogen Safety Panel |
| EM | Engineering Models |
| EoS | Equation of State |
| LH2 | Liquid Hydrogen |
| LOC | Loss of containment |
| FCH JU, FCH 2 JU | The Fuel Cells and Hydrogen 2 Joint Undertaking: name used to refer to the legal entity established as the public & private partnership. |
| MIE | Minimum Ignition Energy |
| QRA | Quantitative Risk Assessment |
| TNO ME | TNO Multienergy |
| TPRD | Thermally activated Pressure Relief Device |
| UDF | User defined functions |
| HAZID | Hazard Identification |
| HAZOP | Hazard and Operability Analysis |
| LOPA | Layer of Protection Analysis |
| PRA | Probabilistic Risk Assessment |
| SWIFT | What If" Analysis, Structured "What If" Technique |
| FMEA | Failure Mode and Effects Analysis |
| FTA | Fault Tree Analysis |
| ETA | Event Tree Analysis (ETA) |
| ISO | International Organization for Standardization |
| SAE | Society of Automotive Engineers |

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| CGA | Compressed Gas Association |
| EIGA | European Industrial Gases Association |
| IEC | International Electrotechnical Commission |
| NFPA | National Fire Protection Association |
| PGS | Publication Series on Hazardous Substances |
| ASME | American Society Of Mechanical Engineers |
| AIAA | American Institute of Aeronautics and Astronautics |
| UL | Underwriters Laboratories |
| ASTM | American Society for Testing and Materials |
| FCHO | Fuel Cells and Hydrogen Observatory |

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## 1. INTRODUCTION

Within the framework of the Task Force 3 activities of the European Hydrogen Safety Panel (EHSP), it was decided to produce a guidance document on hydrogen safety engineering. While there are many publications in the public domain, which cover the topics addressed in this document including risk assessment method (chapter 2), risk analysis tools (chapter 4), engineering (Chapter 5), computational fluid dynamics (CFD) (Chapter 6) models/tools as well as regulations, codes and standards (Chapter 8), many stakeholders need guidance and orientation to navigate through the vast amount of information out there.

In the meantime, with regards to assumptions and source term quantifications, which are required before conducting consequence modelling and quantitative risk analysis (QRA), there is relatively little information available to the public. While some large companies have their own internal guidance, smaller organisations (e.g., EU projects) would really benefit from some assistance. A preliminary guidance has been produced in Chapter 3. The updated version, once available, will be included in an updated version of this document.

With regards to prevention and mitigation strategies, it is perceived that many stakeholders need guidance on the use of the various strategies and their suitability for different configurations and environment. This is provided in Chapter 7, which additionally cautions the readers to take a balanced views when mitigation measures such as barrier wall, while they can serve the purpose of protecting equipment/personnel from the thermal hazards of fires, they can also act as barriers to inhibit the released hydrogen and as obstacles to increase explosion hazards.

The document is organised in such a way to take readers through the most basic elements of consequence analysis to the consideration of prevention and mitigation measures as well as regulations, codes and standards. In practical design and preparation of safety case documents, it is likely that these two considerations may also necessitate the repeating of some of the earlier analysis. Hence, it is strongly recommended that readers should consult all chapters of the documents before embarking on these activities.

**Disclaimer**

The document aims to provide some basic Guidance to point readers in the right direction. It should not be relied upon to provide a complete methodology, which is beyond the scope of the EHSP, which is constrained by its limited resources. Wherever needed, the readers are suggested to follow up the references quoted in the document themselves.

The document is based on the efforts of the experts in their capacity to serve the EHSP as individuals in their own private time; and hence not related to the organisations which employ them.

While the EHSP has endeavoured to collect all the relevant models, tools and approaches during the preparation of the report, it cannot guarantee the completeness of the collection. Recommendations are also welcome for relevant models, tools and approaches to be included in the future update of the document. Any recommendation should also be supported by evidence of validation to justify its reliability and quality.

## 2. RISK ASSESSMENT METHODS AND TOOLS

This chapter starts with an overview of the established risk assessment methods available in literature. This will be followed by list of key references in which each of the listed methods was applied to hydrogen safety applications. Interested readers can follow up some of these references for more detailed information on how to perform a risk assessment on a specific application.

### 2.1 Overview of risk assessment methods

Table 1 summarizes the risk assessment methodologies.

*Table 1: Summary of risk assessment tools*

| | Methodology | Details | References |
|---|---|---|---|
| Qualitative | Probabilistic Risk Assessment (PRA) | A Probabilistic Risk Assessment (PRA) is a technique where the "Probability" as a measure of uncertainty is used. It is an organized as a process to answer the following three questions:<br>• What can go wrong?<br>• How likely is it to happen?<br>• What are the consequences? | 1. Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety, American Institute of Chemical Engineers, 1999.<br>2. https://www.osti.gov/biblio/1691486-probabilistic-risk-assessment-light-water-reactor-coupled-high-temperature-electrolysis-hydrogen-production-plant |
| Qualitative | Checklist Analysis | This qualitative method evaluates the project against existing guidelines using a series of checklists. This technique is most often used to evaluate a specific design, equipment, or process, for which an organization has a significant amount of experience. | 1. Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, a pilot study, a report to the Rijnmond Public Authority (Rijnmond Report, 1982), © Springer Science + Business Media 1982. |
| Qualitative | "What If" Analysis, Structured "What If" | A speculative process where questions of the form "What if … (hardware, software, instrumentation, or operators) (fail, breach, break, lose functionality, | 1. Card AJ, Ward JR, Clarkson PJ (2012). "Beyond FMEA: the structured what-if technique (SWIFT)". J |

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| | Technique (SWIFT) | reverse, etc.)?" are formulated and reviewed. Sometimes described as a light weighted FMEA. | Healthcare Risk Manage. 31: 23-29. doi:10.1002/jhrm.20101 |
| Semi-Quantitative | Layer of Protection Analysis (LOPA) | LOPA is one of several techniques developed in response to a requirement within the process industry to be able to assess the adequacy of the layers of protection provided for an activity. It is a simplified form of numerical risk assessment. It is an order of magnitude approach and hence precise figures are not used. The technique was published by the Centre of Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) in 2001. It builds on qualitative studies such as HAZOP and the aim of the technique is to reduce risk by using Independent Protective Layers (IPLs). The purpose of LOPA is to determine if there are sufficient safeguards/ IPLs for a particular scenario to reduce the risk of it occurring. LOPA applied properly provides a consistent basis for judging within a company or organisation so that similar results are obtained for similar situations. However, LOPA is a simplified form of numerical risk analysis and hence has significant limitations. Also, from auditing and reviewing LOPA studies there is a concern at the level of mistakes being made using the technique. | 1. Layer of Protection Analysis: Simplified Process Risk Assessment, CCPS (Center for Chemical Process Safety). ISBN: 978-0-816-90811-0 |
| Quantitative | Quantitative Risk Assessment (QRA) | QRA is a method to quantify the risk. Risk is the combination of the probability of an event and its consequence (ISO/IEC Guide 73). In other words, the risk is the combination of the probability of occurrence of harm and the severity of that harm. The harm is physical injury or damage to the | 1. Guidelines for Chemical Process Quantitative Risk Analysis, 2nd Edition<br>2. Quantifying and Controlling Catastrophic Risks, George E.Apostolakis, 2008, |

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| | | health of people or damage to property or the environment. | https://doi.org/10.1016/B978-0-12-374601-6.00014-5 |
| Qualitative | Hazard Identification (HAZID) | HAZard IDentification (HAZID) is a well-known and well-documented method. It is a systematic assessment to identify hazards and problem areas associated with plant, system, operation, design and maintenance. It is used both as part of a Quantitative Risk Assessment (QRA) and as a standalone analysis. | 3. Hazard Identification Methods; Frank Crawley, Brian Tyler, IChemE |
| Qualitative | Hazard and Operability Analysis (HAZOP) | A qualitative method that systematically evaluates the causes and impact, consequences respectively, of deviations using project information. The method was developed to identify both hazards and operability problems at chemical process plants.<br><br>The execution of the method relies on using guidewords (for example "such as", "no", "more", "less" …) combined with process parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (such as less flow, more temperature) of the process intention or normal operation. | 1. Guidelines For Process Hazards Analysis (PHA, HAZOP), Hazards Identification & Risk Analysis, Hyatt, Nigel Hyatt, Taylor and Francis, CRC Press, 2003.<br><br>2. Hazard and operability (HAZOP) analysis. A literature review, Jordi Dunjó, Vasilis Fthenakis, Juan A. Vílchez, Josep Arnaldos, https://doi.org/10.1016/j.jhazmat.2009.08.076. |
| Semi-Quantitative | Failure Mode and Effects Analysis (FMEA) | FMEA is a tool to systematically analyse all of the contributing component failure modes and identify the resulting effect on the system. The semi-quantitative method is essentially composed of the following steps:<br>• Define the system and the required level of analysis depth.<br>• Identify hazards and events (potentially with an advanced HAZOP) for related | 1. https://en.wikipedia.org/wiki/Failure_mode_and_effects_analysis1.<br><br>2. NASA Scientific and Technical Information http://www.sti.nasa.gov/ |

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| | | equipment, components, and processes.<br>• Identify potential initiating failure modes and effects for all components and equipment and potentially early detection capabilities.<br>• Determine a risk priority number (RPN). Agree on acceptable limits for the RPN.<br>• In case, identify potential prevention and mitigation corrective action and re-evaluate RPN.<br>The main drawback is that failure modes are considered one by one, and the interaction of multiple failure mode occurrences is often not listed using this method. The overall reliability levels cannot be deduced from it. | |
| Quantitative | Fault Tree Analysis (FTA) | Fault Tree Analysis is a quantitative (with regards to probabilities) and deductive (top-down) method used for the identification and analysis of conditions and factors that can result in the occurrence of a specific failure or undesirable event. This method addresses multiple failures, events, and conditions.<br><br>The method uses graphical representation; therefore, it is easier to understand. The interactions between failure modes can be easily determined from the representation style. It can be quantitatively analysed to calculate the overall system reliability. | 1. Fault Tree Analysis : For Reliability and Risk Assessment Hardback by John Andrews, Joanne Dugan, Part of the Quality and Reliability Engineering Series, John Wiley & Sons Inc. |
| Qualitative | Event Tree Analysis (ETA) | This method is an inductive approach used to identify and quantify a set of possible outcomes. The analysis starts with an initiating event or initial | 1. http://conference.ing.unipi.it/ichs2005/Papers/220003.pdf |

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| | | condition and includes the identification of a set of success and failure events that are combined to produce various outcomes.<br><br>This quantitative method identifies the spectrum and severity of possible outcomes and determines their likelihood. | |

## 2.2 Hazard Identification (HAZID)

HAZID is known as Hazard Identification. It is a workshop based QRA technique commonly used for the identification of potential hazards and threats in a process, installation, or facility. The following references provide useful descriptions of some HAZID applications to hydrogen.


1. Lowesmith, B. J., Hankinson, G., & Chynoweth, S. (2014). Safety issues of the liquefaction, storage and transportation of liquid hydrogen: An analysis of incidents and HAZIDS. International Journal of Hydrogen Energy, 39(35), 20516–20521. https://doi.org/10.1016/j.ijhydene.2014.08.002
2. Nakayama, J., Sakamoto, J., Kasai, N., Shibutani, T., & Miyake, A. (2016). Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fuelling station with an on-site hydrogen production system using organic chemical hydride. International Journal of Hydrogen Energy, 41(18), 7518–7525. https://doi.org/10.1016/j.ijhydene.2016.03.143
3. Oyama, S., Satoh, S., & Sakanaka, S. (2017). HAZID for CO2-Free Hydrogen Supply Chain FEED (Front End Engineering Design). International Journal of Hydrogen Energy, 42(11), 7322–7330. https://doi.org/10.1016/j.ijhydene.2016.07.023
4. Psara, N., van Sint Annaland, M., & Gallucci, F. (2015). Hydrogen safety risk assessment methodology applied to a fluidized bed membrane reactor for autothermal reforming of natural gas. International Journal of Hydrogen Energy, 40(32), 10090–10102. https://doi.org/10.1016/j.ijhydene.2015.06.048
5. Aarskog, F. G., Hansen, O. R., Strømgren, T., & Ulleberg, Ø. (2020). Concept risk assessment of a hydrogen driven high speed passenger ferry. International Journal of Hydrogen Energy, 45(2), 1359–1372. https://doi.org/10.1016/j.ijhydene.2019.05.128
6. Hadef, H., Negrou, B., Ayuso, T. G., Djebabra, M., & Ramadan, M. (2020). Preliminary hazard identification for risk assessment on a complex system for hydrogen production. International Journal of Hydrogen Energy, 45(20), 11855–11865. https://doi.org/10.1016/j.ijhydene.2019.10.162
7. S. Pique, S. Quesnel, B. Weinbergera, Q. Nouvelot, D. Houssin, E. Vyazmina, D. Torrado, J. L. Saw, S. Montel, “Preliminary risk assessment of hydrogen refuelling stations in a multifuel context”, 17th EFCE International Symposium on Loss Prevention and Safety Promotion in Process Industries, Prague, Czech Republic, June 5-8, 2022.
8. D. Houssin-Agbomson, E. Vyazmina, B. Ravinel, G. Bernard-Michel, D. Forero, “Risk assessment and mitigation evaluation for hydrogen vehicles in private garages. Experiments and modelling”, ICHS, Edinburgh, UK, September 21−23, 2021.

### 2.3 Hazard and operability Analysis (HAZOP)

HAZOP is a systematic technique to identify potential HAZard and OPerating problems. This analysis constitutes a formal systematic rigorous examination of the process and engineering facets of a production facility in the context of safety. The following references describe some applications of HAZOP to process safety related to hydrogen.

1. Hienuki, S., Noguchi, K., Shibutani, T., Fuse, M., Noguchi, H., & Miyake, A. (2020). Risk identification for the introduction of advanced science and technology: A case study of a hydrogen energy system for smooth social implementation. International Journal of Hydrogen Energy, 45(30), 15027–15040. https://doi.org/10.1016/j.ijhydene.2020.03.234
2. Markert, F., Marangon, A., Carcassi, M., & Duijm, N. J. (2017). Risk and sustainability analysis of complex hydrogen infrastructures. International Journal of Hydrogen Energy, 42(11), 7698–7706. thttps://doi.org/10.1016/j.ijhydene.2016.06.058
3. Kim, E., Lee, K., Kim, J., Lee, Y., Park, J., & Moon, I. (2011). Development of Korean hydrogen fueling station codes through risk analysis. International Journal of Hydrogen Energy, 36(20), 13122–13131. https://doi.org/10.1016/j.ijhydene.2011.07.053
4. Ahn, J., Noh, Y., Joung, T., Lim, Y., Kim, J., Seo, Y., & Chang, D. (2019). Safety integrity level (SIL) determination for a maritime fuel cell system as electric propulsion in accordance with IEC 61511. International Journal of Hydrogen Energy, 44(5), 3185–3194. https://doi.org/10.1016/j.ijhydene.2018.12.065
5. Casamirra, M., Castiglia, F., Giardina, M., & Lombardo, C. (2009). Safety studies of a hydrogen refuelling station: Determination of the occurrence frequency of the accidental scenarios. International Journal of Hydrogen Energy, 34(14), 5846–5854. https://doi.org/10.1016/j.ijhydene.2009.01.096
6. Ehrhart, B. D., Harris, S. R., Blaylock, M. L., Muna, A. B., & Quong, S. (2021). Risk assessment and ventilation modeling for hydrogen releases in vehicle repair garages. International Journal of Hydrogen Energy, 46(23), 12429–12438. https://doi.org/10.1016/j.ijhydene.2020.09.155
7. Gerbec, M., Jovan, V., & Petrovčič, J. (2008). Operational and safety analyses of a commercial PEMFC system. International Journal of Hydrogen Energy, 33(15), 4147–4160. https://doi.org/10.1016/j.ijhydene.2008.04.063
8. Ghasemzadeh, K., Morrone, P., Iulianelli, A., Liguori, S., Babaluo, A. A., & Basile, A. (2013). H2 production in silica membrane reactor via methanol steam reforming: Modeling and HAZOP analysis. International Journal of Hydrogen Energy, 38(25), 10315–10326. https://doi.org/10.1016/j.ijhydene.2013.06.008
9. Hadef, H., Negrou, B., Ayuso, T. G., Djebabra, M., & Ramadan, M. (2020). Preliminary hazard identification for risk assessment on a complex system for hydrogen production. International Journal of Hydrogen Energy, 45(20), 11855–11865. https://doi.org/10.1016/j.ijhydene.2019.10.162
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11. Jones, N. G. L. (1984). A schematic design for a HAZOP study on a liquid hydrogen filling station. International Journal of Hydrogen Energy, 9(1), 115–121. https://doi.org/10.1016/0360-3199(84)90039-9

12. Kasai, N., Fujimoto, Y., Yamashita, I., & Nagaoka, H. (2016). The qualitative risk assessment of an electrolytic hydrogen generation system. International Journal of Hydrogen Energy, 41(30), 13308–13314. https://doi.org/10.1016/j.ijhydene.2016.05.231
13. Kikukawa, S., Mitsuhashi, H., & Miyake, A. (2009). Risk assessment for liquid hydrogen fueling stations. International Journal of Hydrogen Energy, 34(2), 1135–1141. https://doi.org/10.1016/j.ijhydene.2008.10.093
14. Kim, E., Lee, K., Kim, J., Lee, Y., Park, J., & Moon, I. (2011). Development of Korean hydrogen fueling station codes through risk analysis. International Journal of Hydrogen Energy, 36(20), 13122–13131. https://doi.org/10.1016/j.ijhydene.2011.07.053
15. Mohammadfam, I., & Zarei, E. (2015). Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework. International Journal of Hydrogen Energy, 40(39), 13653–13663. https://doi.org/10.1016/j.ijhydene.2015.07.117
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17. Kikukawa, S., Yamaga, F., & Mitsuhashi, H. (2008). Risk assessment of Hydrogen fueling stations for 70MPa FCVs. International Journal of Hydrogen Energy, 33(23), 7129–7136. https://doi.org/10.1016/j.ijhydene.2008.08.063
18. M. Casamirra, F Castiglia, L. Corchia, M. Giardina, C. Lombardo, G. Messina, Risk analysis of the storage unit in a hydrogen refuelling station, ICHS 2007, http://conference.ing.unipi.it/ichs2007/fileadmin/user_upload/CD/PAPERS/11SEPT/4.1.294.pdf
19. J. Dunjó, V.Fthenakis, J. A.Vílchez, J. Arnaldos, Hazard and operability (HAZOP) analysis. A literature reviews. Journal of Hazardous Materials Volume 173, Issues 1–3, 15 January 2010, Pages 19-32. https://doi.org/10.1016/j.jhazmat.2009.08.076


**2.4 Quantitative Risk Assessment**

QRA is a formal and systematic risk analysis approach to quantifying the risks associated with the operation of an engineering process. A QRA is an essential tool to support the understanding of exposure of risk to employees, the environment, company assets and its reputation. The following provides a list of references which describe the application of QRA in relation to hydrogen installations and facilities.


1. Weiner, S. C. (2014). Advancing the hydrogen safety knowledge base. International Journal of Hydrogen Energy, 39(35), 20357–20361. https://doi.org/10.1016/j.ijhydene.2014.08.001
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4. Pasman, H. J. (2011). Challenges to improve confidence level of risk assessment of hydrogen technologies. International Journal of Hydrogen Energy, 36(3), 2407–2413. https://doi.org/10.1016/j.ijhydene.2010.05.019
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risks. International Journal of Hydrogen Energy, 37(22), 17415–17425. https://doi.org/10.1016/j.ijhydene.2012.04.051

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13. Gye, H.-R., Seo, S.-K., Bach, Q.-V., Ha, D., & Lee, C.-J. (2019). Quantitative risk assessment of an urban hydrogen refueling station. International Journal of Hydrogen Energy, 44(2), 1288–1298. https://doi.org/10.1016/j.ijhydene.2018.11.035
14. Ham, K., Marangon, A., Middha, P., Versloot, N., Rosmuller, N., Carcassi, M., Hansen, O. R., Schiavetti, M., Papanikolaou, E., Venetsanos, A., Engebø, A., Saw, J. L., Saffers, J.-B., Flores, A., & Serbanescu, D. (2011). Benchmark exercise on risk assessment methods applied to a virtual hydrogen refuelling station. International Journal of Hydrogen Energy, 36(3), 2666–2677. https://doi.org/10.1016/j.ijhydene.2010.04.118
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### 2.5 Failure mode and effects analysis

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### 2.6 Fault Tree Analysis

Fault tree analysis (FTA) is a type of failure analysis used to examine an undesired state of a system. Such analysis is mainly used in safety engineering to understand how systems can fail, to identify the best ways to reduce risk and to determine (or get a feeling for) event rates of a safety accident or a particular system level (functional) failure. The following provides a list of references which describe the application of FTA in risk assessment of hydrogen installations and facilities.

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## 2.7 Event Tree Analysis

Event tree analysis (ETA) is a forward, top-down, modeling technique for both success and failure that explores responses through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis. It is frequently used in industrial risk assessment. The following provides a list of references which describe the application of ETA in relation to hydrogen installations and facilities.


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### 2.8 Risk assessment tools

Table 2 summarizes the risk assessment tools. These tools have generally been programmed from the aforementioned risk assessment methodologies as well as some engineering models. They are relatively easy to use, and particularly suitable for screening analysis. However, they are confined by the limitations of the embedded methodology, failure frequency and engineering models. It will be prudent to use the screening analysis to identify critical areas, for which a combination of engineering models and CFD analysis should be conducted.

These risk assessment tools will also need users to make their own assumptions and supply source terms as input, for which some guidance is provided in the proceeding Chapter 3.

#### 2.8.1 Summary of risk assessment tools

Table 2 provides a summary of the established risk assessment tools. Some of these have been around for a relatively long time used by the process industry while some have been developed specifically for hydrogen safety in the past decade. While HyRAM is provided as open source, all the other listed tools are commercially based.  Interested readers should follow the web link and the references to be provided in the next sub-section for further information as well as methods to gain access to any of these tools.

*Table 1: Summary of risk assessment tools*

| | Tool | Description | References |
|---|---|---|---|
| QRA | HyRAM | HyRAM software, developed by SNL (Sandia National Laboratories) for the FCTO (Fuel Cell Technologies Office) of DOE (U.S. Department of Energy). It employs both probabilistic and deterministic models for the identification and quantification of incidental scenarios. It also allows to predict the physical effects associated with them and the consequences that such incidents could generate both on people and on structures, through the use of various damage models. It uses various calculation models to describe the behaviour of hydrogen (thermodynamic state equation), the consequences of the release of hydrogen, the concentration profile of a jet (without ignition).<br><br>The HyRAM+ risk assessment calculations incorporate probabilities of equipment failures for different components for both compressed gaseous and liquefied fuels, and probabilistic models for the effect of heat flux and overpressure on people. The HyRAM+ toolkit can be used to support multiple types of analysis, including code and standards development, safety basis | 1. https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/<br>2. Brian D. Ehrhart, Cianan Sims, Ethan S. Hecht, Benjamin B. Schroeder, Katrina M. Groth, John T. Reynolds, and Gregory W. Walkup. HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models), Version 4.1. Sandia National Laboratories (April 29, 2022); software available at: https://hyram.sandia.gov.<br>3. Brian D. Ehrhart and Ethan S. Hecht. Hydrogen Plus Other Alternative |

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| QRA | Shepherd | Shell Shepherd is Shell's Quantitative Risk Assessment tool for onshore facilities and operations. It allows fast and reliable predictions of risks related to incidents such as the release of flammable or toxic fluid, fires, and explosions. It has been continuously developed and validated by Shell since the 1990s and has been relied upon by oil, gas, and petrochemical operating companies, engineering contractors, insurers, and regulators. Its easy-to-use, high-quality interface enables data to be imported from multiple sources so models and parameters can be exposed to accurate case data. | 1. Shell Shepherd Desktop User Guide - version 3.1,<br>2. https://www.gexcon.com/brochures/shepherd-quantitative-risk-assessment/ |
| QRA | Phast risk (Safeti) | Safeti incorporates Phast consequence analysis software and calculates risk based on user-provided leak frequencies, ignition data, weather data, populations and vulnerability data. | *1. https://www.dnv.com/services/qra-and-risk-analysis-software-phast-and-safeti-1676*<br>*2. https://www.dnv.com/software/services/plant/quantitative-risk-analysis.html* |
| QRA | RISKCURVES | RISKCURVES is an advanced software for performing QRA for storing and transporting dangerous substances in process, chemical and petrochemical facilities. It reports calculation results in a range of ways, including location-specific individual risk contours (LSIR), FN curves, and risk ranking reports. You can use | 1. Methods for the calculation of Physical Effects (The 'Yellow Book'), Committee for the Prevention of Disasters, CPR 14E/PGS2, 2nd rev. print, (2005) 2. |

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| | | 'analysis points' to analyse the risk contribution of scenarios in specific locations.<br><br>It is built on the Coloured Books principles and is used and accepted worldwide in a wide variety of safety studies<br><br>It includes integrated consequence analysis of over 70 specific scenarios, more than 2200 chemical components (DIPPR® chemical database included) and the ability to define your own mixtures, Location-Specific Individual Risk (LSIR), Societal Risk (FN curves and Societal Risk Maps), freely definable Consequence Risk and the ability to import consequence results from other software.<br><br>It is designed to have a short learning curve and be configurable for both experts and occasional users. Results are presented in graphs, reports, tables, and the integrated GIS environment.<br><br>Use your own maps, and drawings, or simply on-line satellite data from various sources. Seamless integration with Microsoft Office™, Google Earth® and dedicated GIS software, so you can quickly create professional presentations. | Guidelines for quantitative risk assessment (The 'Purple Book'), National Institute of Public Health and the Environment (RIVM), CPR 18E, 1st edition (1999/2005).<br>2. https://www.gexcon.com/brochures/riskcurves-comprehensive-quantitative-risk-analysis/ |
| Fault Tree Analysis | FaultTree + | FaultTree+, our powerful fault tree analysis software used in high-profile projects at over 1800 sites worldwide.<br><br>• Quickly build models using drag and drop and libraries.<br>• Fast and accurate system analysis<br>• Fully integrated with FMEA, event tree and Markov analysis<br>• Importance, common cause and confidence analysis all included.<br>• No limit to the number of gates, events and hierarchical levels<br>• ISO 26262 certified<br>• Multiple standards support including ARP 4761, IEC 61508, ISO 26262<br>• Integrated failure data libraries<br>• Directly link to hazard logs for verification | https://www.isograph.com/software/reliability-workbench/fault-tree-analysis-software/ |

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| | | • Import/export facilities to databases and spreadsheets.<br><br>The software has been in continuous development since the 1980s and is the recognized standard for safety and reliability professionals. | |
| FMEA | FMEA-Pro | Sphera's FMEA-Pro software offers a configurable framework for different FMEA methodologies and specialized capabilities for risk data management so you can ensure that proper controls are in place. It links critical quality information across design and manufacturing processes to help you achieve the quality your customers expect | https://sphera.com/fmea-pro-demo-ppc |
| HAZOP | PHA-Pro | Sphera's PHA-Pro software gives you a more comprehensive approach to process safety management, helping you optimize expert time while reducing study time and report time. Its capabilities give you a far more efficient way to manage process safety risk.<br><br>• Dynamically link PHA diagrams and worksheets<br>• Improve release management.<br>• Shorten study time and leverage best practices with our comprehensive knowledge libraries.<br>• Export professional reports<br>• Access international, multi-language support<br>• Link HAZOP and LOPA templates<br>• Enhance workflow with autotype and copy features.<br>• Utilize our recommendations manager tool. | https://www.kenexis.com/open-pha-intro/ |
| HAZOP/LOPA | Open-PHA | Kenexis has developed a best-in-class software application for the facilitation and recording of process hazards analysis (PHA) studies. This software, called Open PHA™, is a leap forward in a category that has been stagnating over the past decade. Most traditional PHA software vendors have not really changed the functionality of their software in over a | https://www.kenexis.com/open-pha-intro/ |

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| | | decade, only making minor modifications to the "look and feel" of the software, but simultaneously rapidly increasing the pricing for licenses and support. Many users feel "trapped" because their existing studies are all recorded in a certain vendor's software application, and due to the nature of the software and data files there is no easy way to get the data out of that software platform so that it can be used elsewhere. | |
| HAZOP | HAZOP Manager | HAZOP Manager Version 7.0 is a comprehensive Personal Computer program for the management of Hazard and Operability Studies (HAZOP) and other similar safety-related reviews*. It is currently helping many companies throughout the world to conduct more efficient and effective studies. The software incorporates features and facilities that:<br><br>• Serve as a framework within which preparation for the review can be structured.<br>• Ease the task of recording the meeting minutes and help to maintain the team's focus of attention and interest.<br>• Give speedy access to material useful to the study team, such as previously identified problems, failure rate data and other historical information.<br>• Allow professionally formatted reports to be produced with a minimum of effort.<br>• Permit additional management information to be extracted from the study records.<br>• Provide a comprehensive and easy-to-use system for effective action follow-up and close-out, without the significant administrative burden that this usually entails. | *https://www.lihoutech.com* |

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## 3. ASSUMPTIONS AND SOURCE TERMS

Following the basic risk assessment, the next step will be to define the source terms for the loss of containment scenarios that need to be considered. This is needed to quantify the level of the risk associated with loss of containment of hydrogen. In this process, it is not possible to consider all the detailed geometry and operating conditions. Some assumptions will need to be made. These will guide the reader to determine the source terms that should be used as input and boundary conditions for the subsequent analysis by using available risk assessment tools (Chapter 4), or by conducting its own consequences analysis using engineering (Chapter 5) and CFD models (Chapter 6).

This chapter provides an overview and preliminary recommendations about the assumptions and source terms to facilitate hydrogen risk assessment. These recommendations should be considered with care and in combination with the local regulations, environment and geometrical conditions.

### 3.1 Assumption and source terms for hydrogen risk assessment

The following approaches are universal; and in several situations can be considered as conservative. These approaches can be refined for specific installations. However, any adjustment should be appropriately justified.

#### 3.1.1 Release

1. *Gaseous releases*:
    a. **Leak shape**: To simplify the approach for consequence assessment it is recommended to consider the shape of the crack to be round instead of another shape e.g., slits.
    b. **Leak flow rate**: It is recommended to consider continuous releases (steady state) at a maximum flow rate. In case of the solenoid valves functioning or other ways to stop the release, puff releases or other types of non-stationary releases, a transient approach can be used with the variation in time of the flow rate. However, the transient approach will be no longer conservative and needs additional justification to be used in the risk assessment.
    c. **Leak sizes**:
        i. Small leakage corresponds to 1% of the external diameter of the pipe/hose.
        ii. Medium leakage is 10% of the external diameter of the pipe/hose.
        iii. External diameter corresponds to the full-bore rupture, which is the most conservative scenario.
        iv. In case of the presence of the flow restrictor (restriction orifice) within the pipe, the maximum flow rate downstream is defined by the diameter of the calibrated orifice.
        v. In the case of a presence of excess flow valves, the flow rate for the excess flow valve is characterised by the valve design (sufficient flow or force to overcome the power of the spring holding it open).
    d. **Leakage direction**: In most of cases horizontal releases give the largest flammable hydrogen-air mixture. In cases where the obstacles are present such that it significantly prevents the flow of hydrogen pasts the obstacle. For example, jet release into the ground or wall/ tank surface. Then, jet impingement should be considered. In this, a CFD-based approach could be used to estimate the length of the plume.
    e. **Release Height**: The release height corresponds to the lowest (from ground) leakage point in the hydrogen system installation.

***Example***: A pipe containing gaseous hydrogen of 0.5 inches at 1000 bar at ambient temperature (T=20°C) will give a mass flow rate of ~7 kg/s for large leakage.

2. *Liquid releases*:
   a. **Leak size**: the conservative approach is to use 10% of the internal diameter of the doubled-walled pipe. However, for hoses the full-bore rupture should be considered. Note that flashing of liquid hydrogen release can significantly reduce the mass flow rate, therefore it is important that flashing is calculated accurately. If it is not possible to accurately estimate the flash fraction, then as a conservative it shall be assumed that there is no flashing.
   b. **Leak flow rate and Inventory**: It is assumed that the flow is continuous at its maximum flow rate for jet release. For pool release, inventory is needed if the flow is shut down at a certain time, then inventory is calculated based on the leak flow rate as function of time and flow shut down time.
   c. **Leakage direction**: In most of the cases horizontal releases give the largest clouds. In case of the presence of obstacles or potential orientation of the jet downwards, jet impingement should be considered as well, which can lead to a pool formation.
   d. **Release Height**: The release height corresponds to the lowest (from ground) leakage point in the hydrogen system installation.

### 3.1.2 Pool

Depending upon the release height and release direction and conditions, liquid hydrogen can rainout to form a pool. In this case, pool spreading as a function of time must be calculated to obtain the pool area and pool evaporation. The effects of the presence of a retention pit and bund must be included as this limit the size of the pool, thereby limiting the maximum pool area. In addition, the effects of pool spreading on ground surfaces e.g., gravels, concrete, grass, and water surface[1] etc.) and its effect on pool evaporation rate must be considered. In cases, where liquid hydrogen impinges on metal structure, then CFD based modelling can be used to estimate temperature profiles of the metal surface.

***Example***: A large release from a pipe of 0.5 inches at 5 bars at a temperature of liquid (T=-253 ◦C), ambient temperature is 15°C will give a flow rate 0.36 kg/s if the release is detected and shut down within 5s, the volume of liquid hydrogen could result in the pool formation. It is assumed that the release is downward towards the ground promoting pool formation.

### 3.1.3 Atmospheric dispersion of hydrogen

1. The atmospheric conditions (or wind profile) usually are taken into account by the consequence assessment.
2. The ground effects on the jet dispersion should be taken into account.
3. The effect of the atmospheric boundary layer[2] must be taken into account for gaseous releases and hydrogen evaporated from the liquid pool.
4. Typical weather conditions to consider are F1.5, F3, D5, D9 (here F corresponds to stable weather conditions, whereas D corresponds to the neutral condition, the number represents the wind velocity in m/s at 10m height above the ground).
   a. An important parameter for the wind profile is the ground roughness, which represents the effect of the upstream obstacles, which are not modelled, in general,

[1] Note that liquid hydrogen when it comes in contact with water can lead to significant evaporation, this must be properly accounted for.
[2] The atmospheric boundary layer is defined as that part of the atmosphere that directly feels the effect of the earth's surface, hence the releases that occurred close to the earth's surface (at a height less than 100m-400m) are affected by the atmospheric boundary layer.

it is assumed to be 1/20 or 1/30 of the average height of these obstacles. The general guideline for the roughness is:

i. 3 m for city centre with high- and low-rise buildings
ii. 1m for regular large obstacles (suburban, forest)
iii. 0.5m for bushes and numerous obstacles
iv. 0.1m for low crops and occasional large obstacles
v. 0.18m is recommended by the Compressed Gas Association for industrial and rural environments
vi. Other wind conditions can be considered if the wind rose (a diagram that depicts the distribution of wind direction and speed at a location over a period of time of several years) is available for the site under consideration.

### 3.1.4 Built-up (dispersion inside an enclosure or confinement)

1. It is recommended to consider continuous build-up (steady state) at a maximum flow rate for the estimation of the maximum concentration and the corresponding flammable volume/mass. If for some reason a transient approach is used, it should be justified, since the results are no longer conservative.
2. Consider the homogeneous concentration within the enclosure applying the most conservative approach for the flammable mass.
3. If the estimated concentration is higher than 30 % H2 in air, then worst case (stoichiometric concentration 30 %) should be considered.
4. Natural and forced ventilation should be taken into account for the concentration estimation: for this purpose, only effective ventilation areas should be considered (effect of the grid, obstacles, vent protections etc.). A CFD approach is more appropriate/accurate for modelling of effects of ventilation on hydrogen-air flammable mixture.

***Example***: A small release from a pipe containing gaseous hydrogen of 0.5 inches at 1000 bar at ambient temperature (T=20°C) in 4m$^3$ enclosure of 2m high with 2 natural ventilations (one on the bottom, one on the upper side of the opposite lateral wall with sizes of 2m length and 20 cm height) will give a mass flow rate of ~0.0007 kg/s and the maximum hydrogen concentration of 7%. In this case a homogeneous layer with a concentration of 7% appears 30cm below the ceiling, corresponding to the flammable volume of 0.6m$^3$.

### 3.1.5 Flammable mass

Flammable mass and volume are needed to estimate the size of the cloud which takes part in explosion.

1. Flammable limits of hydrogen in air: 4%-75%, this represents the most conservative approach.
2. Explosive limits in air can be considered for:
   a) 8%-75%, according to NFPA 2020, Annex I.7, there is no sustainable ignition at hydrogen at concentrations lower than 8%, [15].
   b) hydrogen mass contributing to fast deflagration is within 10%-75% concentration range.

### 3.1.6 Unconfined Vapour Cloud Explosion

In case of unconfined vapour cloud explosion, the following approach is recommended.

1. The centre of the explosion is needed to be estimated to calculate the overpressure at a certain distnce. It is recommended to place centre of explosion at 10 % of the concentration (the most conservative approach for the distance definition).

2. The Initial turbulence generated by the jet should be considered for the overpressure calculation.
3. The possibility of deflagration to detonation transition should be considered (if appropriate, for instance the presence of repeated obstacles or high congested area and confinement), .
4. An explosion can have impact on people (e.g., injury or fatality) and structures (buildings, fire water tanks etc) (see Appendix 1 for further details). The former effects should be based on overpressure, while the latter should be based on impulse and overpressure. The following effects should be considered (the corresponding overpressure and impulse threshold depends on local regulations and should be adapted accordingly):
    a. indirect effects (for instance, broken windows, indirect effects of possible potential fragments on human being).
    b. irreversible effects (for example, light structural damage, for instance eardrum injuries etc.).
    c. first lethal effects (significant effect on the structure, 1% of the exposed humans are killed).
    d. significant lethal effects (high probability of the structural distinction, 5% of the exposed humans are killed)

***Example***: A medium release from a pipe of 0.5 inches at 1000 bar at ambient temperature (T=20°C) will give the mass flow rate of 0.07kg/s, flammable (4%-75%) mass/volume of 0.044kg 9.35m$^3$ and explosive mass (10%-75%) of 0.007 kg, the horizontal distances corresponding to overpressure of 100 mbar and 40 mbar are 5.8m and 8.1m.

### 3.1.7 Flash fire

A flash fire can have impact only on people (operators inside/outside of the occupied building). Effects to be considered (the corresponding heat flux threshold depends on local regulations and should be adapted accordingly):

a. irreversible effects (injuries etc.).
b. first lethal effects (1% of the exposed humans are killed).

### 3.1.8 Jet fire

Effects to be considered (the corresponding heat flux- threshold depends on local regulations and should be adapted accordingly – see Appendix 2 for further details):

a. flame length and flame width
b. irreversible effects (for example, light structural damage, for instance injuries etc.).
c. first lethal effects (significant effect on the structure, 1% of the exposed humans are killed).
d. significant lethal effect(high probability of the structural distinction, 5% of the exposed humans are killed).

***Example***: A jet fire from a large release from a pipe of 0.5 inches at 1000 bar at ambient temperature (T=20°C) in the horizontal direction will give the flame length of 10 m and 2 m width, the thermal radiation distances at corresponding to heat flux values of 1.5, 3 and 6.3 kW/m$^2$ are 19m, 16m and 13m correspondingly.

### 3.1.9 Burst[3]

1. Effects to be considered (the corresponding overpressure threshold depends on local regulations and should be adapted accordingly; it is to be effects of blast on structure will depend on overpressure and impulse):
    a. indirect effects.

[3] Boiling Liquid Expanding Vapour Explosion should be modelled in case of presence of liquid hydrogen storage tanks.

b. irreversible effects.
c. first lethal effects.
d. significant lethal effects.

2. Burst effects depend only on the pressure and volume of the corresponding equipment (tank) and rupture coefficient (the working pressure should be multiplied by the rupture coefficient):
    a. Rupture coefficient is 1 for the external mechanical aggression.
    b. For fire aggression:
        i. Rupture coefficient is 1.9 for cylinders of type 1 and 2.
        ii. Rupture coefficient is 1.9 for cylinders of type 1 and 2.
        iii. Rupture coefficient is 1.7 for cylinders of type 3.
        iv. Rupture coefficient is 1.1 for cylinders of type 4.

***Example**:* A rupture in a fire of a 300l type 4 TPRD-less tank at 700 bar: the rupture pressure is considered to be 770 bar, the burst energy is ~$6x10^7$ J , than for instance Brode model [7] can be used for the calculations of the corresponding distances to the overpressure threshold of 200mbar and 50mbar of 13m and 43m correspondingly.

### 3.1.10 Vapour Cloud Explosion (VCE)

1. It is recommended to consider the most conservative results from the built-up for the VCE in terms of the explosive flammable hydrogen-air mixture i.e., mass/volume based on 10-75 % hydrogen concentration.
2. The possibility of deflagration to detonation transition should also be considered if appropriate (for instance the presence of repeated obstacles or high congested area)
3. Initial turbulence[4] generated by the release should be considered for the overpressure and impulse calculation.
4. Pressure panels:
    a. the presence overpressure panels (if they are not blocked) should be taken into account: effective size, opening pressure.
    b. ventilation is considered as pressure panel with zero opening pressure.
    c. doors (if not locked) or other light parts of the construction can also be considered as pressure panels: the opening pressure used for such calculation should be justified.
5. the strength of the enclosure and hence the corresponding overpressure leading to the destruction of the enclosure can be modelled.
6. Acoustic wave generated within the enclosure can be calculated using CFD based approach, in addition it can be used to calculate external explosion overpressure.

### 3.1.11 Venting

Consequence assessment would be needed in case of release of hydrogen from vents. For vents vertical release direction is the most appropriate in most of the cases, except a special design of a vent where release is oriented towards horizontal direction.

a. **Vent size**: size of the exit of the vents
b. **Venting direction**: Depending on the vent exit.
c. **Venting Height**: The release height corresponds to lowest (from ground) leakage point in the hydrogen system installation.
d. **Vent flow Rate**: Estimated based on the vent size, pressure and temperature.

**Dispersion and flammable mass**: The dispersion of hydrogen release from the vent should consider the atmospheric conditions (or wind profile) usually is taken into account by the consequence assessment. Typical weather conditions to consider are F1.5, F3, D5 and D9.

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[4] this is quite important for high pressure releases.

**Jet fire**: Immediate ignition can lead to jet fire getting established at the base of the vent exit, this should be modelled. The effects of flame impingement and heat flux on adjacent structure and people present within the vicinity should be modelled.
**Explosion**: The centre of the explosion should be placed at 10% of the concentration (the most conservative approach for the distance definition), except for the vertical releases (vents, TPRD etc), where the centre of the explosion corresponds to the release point or 10 % concentration. It will depend on the overpressure receiver. It is recommended to estimate the flammable mass and volume of plume of hydrogen-air mixture between 10-75 % boundary.

***Example***: A horizontal release of hydrogen from a vent exit (25.4 mm diameter) at temperature of 20°C at 40bar and mass flow rate of 1 kg/s can lead to horizontal distances of corresponding to 4 % and 10 % are 45m and 18m. The flammable mass/volume corresponds to 2.61kg, explosive mass is 0.38kg. The flame length and width of jet fire is 18.66 m and 3.17 respectively. The horizontal distance and vertical distance from ground level corresponding to a heat flux value of 6.3 and 3 kW/m$^2$ are 26m and 33m. The horizontal distances corresponding to overpressure values of 100 mbar and 40 mbar are 40m and 67m correspondingly.

Note this chapter do not cover source terms and assumptions for pressure peaking phenomena [16] and mitigation effects (e.g., effects of firewall on flame length and heat flux from a jet fire). It is to be noted that CFD based approach is more appropriate for mitigation effects.

### 3.2 Summary

This chapter summaries some preliminary approaches to estimate the source terms and consider hypotheses when conducting risk assessment of installations/facilities. These approaches and hypothesis should be refined following international harmonisation in the next several years, which is being addressed in the frame of the International Energy Agency (IEA) TCP Task 43.

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**Appendix 1**: ***Blast injury and damage***

Blast waves generated during the vapour cloud explosion, overpressure or tank rupture can have a damaging effect on the human body e.g., blast waves can have eardrum rupture, lung damage and translation of a body with negative consequences like hitting a wall or a floor. Furthermore, blast waves can also damage civil structures e.g., windows, doors, storage tanks and buildings etc. The effects of blast waves on the human body and on civil structures can be obtained from data generated and documented by Baker et al. [8,9] and UK HSE [10]. There are numerous references (e.g., Baker et al. [8], Merx [11] and CCPS [12]) that describe methods for the determination of possible damage of blast waves on civil structures or buildings. It is to be noted that damage of the buildings will depend on the type of buildings.

**Appendix 2**: ***Heat Flux Effects on Structure and People***

The heat flux can have impact on people and storage tanks. For example, PGS-35 recommends the heat radiation at ground level is lower than 3 kW/m$^2$ within the establishment limit and lower than 1 kW/m$^2$ outside the establishment limit. The heat radiation intensity from a jet fire from the central vent stack on the gaseous hydrogen storage unit is less than 10 kW/m$^2$; the heat radiation intensity from a flare on the liquid hydrogen storage unit is less than 35 kW/m$^2$.

IOGP [14] provides guidance on vulnerability of fire and plant/structure. Table 2.1 [14] gives typical times to failure of time to failure of pipework, vessels, equipment and structures affected by fire. The critical temperatures for failure of various components and vessels are shown in Table 2.2 [14].
NFPA 2[5] [15] summarised distance for three different groups of exposure to hydrogen refuelling station. The Group 1 exposures consist of lot lines, air intakes, openings in buildings and structures, and ignition sources. The two Group 2 exposures are exposed persons other than those involved in servicing of the system and parked cars. The Group 3 exposures consisting mostly of buildings and other flammable or hazardous materials. Following criteria is used for each respective groups as: (a) Group 1 exposures: the furthest distance to an average mole fraction of 8 %, a heat flux of 4.732 kW/m$^2$ or an overpressure of 0.05 bar. (b) Group 2 exposures: the furthest distance to a heat flux of 4.732 kW/m$^2$ or an overpressure of 0.16 bar. (c) Group 3 exposures: the furthest distance to a heat flux of 20 kW/m$^2$, the visible flame length, or an overpressure of 0.7 bar.

[5] This code provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form.

## 4. AVAILABLE ENGINEERING MODELS AND TOOLS

This chapter summarises the available Engineering Models (EM) and tools. Wherever possible, differentiation is made between the models and the tools. The former is derived from the mathematical representation of physical phenomena from balance equations, correlations for mass, energy and momentum transfer terms, equations of state, etc. The latter represents a numerical tool consisting of one or more models describing physical phenomena. To become a reference, models must be based on a solid scientific approach and a coherent validation database. The latter should cover different scales of experiments. In addition, publication in a peer-reviewed journal is considered an additional guarantee of the model quality.

These engineering models allow treating in a simplified way of underlying physical phenomena to predict the consequences of a degraded operation of a hydrogen infrastructure. It is also useful to estimate the hazard distances with respect to property and people for the various infrastructures. Some of the engineering tools implement a QRA module.

However, the proliferation of projects related to the use of hydrogen as an energy carrier implies a continuous enrichment of the validation databases and a continuous update of the QRA data. A state of the art is only a snapshot at a given time and the continuous confrontation of these models with new data and new needs must be a guideline to guarantee a high level of safety. On the other hand, as resources are often allocated to a specific project, it is difficult to guarantee monitoring of the validation database of the engineering models. Each user or each research group is therefore independently responsible for monitoring this validation and for open computer tools, this is a real challenge. The remainder of this chapter will therefore focus on solutions to guarantee the continuation of the validation of these engineering models and the enrichment of the models to deal with upcoming new issues.

### 4.1 Engineering models available in open access or commercial tools

The engineering tools for dealing with hydrogen safety can be classified into two broad categories with respect to the accessibility of these tools. Some are freely available while others are commercially available. The tools are described in this chapter under these two categories with the related references to engineering models contained in them. Engineering models which have been developed and tested by the developers in various programming environment but not available online will be listed in the next chapter.

#### 4.1.1 Open access tools

Regarding open tools, the e-Laboratory of Hydrogen Safety was conceived within the FCH 2 JU NET-Tools project (https://www.h2fc-net.eu/net-tools) and is currently supported within the HyResponder (https://hyresponder.eu) project coordinated by Ulster University. The e-Laboratory is free to access the state-of-the-art online tools for hydrogen hazards assessment. It includes a large number of tools for hazard assessment (short description, instructions for using a tool and references to publications with model description and tool validation are available when the tool is opened):

- Release
    - Hydrogen under-expanded jet parameters model [1].
    - Similarity law for concentration decay in hydrogen unignited jets [1].

  - Effect of buoyancy on the decrease of hazard distance for unignited release [2].
  - Blowdown time from a tank through TPRD [7].
  - Pressure peaking phenomenon in enclosures for unignited releases [8,9].
  - Upper limit of hydrogen inventory in closed spaces like warehouses [11,12].
  - Passive ventilation of hydrogen leak in an enclosure with one vent [8,13].
  - Forced ventilation system parameters (flow balance for a given hydrogen flow rate, it calculates the air flow rate to reach a given hydrogen concentration in the air).
- Fire
  - Flame length correlation and three hazard distances for jet fire [3].
  - Pressure peaking phenomenon in enclosures for ignited releases [8,9].
- Explosion
  - Calculation of fireball diameter[4,5].
  - Blast wave after hydrogen tank rupture in a fire [6].
  - Mitigation of hydrogen-air deflagrations by venting technique [10].
- Miscellaneous
  - The Abel-Noble Equation-of-State (EoS) to calculate CGH2 mass in a volume by pressure and temperature [14].

The e-Laboratory is extensively used for education in hydrogen safety at Ulster University. For example:

- Postgraduate Certificate in Hydrogen Safety: https://www.ulster.ac.uk/skillup/energy/hydrogen-safety
- Part-time Postgraduate Short Courses and CPD
  - Principles of Hydrogen Safety: https://www.ulster.ac.uk/principles-hydrogen-safety
  - Hydrogen Safety Technologies: https://www.ulster.ac.uk/hydrogen-safety-technologies

To get access to the online e-Laboratory of Hydrogen Safety please contact Dr Volodymyr Shentsov (v.shentsov@ulster.ac.uk) with a copy to Prof Vladimir Molkov (v.molkov@ulster.ac.uk).

Presently, the e-Laboratory of Hydrogen Safety does not provide any modules to perform QRA. Concerning other tools under a free license, the HyRAM+ toolkit [15] [16] (https://h2tools.org/hyram) integrates deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing hydrogen hazards' impact on people and structures. It incorporates generic probabilities for equipment failures and probabilistic models for heat-flux impact on humans and structures. The models cover:

- Release
  - Component leak frequencies [18].
  - Release characteristics (notional nozzle [1, 20–23], jet/plumes [24], accumulation [25,26]).
- Ignition
  - Ignition probability [19].
- Fire
  - Flame properties (jet fires [26–28])
- Explosion
  - Deflagration within enclosures [26, 29]
- Miscellaneous:
  - Generic data for gaseous hydrogen (CGH2) and liquid hydrogen (LH2) systems [17];
  - Probabilistic models for human harm from thermal and overpressure hazards.

- Calculates common risk metrics for user-defined systems e.g., Fatal Accident Rate (FAR), Average Individual Risk (AIR), Potential Loss-of-Life (PLL) and frequency of fires.

#### 4.1.2 Commercial tools

Commercial tools are available to deal with hydrogen safety issues by the use of engineering models:

- FRED package from SHELL (https://www.gexcon.com/products-services/shell-fred-software).
- PHAST package from DNVGL (https://www.dnv.com/software/services/phast/index.html).
- PRONUSS (https://www.pronuss.de).
- EFFECTS from TNO (https://www.gexcon.com/products-services/effects-consequence-modelling-software).
- Tool of H2-Fill of Wenger [33] (https://www.wenger-engineering.de/en) was used for the protocol development for buses in the frame of the Clean Energy Partnership.

Note that some of the companies listed above also have software packages of their own for QRA analysis:

- SHEPHERD from SHELL (https://www.gexcon.com/products-services/shell-shepherd-software).
- SAFETI from DNVGL (https://www.dnv.com/services/qra-software-safeti-1715).

Due to the commercial nature of these tools, limited descriptions are freely available in literature. Consequently, a detailed and critical review of capabilities is out-of-the-scope of the present chapter.

### 4.2 Other published engineering models

In addition, there are also engineering models which have been developed and tested by different organisations with their validation published. However, these models have not been programmed into tools and released online for which the users can directly use. These include those developed in previous FCH 2 JU funded projects as well as elsewhere.

These models are freely available to address specific situations. They focus on:

- Release:
    - Atmospheric dispersion of hydrogen (VentJet) developed in the frame of the Compressed Gas Association [30];
    - Natural and forced ventilation models in enclosures [42]–[45];
    - Non-adiabatic blowdown model accounting for heat transfer through the tank wall [50] [51];
    - Steady-state single / two-phase choked/expanded flow through a discharge line with a variable cross-section with account of friction and extra resistances [52]–[54];
    - Extent of cryogenic pools [49];
    - Method for calculating the final state when mixing liquid hydrogen and moist air [49];

- Ignition:
    - Minimum Ignition Energy (MIE) of hydrogen-air mixtures for ambient and cryogenic temperatures [49];
    - Electrostatic field built-up generated during hydrogen releases [49];

- Fire:
    - Hazard distances by thermal radiation from hydrogen jet fire [55];
    - Design of TPRD to avoid flame blow-off [57];
    - Time of tank to rupture in a fire in case of TPRD failure [58];
- Explosion:
    - A vented explosion model developed by Warwick University during the HySEA project based on the paper [41];
    - Deflagration pressure from delayed ignition of under-expanded hydrogen jet [49];
    - Laminar burning velocity and expansion ratio for cryogenic hydrogen-air mixtures [49];
    - Flame acceleration and deflagration-to-detonation transition for cryogenic hydrogen-air mixtures [56];
    - Fireball size after liquid hydrogen spill combustion [49];
    - Correlation for deflagration from a spurious hydrogen release [57];
    - Venting of non-uniform hydrogen-air deflagrations [57];
    - Correlation for DDT in horizontal and vertical systems [57];
    - Parameters of blast wave after hydrogen tank rupture in a tunnel [59], [60];
    - Parameters of the fireball of hydrogen tank rupture in a tunnel [57], [60];
    - Shock and detonation models and databases:<br>https://shepherd.caltech.edu/EDL/PublicResources/sdt/<br>https://shepherd.caltech.edu/EDL/PublicResources/detdata/det_props.xls
    - Chemical equilibrium models:<br>http://www.gaseq.co.uk<br>https://cearun.grc.nasa.gov
- Miscellaneous:
    - CGH2 filling modelling:
        - There are different models which can reproduce the refuelling issues [31]–[36], these models are used for the refuelling protocol development within the PrHyde project;
        - The safety watchdog model [37] is dedicated to the safety module to monitor the refuelling and under safety conditions;
        - tool (H2FILLS) developed by NREL (https://www.nrel.gov/hydrogen/h2fills.html) and based on the paper of [33], [38]–[40] is also used in PrHyde project;
    - Properties:<br>https://www.nist.gov/srd/refprop<br>https://webbook.nist.gov/chemistry

Finally, some national projects within Europe have supported the development and benchmarking of hydrogen safety-related engineering tools:

- The IDEAL project (https://h2-idealenergy.com) in Spain is funded by the Spanish Research Agency.
- The DRIVE [46], HYDROMEL [47] and DIMITRHY [48] projects in France are funded by the French Research Agency.

### 4.3 Summary

This chapter gives a list and references of engineering models used in hydrogen safety. The focus is on the unlicensed free models and only a list is given for the main commercial models. Table 2 summarizes the present capabilities of the different open-science tools concerning the main physical phenomena involved in a hydrogen accident. It also includes the related references.

*Table 2: Summary of engineering models included in the two main open access tools.*

| Category | e-LABORATORY | HYRAM+ |
|---|---|---|
| Release | [1], [2], [7]–[9], [11]–[13] | [1], [20]–[23], [24], [25] |
| Ignition | | [19] |
| Fire | [3]–[5] | [27], [28] |
| Explosion | [6] | [29] |

This work is only a snapshot at a given time and new models or additional validation data are continuously produced and published in peer-reviewed journals. It would therefore be important to set up a periodic follow-up of the models and their validation to ensure that they are always state of the art.

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## 5. CFD MODELS AND TOOLS FOR HYDROGEN SAFETY APPLICATIONS

Computational fluid dynamics (CFD) models are often used to assess the consequences of hazardous scenarios associated with the loss of containment (LOC) of hydrogen. These models can be based on in-house, open source or commercial CFD codes.

The predictions of a CFD code not only depends on the code itself, but also the sub-models adopted to address the underlying physical/chemical processes. Furthermore, the quality of the predictions also depends on the skills and experience of the users, which directly influences the specifications of relevant boundary and initial conditions, treatment of physical properties and the computational grids. As such, the same code when used by different users could lead to different predictions for the same LOC scenario. Within the framework of the Task Force 3 activities of the European Hydrogen Safety Panel (EHSP), this report is compiled to provide a list of the available CFD models. In the content of the report, a CFD model represents the combination of the CFD code as well as any additional development and set up used by the organisations which nominated them for listing. The same code may hence be listed more than once by different organisations with their own modelling approaches, which could include modifications where appropriate and setups of boundary and initial conditions.

In-house CFD codes or modified versions of open source CFD codes are generally used for internal research/application within the developers' organisations. Quite often, when the same open source CFD code, e.g., OpenFOAM, is used, users have introduced their own modifications to improve the treatment of the scenario. Some users may name the modified code with a new name for clarity. An example is HyFOAM, which is a collection of the modified solvers for different LOC scenarios developed within the frame of open source CFD code OpenFOAM. Some users still describe the in-house modified OpenFOAM code as OpenFOAM but provide references which document the modifications and validation.

Similarly, when commercial CFD codes are used, some users also develop their own User Defined Functions (UDF) to improve the predictions. These codes are generally still referred to by the original names of the commercial software, e.g., ANSYS FLUENT, but the developed UDFs are described in the references provided by the organisations which nominated the model for inclusion in this chapter.

In the remaining chapter, the CFD models, which were nominated for inclusion by the relevant organisation, are categorised according to the LOC scenarios addressed as follows:

- Release
- Ignition
- Fire
- Explosion
- Miscellaneous

Some models will appear more than once under the same name for different LOC scenarios.

**Scope and remit:** The aim of this chapter is to provide information on available CFD codes for hydrogen safety applications, by providing lists of CFD codes which have been developed applied to typical LOC scenarios. In addition to list the organisations which developed the original codes, the organisations which have modified or adapted the codes to establish models for different LOC scenarios are listed with references reporting on the simulations/validation. The chapter is compiled from the information submitted by the relevant stakeholders, which mainly consists of those organisations whose codes/models are listed and a provided references for their application or validation studies. The inclusion of the models and references, by no means, represent view of the EHSP on the quality of any specific model or its validation.

If a reader is interested in a particular model, he/she should follow the contact information provided to get in touch with the relevant organisation. The chapter should help to point relevant stakeholders in the right direction to seek additional information, to discussion collaboration or consultancy services as well as seek expert advice subject to mutual agreement of both sides.

### 5.1 Release

This section covers models for both gaseous and liquid hydrogen releases. The relevant LOC scenarios includes pressurised jets and their dispersion in the open and enclosed environment of hydrogen gas at ambient temperature as well as in cryogenic conditions. For indoor release, the potential scenario of pressure peaking is also included, for liquid hydrogen, the LOC scenarios additionally include pool formation, spread, evaporation and the subsequent dispersion of the resulting hydrogen vapour cloud.

*Table 3: CFD models for hydrogen release*

| Name of the code/original developer | Organisation using the code with and without modification/Contact email | Key publications |
|---|---|---|
| ADREA-HF | National Centre for Scientific Research “Demokritos”, in-house CFD code.<br><br>www.ipta.demokritos.gr<br><br>Dr. Alexandros G. Venetsanos<br><br>venets@ipta.demokritos.gr | 1. Venetsanos A.G., Papanikolaou E., Bartzis J.G., The ADREA-HF CFD code for consequence assessment of hydrogen applications, Int. J. Hydrogen Energy 35 (2010) 3908–3918 |
| ANSYS Fluent<br><br>Commercial code www.ansys.com | Air Liquide<br><br>https://www.airliquide.com/<br><br>Dr. Elena Vyazmina<br><br>Elena.vyazmina@airliquide.com | 1. D. Houssin-Agbomson, E.Vyazmina, C. Guiberteau, “Impact of mechanical ventilation on build-up and concentration distribution inside a 1-m3 enclosure considering Hydrogen Energy applications conditions of use. Experiments and modelling”, ICHS, Adelaide, Australia, September 24−26, 2019. |
| ANSYS Fluent<br><br>Commercial code www.ansys.com | University of Ulster with user defined functions<br><br>www.ulster.ac.uk | **Indoor**<br><br>1. V. Molkov, V. Shentsov. Numerical and physical requirements to simulation of gas release and dispersion in an enclosure with one |

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| | Prof. Vladimir Molkov<br><br>*v.molkov@ulster.ac.uk* | vent. *International Journal of Hydrogen Energy*, 2014; 39:13328-13345.<br><br>**Car park**<br><br>1. Hussein H, Brennan S, Molkov V. Dispersion of hydrogen release in a naturally ventilated covered car park. International Journal of Hydrogen Energy, 2020;45:23882-23897. https://doi.org/10.1016/j.ijhydene.2020.06.194<br><br>**The pressure peaking phenomenon**<br><br>1. S Brennan, HG Hussein, D Makarov, V Shentsov, V Molkov. Pressure effects of an ignited release from onboard storage in a garage with a single vent. International Journal of Hydrogen Energy, 2019;44: 8927-8934. |
| COM3D | Karlsruhe Institute of Technology, in-house code<br><br>Dr. Alexei Kotchourko<br>*alexei.kotchourko@kit.edu* | **Jet release in confined vented environment**<br><br>1. Z Xu, Z Zhang, A Kotchourko, A Lelyakin, T Jordan, Numerical simulations of suppression effect of water mist on hydrogen deflagration in confined spaces, *Conf. on Hydrogen Safety (ICHS 2021), Edinburg, UK, 2021.* |
| containmentFOAM developed within the frame of OpenFOAM *www.openfoam.com* | Forschungszentrum Jülich GmbH<br><br>*www.fz-juelich.de*<br><br>*s.kelm@fz-juelich.de* | **1.** Kelm S, Kampili M, Liu X, George A, Schumacher D, Druska C, Struth S, Kuhr A, Ramacher L, Allelein H-J, Prakash KA, Kumar GV, Cammiade LMF, Ji R. The Tailored CFD Package 'containmentFOAM' for Analysis of Containment Atmosphere Mixing, $H_2$/CO Mitigation and Aerosol Transport. *Fluids*. 2021; 6(3):100. https://doi.org/10.3390/fluids6030100 |
| *Fire Dynamics Simulator (FDS)*<br><br>*(Open source)* | *Kevin McGrattan*<br><br>*kevin.mcgrattan@nist.gov*<br><br>*Jason Floyd* | **Hydrogen release and dispersion (low-Mach number)**<br><br>1. Prasad, K. , Pitts, W. and Yang, J. (2011), A NUMERICAL STUDY OF |

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| *NIST*<br><br>*https://pages.nist.gov/fds-smv/* | *jason.floyd@ul.org*<br><br>Simo Hostikka<br><br>*simo.hostikka@aalto.fi*<br><br>Randall McDermott<br><br>*randall.mcdermott@nist.gov*<br><br>Marcos Vanella<br><br>*marcos.vanella@nist.gov* | THE RELEASE AND DISPERSION OF A BUOYANT GAS IN PARTIALLY CONFINED SPACES, International Journal of Hydrogen Energy. http://dx.doi.org/10.1016/j.ijhydene.2011.01.118<br><br>**Hydrogen dispersion and mechanical ventilation**<br><br>1. Brzezinkska D. Hydrogen Dispersion and Ventilation Effects in Enclosures under Different Release Conditions. Energies (2021) 14, 4029. *https://doi.org/10.3390/en14134029*<br><br>**Hydrogen release, jet velocity, radiation to targets**<br><br>1. Floyd J. Siting Requirements for Hydrogen Supplies Serving Fuel Cells in Non-combustible Enclosures. The Fire Protection Research Foundation Technical Report, 2006.<br><br>**Hydrogen release, flammability limits**<br><br>1. Sharma PK, Gera B, Singh RK. Validation of in-house k-epsilon RANS and open source SGS LES based CFD to predict distribution and mixing of hydrogen for an HYSAFE international benchmark. In Transactions, SMiRT 21, Nov 2011, New Delhi, India. |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | Gexcon<br><br>Djurre Siccama<br><br>*djurre.siccama@gexcon.com* | 1. P. Middha, O. R. Hansen, I. E. Storvik, Validation of CFD-model for hydrogen dispersion, Journal of Loss Prevention in the Process Industries 2009; 22 (6): 1034-1038. |
| FLACS<br><br>Commercial code<br><br>www.gexcon.com | Air Liquide<br><br>*https://www.airliquide.com/*<br><br>Dr. Elena Vyazmina<br><br>*Elena.vyazmina@airliquide.com* | 1. J. Daubech, J. Hebrard, S. Jallais, E Vyazmina, D Jamois, F. Verbecke, “Un-ignited and ignited high pressure hydrogen releases: Concentration - turbulence mapping and overpressure effects”, Journal of Loss Prevention in the Process Industries, |

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| FLACS<br><br>Commercial code<br><br>www.gexcon.com | AVT, Center for hydrogen safety and Codes and Standards (COS)<br><br>http://www.tchouvelev.org<br><br>Université du Québec à Trois-Rivières<br>https://uqam.ca<br><br>Model developed from CFD code and then implemented in in-house toolkit.<br><br>Dr. Andrei Tchouvelev<br>andrei.tchouvelev@hydrogencouncil.com<br><br>Mr. Benjamin Angers<br>benjamin.angers@uqtr.ca | 1. P. Bénard, A. Hourri, B. Angers, A. Tchouvelev, Adjacent Surface Effect on The Flammable Cloud of Hydrogen and Methane Jets: Numerical Investigation and Engineering Correlations, (2016) International Journal of Hydrogen Energy, 41 (41), 18654-18662. |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | HYEX Safety with enhanced functionality by user settings<br><br>hyexsafety.com<br><br>Olav Roald Hansen<br><br>olav@hyexsafe.com | 1. |
| GASFLOW<br><br>Commercial code<br><br>www.gasflow-mpi.com | Karlsruhe Institute of Technology<br><br>www.kit.edu<br><br>Dr. Jianjun Xiao<br>jianjun.xiao@kit.edu<br><br>Prof. Dr. Thomas Jordan<br>thomas.jordan@kit.edu | **Turbulent flows at wide mach number regimes**<br><br>1. Jianjun Xiao, Wolfgang Breitung, M. Kuznetsov, H. Zhang, John R. Travis, R. Redlinger, Thomas Jordan, GASFLOW-MPI: A new 3-D parallel all-speed CFD code for turbulent dispersion and combustion simulations: Part I: Models, verification and validation, International Journal of Hydrogen Energy, March 2017. |
| HyFOAM<br><br>Developed within the frame of | Centre for Energy Resilience, University of Surrey. Modified in-house version. | **Gas Hydrogen**<br><br>1. Trygve Skjold, Helene Hisken, Laurence Bernard, Lorenzo Mauri, Gordon Atanga, Sunil Lakshmipathy, Melodia Lucas, Marco Carcassi, |

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| OpenFOAM<br>www.openfoam.com<br><br>for hydrogen safety applications | www.surrey.ac.uk/Centre for energy resilience<br><br>Prof. Jennifer X .Wen<br><br>j.wen@surrey.ac.uk | Martino Schiavetti, Vendra Chandra Madhav Rao, Anubhav Sinha, Jennifer X. Wen, Ilias C. Tolias, Stella G. Giannissi, Alexandros G. Venetsanos, James R. Stewart, Olav Roald Hansen, Chenthil Kumar, Laurent Krumenacker, Florian Laviron, Romain Jambut, Asmund Huser, Blind-prediction: Estimating the consequences of vented hydrogen deflagrations for inhomogeneous mixtures in 20-foot ISO containers, Journal of Loss Prevention in the Process Industries, Volume 61, 2019, Pages 220-236.<br><br>**Cryogenic hydrogen jets**<br><br>1. Ren, Zhaoxin and Wen, Jennifer X. (2020) Numerical characterization of under-expanded cryogenic hydrogen gas jets. AIP Advances, 10 (9). 095303. doi:10.1063/5.0020826<br><br>**Liquid hydrogen**<br><br>1. Baopeng Xu, Simon Jallais, Deborah Houssin, Elena Vyazmina, Laurence Bernard and Jennifer X. Wen, Numerical simulations of atmospheric dispersion of large-scale liquid hydrogen releases, Int. Conf. on Hydrogen Safety, Sep. 2021, Edinburgh, UK.<br><br>2. F. Nazar Pour, S. Dembele and J. Wen, On Modelling Hydrogen Spill, Spread, Evaporation and Dispersion, *Proc. 7th International Conference on Hydrogen Safety, 11-14 Sep. 2017, Germany.* |
| OpenFOAM<br>www.openfoam.com | University of Ulster<br><br>www.ulster.ac.uk<br><br>Prof. Vladimir Molkov<br><br>v.molkov@ulster.ac.uk | **Under-expanded jets**<br><br>1. J.J. Keenan, D.V. Makarov and V.V. Molkov. Modelling and simulation of high-pressure hydrogen jets using notional nozzle theory and open-source code OpenFOAM, *International Journal of Hydrogen Energy*, 2017;42: 7447-7456. |

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| PHOENICS<br><br>CHAM<br><br>https://www.cham.co.uk | AVT, Center for hydrogen safety and Codes and Standards (COS)<br><br>http://www.tchouvelev.org<br><br>Université du Québec à Trois-Rivières<br>https://uqam.ca<br><br>With modified PLANT formulae in Q1 files<br><br>Dr. Andrei Tchouvelev<br>andrei.tchouvelev@hydrogencouncil.com<br><br>Mr. Benjamin Angers<br>benjamin.angers@uqtr.ca | 1. Andrei V. Tchouvelev, William J. Buttner, Daniele Melideo, Daniele Baraldi, Benjamin Angers, Development of risk mitigation guidance for sensor placement inside mechanically ventilated enclosures – Phase 1, International Journal of Hydrogen Energy, Volume 46, Issue 23, 2021, Pages 12439-12454. |
| Sierra Code Suite<br><br>Sandia National Laboratories<br>https://www.sandia.gov | In-house code suite for Sandia National Labs. Low-Mach Fluids Module and Thermal Module.<br><br>The modules can be coupled for jet fire/solid-thermal interactions.<br><br>Dr. Myra Blaylock<br>mlblayl@sandia.gov | 2. B.D. Ehrhart, S.R. Harris, M.L. Blaylock, A.B. Muna, S. Quong, Risk assessment and ventilation modeling for hydrogen releases in vehicle repair garages, International Journal of Hydrogen Energy, Volume 46, Issue 23, 2021, Pages 12429-12438, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2020.09.155 |

### 5.2 Ignition

This section lists the models which have been developed/applied to spontaneous ignition of hydrogen.

*Table 4: CFD models for hydrogen spontaneous ignition*

| **Name of the code/original developer** | **Organisation using the code with and without modification/Contact email** | **Key publications** |
|---|---|---|
| *GASFLOW*<br><br>*Commercial code*<br><br>*www.gasflow-mpi.com* | *Karlsruhe Institute of Technology*<br><br>*www.kit.edu*<br><br>*Dr. Jianjun Xiao*<br><br>*jianjun.xiao@kit.edu* | **Spontaneous Ignition**<br><br>1. Zhilei Wang, Han Zhang, Xuhai Pan, Yiming Jiang, Qingyuan Wang, Jianjun Xiao, Thomas Jordan, Juncheng Jiang, Experimental and numerical study on the high-pressure hydrogen jet and explosion induced by sudden released into the |

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| | *Prof. Dr. Thomas Jordan*<br><br>*thomas.jordan@kit.edu* | air through tubes, International Journal Of Hydrogen Energy, Volume 45, Issue 7, 2020. |
| KIVA-3V<br><br>Los Alamos National Laboratory<br><br>*https://www.lanl.gov/* | Centre for Energy Resilience, University of Surrey. Modified in-house version.<br><br>*www.surrey.ac.uk/Centre for energy resilience*<br><br>Prof. Jennifer X .Wen<br><br>*j.wen@surrey.ac.uk* | **Spontaneous Ignition**<br><br>1. Wen, Jennifer X., Xu, B. P. and Tam, V. H. Y. (2009) Numerical study on spontaneous ignition of pressurized hydrogen release through a length of tube. *Combustion and Flame, Volume 156 (Number 11). pp. 2173-2189. doi:10.1016/j.combustflame.2009.06.012.*<br><br>2. Xu, B. P., Wen, Jennifer X. and Tam, V. H. Y. (2011) The effect of an obstacle plate on the spontaneous ignition in pressurized hydrogen release: a numerical study. *International Journal of Hydrogen Energy, Volume 36 (Number 3). pp. 2637-2644. doi:10.1016/j.ijhydene.2010.03.143.* |

### 5.3 Fire

Models have been developed and applied to hydrogen fire scenarios in the open as well as in enclosure, such as car parks. This section also further includes models applied to simulate car fires of vehicles powered by hydrogen fuel cell as well as flash fires resulting from liquid hydrogen releases.

*Table 5: CFD models for hydrogen fires*

| **Name of the code/original developer** | **Organisation using the code with and without modification/Contact email** | **Key publications** |
|---|---|---|
| ADREA-HF | National Centre for Scientific Research “Demokritos”, in-house CFD code.<br><br>*www.ipta.demokritos.gr*<br><br>Dr. Alexandros G. Venetsanos<br><br>*venets@ipta.demokritos.gr* | 1. Momferatos G., Venetsanos A. G., Russo P., Numerical Investigation of Thermal Hazards from Under-expanded Hydrogen Jet Fires Using a New Scheme for the Angular Discretization of the Radiative Intensity, ICHS-9, Edinburgh 21-23 September 2021. |

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| ANSYS Fluent<br><br>Commercial code www.ansys.com | University of Ulster<br><br>*www.ulster.ac.uk*<br><br>Prof. Vladimir Molkov<br><br>*v.molkov@ulster.ac.uk* | **Hydrogen fire regimes in enclosure**<br><br>1. V. Molkov, V. Shentsov, S. Brennan, D. Makarov. Hydrogen non-premixed combustion in enclosure with one vent and sustained release: Numerical experiments. *International Journal of Hydrogen Energy*, 2014; 39: 10788-10801.<br><br>**Thermal radiation from jet fire**<br><br>2. DMC Cirrone, D Makarov, V Molkov. Thermal radiation from cryogenic hydrogen jet fires. *International Journal of Hydrogen Energy*, 2019;44: 8874-8885. |
| Fire Dynamics Simulator (FDS)<br><br>(Open source)<br><br>NIST<br><br>*https://pages.nist.gov/fds-smv/* | Kevin McGrattan<br><br>*kevin.mcgrattan@nist.gov*<br><br>Jason Floyd<br><br>*jason.floyd@ul.org*<br><br>Simo Hostikka<br><br>*simo.hostikka@aalto.fi*<br><br>Randall McDermott<br><br>*randall.mcdermott@nist.gov*<br><br>Marcos Vanella<br><br>*marcos.vanella@nist.gov* | **Compartment fire flammability limits**<br><br>1. Nobili M, Caruso G. Comparative CFD simulations of a hydrogen fire scenario. In 34th UIT Heat Transfer Conference 2016. Journal of Physics: Conf. Series 796 (2017) 012035. doi:10.1088/1742-6596/796/1/012035<br><br>**Flammability limits, gas dispersion, jet fires, fire plumes, compartment fires, radiation to targets**<br><br>McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M. Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation. NIST Special Publication 1018-3, Sixth Ed. 2022. *http://dx.doi.org/10.6028/NIST.SP.1018*<br><br>**Fuel cell vehicle fires**<br><br>1. Shibani, Salehi F., Baalisampang T., Abbassi R. Numerical modelling towards the safety assessment of multiple hydrogen fires in confined areas. Process Safety and Environmental Protection. 160:594-609, 2022. *https://doi.org/10.1016/j.psep.2022.02.057*<br><br>(N.B. FDS is a low-Mach flow solver, hence limited to simulations of dispersion, |

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| | | gas mixing, and deflagration scenarios involving hydrogen.) |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | Gexcon<br><br>Djurre Siccama<br><br>djurre.siccama@gexcon.com | 1. D. Muthusamy, Validation of FLACS-Fire for Large Scale Fires of Natural Gas/Hydrogen Mixtures. 26th International Colloquium on the Dynamics of Explosions and Reactive Systems, July 30 - August 4, 2017, Boston, USA. |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | HYEX Safety with enhanced used developed functionality www.hyexsafety.com<br><br>Olav Roald Hansen olav@hyexsafe.com | 1.https://h2tools.org/bibliography/modelling-hydrogen-jet-fires-using-cfd<br><br>(N.B. Not using jet-fire models for detailed radiation assessments, more for flow calculations with burning plume) |
| GASFLOW<br><br>Commercial code<br><br>www.gasflow-mpi.com | Karlsruhe Institute of Technology<br><br>www.kit.edu<br><br>Dr. Jianjun Xiao<br><br>jianjun.xiao@kit.edu<br><br>Prof. Dr. Thomas Jordan<br><br>thomas.jordan@kit.edu | **Vertical jet fire with heat losses**<br><br>1. Jianjun Xiao, Mike Kuznetsov, John R. Travis, experimental and numerical investigations of hydrogen jet fire in a vented compartment, Int. J of Hydrogen energy, volume 43, issue 21, 2018.<br><br>**Horizontal Jet Flame**<br><br>1. Qingxin BA, Jianjun Xiao, Thomas Jordan, T. Huang, M. Zhao, G. Xiao, X. Li, Measurement And Modeling On Hydrogen Jet And Combustion From A Pressurized Vessel, 8th International Conference On Hydrogen Safety, Edinburgh On 21-23 September 2021. |
| HyFOAM<br><br>Developed within the frame of OpenFOAM www.openfoam.com<br><br>for hydrogen safety applications | Centre for Energy Resilience, University of Surrey. Modified in-house version.<br><br>www.surrey.ac.uk/Centre for energy resilience<br><br>Prof. Jennifer X .Wen<br><br>j.wen@surrey.ac.uk | **Jet fire**<br><br>1. Wang, C. J., Wen, Jennifer X., Chen, Z. B. and Dembele, S. (2014) Predicting radiative characteristics of hydrogen and hydrogen/methane jet fires using FireFOAM. International Journal of Hydrogen Energy, 39 (35). pp. 20560-20569. doi:10.1016/j.ijhydene.2014.04.062<br><br>**Cryogenic jet fire** |

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| | | 1. Ren, Zhaoxin and Wen, Jennifer X. (2022), The evolution and structure of ignited high-pressure cryogenic hydrogen jets, accepted by Int. J of Hydrogen Energy.<br><br>**Flash fire**<br><br>1. Shelke, Ashish V. and Wen, Jennifer X. (2020) The burning characteristics and flame evolution of hydrocarbon and hydrogen flash fires. Proceedings of the Combustion Institute. 38(3) : 4699-4708.<br>doi :10.1016/j.proci.2020.05.013 |
| Sierra Code Suite<br><br>Sandia National Laboratories<br>https://www.sandia.gov | In-house code suite for Sandia National Labs. Dr. Myra Blaylock mlblayl@sandia.gov | 1. W. Houf, R. Schefer, and G. Evans. Analysis of Barriers for Mitigation of Unintended Releases of Hydrogen. Presented at 2008 Annual Hydrogen Conference and Hydrogen Expo USA, March 30 – April 3, Sacramento, CA SAND2008-2034C.<br>2. https://www.osti.gov/servlets/purl/1145661 |

### 5.4 Explosion

This section comprehensively covers models developed for hydrogen deflagrations, deflagration to detonation transition (DDT) as well as detonation. The simulated explosion scenarios include those in the open, confined and semi-confined environment in the presence of obstacles as well as vented hydrogen explosions.

*Table 6: CFD models for hydrogen explosions*

| **Name of the code/original developer** | **Organisation using the code with and without modification/**<br><br>**Contact email** | **Key publications** |
|---|---|---|
| ADREA-HF | National Centre for Scientific Research “Demokritos”, in-house CFD code.<br><br>www.ipta.demokritos.gr | 1. Tolias I.C., Venetsanos A.G., Kuznetsov M., Koutsoukos S., Evaluation of an improved CFD model against nine vented deflagration experiments, Int. J. of Hydrogen Energy, 46 (2021) 12407-12419. |

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| | Dr. Alexandros G. Venetsanos<br><br>venets@ipta.demokritos.gr | |
| ANSYS CFX<br><br>Commercial code www.ansys.com | Diözese Rottenburg Stuttgart: Startseite<br><br>www.grs.de<br><br>Berthold.Schramm@grs.de | 1. A. Bentaib, N. Chaumeix, A. Bleyer, A. Dehbi, M. Frankova, L. Gastaldo, R. Grosseuvres, Hallouane, T. Holler, S. Jallais, I. Kljenak, S. Kudriakov, L. Maas, Y. Maruyama, J. Murgatroyd, T. Nishimura, M. Povilaitis, B. Schramm, T. Veikko, E. Vyazmina, "ETSON-MITHYGENE benchmark on simulations of upward flame propagation experiment in the ENACCEF2 experimental facility", NUTHOS-12, Qingdao City, Shandong Province, China, October, 2018. |
| ANSYS Fluent<br><br>Commercial code www.ansys.com | Air Liquide with user defined functions<br><br>https://www.airliquide.com/<br><br>Elena.vyazmina@airliquide.com | 1. A. Bentaib, N. Meynet, A. Bleyer, R. Grossoeuvres, L. Gastaldo, N. Chaumeix, E. Studer, S. Kudriakov, S. Jallais, E. Vyazmina, "MITHYGENE Hydrogen Deflagration Benchmark Main outcomes and conclusions", NUTHOS-11, Gyeongju, Korea, October, 2016.<br>2. Bentaib, N. Chaumeix, A. Bleyer, A. Dehbi, M. Frankova, L. Gastaldo, R. Grosseuvres, Hallouane, T. Holler, S. Jallais, I. Kljenak, S. Kudriakov, L. Maas, Y. Maruyama, J. Murgatroyd, T. Nishimura, M. Povilaitis, B. Schramm, T. Veikko, E. Vyazmina, "ETSON-MITHYGENE benchmark on simulations of upward flame propagation experiment in the ENACCEF2 experimental facility", NUTHOS-12, Qingdao City, Shandong Province, China, October, 2018. |
| ANSYS Fluent<br><br>Commercial code<br><br>www.ansys.com | Nuclear Research and Consultancy Group with user defined functions<br><br>https://www.nrg.eu<br><br>Ed Komen komen@nrg.eu | Pratap Sathiah, Tadej Holler, Ivo Kljenak and Ed Komen, The role of CFD combustion modeling in hydrogen safety management – V: Validation for slow deflagrations in homogeneous hydrogen-air experiments- Nuclear Engineering and |

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| | | Design 310, DOI:10.1016/j.nucengdes.2016.06.030 |
| ANSYS Fluent<br><br>Commercial code<br><br>*www.ansys.com* | University of Ulster with user defined functions<br><br>*www.ulster.ac.uk*<br><br>Prof. Vladimir Molkov<br><br>*v.molkov@ulster.ac.uk* | **Closed vessel deflagrations**<br><br>1. Rudy W, Pekalski A, Makarov D, Teodorczyk A, Molkov V. Prediction of Deflagrative Explosions in Variety of Closed Vessels. Energies, 2021, 14(8), 2138; *https://doi.org/10.3390/en14082138*<br><br>**Flame blow-off from TPRD**<br><br>1. Takeno K, Yamamoto S, Sakatsume R, Hirakawa S, Shentsov V, Makarov D, Molkov V. Effect of shock structure on stabilization and blow-off of hydrogen jet flames. International Journal of Hydrogen Energy, 2020;45:10145-10154. *https://doi.org/10.1016/j.ijhydene.2020.01.217*<br><br>**Blast wave and fireball after tank rupture in a fire**<br><br>1. Molkov VV, Cirrone DMC, Shentsov VV, Dery W, Kim W, Makarov DV. Dynamics of blast wave and fireball after hydrogen tank rupture in a fire in the open atmosphere. International Journal of Hydrogen Energy, 46 (2021) 4644-4665. *https://doi.org/10.1016/j.ijhydene.2020.10.211* |
| COM3D | Karlsruhe Institute of Technology, in-house code<br><br>Dr. Alexei Kotchourko *alexei.kotchourko@kit.edu* | **Deflagrations with highly accurate model for laminar burning speed for wide range of pressure and temperatures implemented.**<br><br>1. Szabo, T, Yanez, J, Kotchourko, A, Kuznetsov, M, Jordan, T, Parameterization of Laminar Burning Velocity Dependence on Pressure and Temperature in Hydrogen/Air/Steam Mixtures, Combustion science and technology, 188, pp 1427-1444. |

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| | | **Flame acceleration predictions confirmed experimental criteria for the semi-confined distribution combustion.**<br><br>1. Yanez, J., Kotchourko, A., Kuznetsov, M., Lelyakin, A., & Jordan, T. (2011). Modeling of the flame acceleration in flat layer for hydrogen-air mixtures. 4th Internat. Conf. on Hydrogen Safety (ICHS 2011), San Francisco, Calif., September 12-14, 2011.<br><br>**DDT with hybrid model**<br><br>1. K Ren, A Kotchourko, A Lelyakin, T Jordan, Numerical Reproduction of DDT in Small Scale Channels, 2017, 25th International Conference on Nuclear Engineering, DOI: 10.1115/ICONE25-67150 |
| Europlexus | In-house code<br><br>CEA/Saclay<br><br>*http://www-epx.cea.fr/*<br><br>Dr. E. Studer<br><br>*etienne.studer@cea.fr*<br><br>Dr. S. Koudriakov<br>*sergey.kudriakov@cea.fr* | **Explosion with concentration gradient**<br><br>1. S Kudriakov, M Kuznetsov, E Studer, J Grune, Hydrogen-air deflagration in the presence of longitudinal concentration gradients, ASME International Mechanical Engineering Congress and Exposition, 2013.<br><br>**Blast wave.**<br><br>1. E. Vyazmina, S. Jallais, A. Beccantini, S. Trelat, "CFD design of protective walls against the effects of vapor cloud fast deflagration of hydrogen", ICHS 6th, Yokohama, Japan, 2015.<br><br>**Vented explosion**<br><br>1. E. Vyazmina, S. Jallais L. Krumenacker, A. Tripathi, A. Mahon, J. Commanay, S. Kudriakov, E. Studer, T. Vuillez, F. Rosset, "Vented explosion of hydrogen/air mixture: an intercomparison benchmark exercise", International Journal of Hydrogen Energy, Vol 44, Issue 17 |

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| | | (2019), 8914-8926. DOI: 10.1016/j.ijhydene.2018.07.195<br><br>**DDT**<br><br>1. A.Velikorodny, E.Studer, S.Kudriakov, A.Beccantini, Combustion modeling in large scale volumes using EUROPLEXUS code, J. of Loss Prevention in the Process Ind., 35, 2015. |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | Gexcon<br><br>Djurre Siccama<br><br>djurre.siccama@gexcon.com | **1.** P. Middha, 2010, Development, use, and validation of the CFD tool FLACS for hydrogen safety studies, PhD thesis, Department of Physics and Technology, University of Bergen, Norway. |
| FLACS<br><br>Commercial code<br><br>www.gexcon.com | Air Liquide<br><br>https://www.airliquide.com/<br><br>Dr. Elena Vyazmina<br><br>Elena.vyazmina@airliquide.com | **Confined explosions**<br><br>1. Bentaib, N. Meynet, A. Bleyer, R. Grossoeuvres, L. Gastaldo, N. Chaumeix, E. Studer, S. Kudriakov, S. Jallais, E. Vyazmina, “MITHYGENE Hydrogen Deflagration Benchmark Main outcomes and conclusions”, NUTHOS-11, Gyeongju, Korea, October 2016.<br><br>2. 2. A. Bentaib, N. Chaumeix, A. Bleyer, A. Dehbi, M. Frankova, L. Gastaldo, R. Grosseuvres, Hallouane, T. Holler, S. Jallais, I. Kljenak, S. Kudriakov, L. Maas, Y. Maruyama, J. Murgatroyd, T. Nishimura, M. Povilaitis, B. Schramm, T. Veikko, E. Vyazmina, “ETSON-MITHYGENE benchmark on simulations of upward flame propagation experiment in the ENACCEF2 experimental facility”, NUTHOS-12, Qingdao City, Shandong Province, China, October, 2018.<br><br>**Jet explosions**<br><br>1. J. Daubech, J. Hebrard, S. Jallais, E Vyazmina, D Jamois, F. Verbecke, |

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| | | "Un-ignited and ignited high pressure hydrogen releases: Concentration - turbulence mapping and overpressure effects", Journal of Loss Prevention in the Process Industries, 36 (2015) 439-446, DOI:10.1016/j.jlp.2015.05.013<br><br>2. S. Jallais, E. Vyazmina, D. Miller, J. K. Thomas, "Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment", Process Safety Progress, Vol 37, No 3 (2018) 397-410, 2018. DOI:10.1002/prs.11965.<br><br>**Vented explosions**<br><br>3. E. Vyazmina, S. Jallais, "Validation and recommendations for FLACS CFD and engineering approaches to model hydrogen vented explosions: Effects of concentration, obstruction vent area and ignition position", International Journal of Hydrogen Energy, 41 (2016) 15101-15109. DOI: 10.1016/j.ijhydene.2016.05.189<br><br>4. E. Vyazmina, S. Jallais L. Krumenacker, A. Tripathi, A. Mahon, J. Commanay, S. Kudriakov, E. Studer, T. Vuillez, F. Rosset, "Vented explosion of hydrogen/air mixture : an intercomparison benchmark exercise", International Journal of Hydrogen Energy, Vol 44, Issue 17 (2019), 8914-8926. DOI: 10.1016/j.ijhydene.2018.07.195<br><br>**Blast wave.**<br><br>1. E. Vyazmina, S. Jallais, A. Beccantini, S. Trélat, "Protective walls against effects of vapor cloud fast deflagration: CFD recommendations for design", Process Safety Progress, Vol 37, No 1 (2018) 56-66, DOI: 10.1002/prs.11930. |

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| | | **DDT potential**<br><br>1. J. K. Thomas, J. Geng, O. Rodriquez, S. Jallais, E. Vyazmina, D. Miller, B. Lindberg, R. Pawulski, "Potential for Hydrogen DDT with Ambient Vaporizers", Mary Kay O'Connor Process Safety Center International Symposium, Texas, USA, October 2018. |
| FLACS Commercial code<br><br>Gexcon<br><br>www.gexcon.com | HYEX Safety with enhanced functionality by user settings<br><br>www.hyexsafety.com<br><br>Olav Roald Hansen<br><br>olav@hyexsafe.com | **Explosion**<br><br>http://conference.ing.unipi.it/ichs2005/Papers/120075.pdf<br><br>**DDT**<br><br>2. Middha, P. & Hansen, O.R. (2008). Predicting deflagration to detonation transition in hydrogen explosions. Process Safety Progress, 27 (3): 192-204. (N.B. One of several papers demonstrating reasonable ability to predict conditions for DDT)<br><br>**Detonation (and accurate blast waves)**<br><br>3. Hansen, O.R. and Johnson, D.M. (2015) Improved far-field blast predictions from fast deflagrations, DDTs and detonations of vapour clouds using FLACS CFD, Journal of Loss Prevention in the Process Industries 35:293-316, May 2015 (N.B. Paper is not hydrogen specific. Approach is used on monthly basis to study likelihood for DDT as well as detonation consequences for hydrogen risk assessments. Method for increased precision of blast waves.)<br><br>**Tank burst with delayed explosion.**<br><br>4. Aarskog, F. G., Hansen, O. R., Strømgren, T., & Ulleberg, Ø. (2020). Concept risk assessment of a hydrogen driven high speed passenger ferry. International Journal of Hydrogen Energy, 45(2), 1359-1372. (N.B. Frequently used for |

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| | | risk assessment, studying both physical tanks burst as well as delayed explosion with potential for detonation).<br><br>**Received loading.**<br><br>5. Hansen, O.R., Kjellander, M.T. and Pappas, J.A. (2016), Explosion loading on equipment from CFD simulations, Journal of Loss Prevention in the Process Industries 44:601-613, November 2016. (N.B. Extraction of more detailed explosion loads onto piping, equipment, people and buildings) |
| GASFLOW<br><br>Commercial code<br><br>www.gasflow-mpi.com | Karlsruhe Institute of Technology<br><br>www.kit.edu<br><br>Dr. Jianjun Xiao<br><br>jianjun.xiao@kit.edu<br><br>Prof. Dr. Thomas Jordan<br><br>thomas.jordan@kit.edu | **Slow Deflagration with Heat Losses**<br><br>1. Jianjun Xiao, Wolfgang Breitung, M. Kuznetsov, Han Zhang, Numerical investigations of turbulent slow deflagration of premixed H2-air-H2O mixture in THAI test HD-22 using CFD code GASFLOW-MPI, The 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Qujiang Int'l Conference Center, Xi'an, China, September 3 – 8, 2017.<br><br>**Fast Deflagration with Heat Losses**<br><br>Jianjun Xiao, John R Travis, Mike Kuznetsov, Numerical Investigations of Heat Losses to Confinement Structures from Hydrogen-Air Turbulent Flames in ENACCEF Facility, International Journal of Hydrogen Energy, Volume 40, Issue 38, 2015.<br><br>**Detonation in Open Atmosphere**<br><br>Jianjun Xiao, Wolfgang Breitung, M. Kuznetsov, John R. Travis, R. Redlinger, Development and validation of the parallel all-speed CFD code GASFLOW-MPI for detonation of premixed H2-air mixture in a hemispherical balloon, Proceedings of the 25th International Conference on Nuclear Engineering, |

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| | | ICONE25, Shanghai, China, July 2-5, 2017.<br><br>**<u>Detonation in Confined Geometry</u>**<br><br>Han Zhang, Yabing Li, JianjunXiao, Mike Kuznetsov, Thomas Jordan, Numerical Study of The Detonation Benchmark Using GASFLOW-MPI, International Conference on Hydrogen Safety, Adelaide, Australia, 24-26 September 2019. |
| HyFOAM<br><br>Developed within the frame of OpenFOAM *www.openfoam.com*<br><br>for hydrogen safety applications | Centre for Energy Resilience, University of Surrey. Modified in-house version.<br><br>*www.surrey.ac.uk/Centre for energy resilience*<br><br>Prof. Jennifer X .Wen<br><br>*j.wen@surrey.ac.uk* | **<u>Confined explosions</u>**<br><br>Wen, Jennifer X., Vendra, C. Madhav Rao and Tam, V. H. Y. (2010) Numerical study of hydrogen explosions in a refuelling environment and in a model storage room. *International Journal of Hydrogen Energy, Volume 35 (Number 1). pp. 385-394. doi:10.1016/j.ijhydene.2009.10.052*<br><br>**<u>Semi confined explosions with obstacles</u>**<br><br>Vendra, C. Madhav Rao, Sathiah, Pratap and Wen, Jennifer X. (2018) Effects of congestion and confining walls on turbulent deflagrations in a hydrogen storage facility-part 2 : numerical study. *International Journal of Hydrogen Energy, 43 (32). pp. 15593-15621. doi:10.1016/j.ijhydene.2018.06.100*<br><br>**<u>Vented explosions</u>**<br><br>Vendra, C. Madhav Rao and Wen, Jennifer X. (2019) Numerical modelling of vented lean hydrogen deflagrations in an ISO container. *International Journal of Hydrogen Energy. 44(17), pp. 11247-11258. doi :10.1016/j.ijhydene.2018.11.093*<br><br>**<u>Liquid hydrogen vapour cloud explosions</u>**<br><br>BP Xu and JX Wen (2022) *"Evaluation of safety zones and mitigation measures for hydrogen refueling infrastructure at* |

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| | | *airports" Final report for UK Catapult project.*<br><br>**DDT**<br><br>Khodadadi Azadboni, Reza, Heidari, Ali, Boeck, Lorenz R. and Wen, Jennifer X. *(2019)* The effect of concentration gradients on deflagration-to-detonation transition in a rectangular channel with and without obstructions – a numerical study. *International Journal of Hydrogen Energy, 44 (13). doi:10.1016/j.ijhydene.2019.01.157.*<br><br>**Detonation**<br><br>Heidari, A., Ferraris, S., Wen, Jennifer X. and Tam, V. H. Y. *(2011)* Numerical simulation of large-scale hydrogen detonation. *International Journal of Hydrogen Energy, Volume 36 (Number 3). pp. 2538-2544. doi:10.1016/j.ijhydene.2010.05.093* |
| OpenFOAM<br>*www.openfoam.com*<br><br>PDRFOAM<br><br>/<br><br>PDRFOAM-R | Embedded in OpenFOAM release.<br><br>Shell India Markets Private Limited, India<br><br>*www.shell.com*<br><br>Dr Saurabh Kumar<br><br>*Saurabh.Kumar3@shell.com* | J. Puttock, F. Walter, D. Chakraborty, S. Raghunath and P. Sathiah, Numerical simulations of gas explosion using Porosity Distributed Resistance Approach Part -1: Validation against small-scale experiments – Paper accepted to be published in International Journal of Loss Prevention in the Process Industries (PDRFOAM**).**<br><br>Arun K Ampi and Pratap Sathiah, Numerical Simulation of Hydrogen Deflagration using – Paper ID, 107 Presented in ICHS Conference, Edinburgh. (PDRFOAM-R**)** |
| Fluidyn-VENTEX commercial code<br><br>*www.fluidyn.com/* | Fluidyn<br><br>*www.fluidyn.com/*<br><br>*amita.tripathi@fluidyn.com* | **Vented explosion**<br><br>E. Vyazmina, S. Jallais L. Krumenacker, A. Tripathi, A. Mahon, J. Commanay, S. Kudriakov, E. Studer, T. Vuillez, F. Rosset, "Vented explosion of hydrogen/air mixture : an intercomparison benchmark exercise", International Journal of Hydrogen Energy, Vol 44, Issue 17 (2019), |

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| | | 8914-8926. DOI: 10.1016/j.ijhydene.2018.07.195 |
| LS-DYNA<br><br>Commercial code<br><br>www.ansys.com | French public expert in nuclear and radiological risks<br><br>www.irsn.fr/EN/Pages/Home.aspx<br><br>sophie.trelat@irsn.fr | **Blast wave.**<br><br>E. Vyazmina, S. Jallais, S. Trélat, "CFD based design of a protective blast walls to mitigate the consequences of explosion: method validation and best practices", 20ème congrès Lambda Mu, Saint-Malo, France, 2016. DOI: 10.4267/2042/61799 |
| OpenFOAM<br>www.openfoam.com | In-house modification<br><br>Airbus<br><br>www.apsys-airbus.com<br><br>Alban.Mahon@apsys-airbus.com | **Vented explosion**<br><br>E. Vyazmina, S. Jallais L. Krumenacker, A. Tripathi, A. Mahon, J. Commanay, S. Kudriakov, E. Studer, T. Vuillez, F. Rosset, "Vented explosion of hydrogen/air mixture: an intercomparison benchmark exercise", International Journal of Hydrogen Energy, Vol 44, Issue 17 (2019), 8914-8926. DOI: 10.1016/j.ijhydene.2018.07.195. |
| $P^2$REMICS<br><br>www.irsn.fr/ | In-house code<br><br>IRSN<br><br>laura.gastaldo@irsn.fr | **Confined explosion**<br><br>A. Bentaib, N. Meynet, A. Bleyer, R. Grossoeuvres, L. Gastaldo, N. Chaumeix, E. Studer, S. Kudriakov, S. Jallais, E. Vyazmina, "MITHYGENE Hydrogen Deflagration Benchmark Main outcomes and conclusions", NUTHOS-11, Gyeongju, Korea, October 2016.<br><br>A. Bentaib, N. Meynet, A. Bleyer, R. Grossoeuvres, L. Gastaldo, N. Chaumeix, E. Studer, S. Kudriakov, S. Jallais, E. Vyazmina, "MITHYGENE Hydrogen Deflagration Benchmark Main outcomes and conclusions", NUTHOS-11, Gyeongju, Korea, October 2016.<br><br>A. Bentaib, N. Chaumeix, A. Bleyer, A. Dehbi, M. Frankova, L. Gastaldo, R. Grosseuvres, Hallouane, T. Holler, S. Jallais, I. Kljenak, S. Kudriakov, L. Maas, Y. Maruyama, J. Murgatroyd, T. Nishimura, M. Povilaitis, B. Schramm, T. Veikko, E. Vyazmina, "ETSON-MITHYGENE benchmark on simulations |

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| | | of upward flame propagation experiment in the ENACCEF2 experimental facility", NUTHOS-12, Qingdao City, Shandong Province, China, October 2018.<br><br>**Jet explosion**<br><br>E. Vyazmina, S. Jallais, L. Gastaldo, "Delayed explosion of hydrogen high pressure jets: an inter comparison benchmark study", ICHS, Hamburg, Germany, September 2017. |

### 5.5 Miscellaneous

This section encompasses those applications not directly fall into any of the above categories, such as tank refill.

*Table 7: CFD models related to other hydrogen applications*

| Name of the code/original developer | Organisation using the code with and without modification/Contact email | Key publications |
|---|---|---|
| COM3D | Karlsruhe Institute of Technology, in-house code<br><br>Dr. Alexei Kotchourko<br>*alexei.kotchourko@kit.edu* | **CFD coupled with ABAQUS structure dynamics.**<br><br>A Kotchourko, A Lelyakin, T Jordan, Modelling of hydrogen flame dynamics in narrow gap with bendable wall, International Conference on Hydrogen Safety (ICHS 2017), Hamburg, Germany, 2017.<br><br>**Water spray with sub-model for shockwave-droplet interaction with accounting of droplet atomization**<br><br>A Kotchourko, J Mohacsi, A Lelyakin, Z Xu, T Jordan, Study of attenuation effect of water droplets on shockwaves hydrogen explosion, International Conference on Hydrogen Safety (ICHS 2021), Edinburg, UK, 2021. |

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| Europlexus<br><br>www-epx.cea.fr/ | In-house code<br><br>CEA/Saclay<br><br>Dr. E. Studer<br><br>etienne.studer@cea.fr<br><br>Dr. S. Koudriakov<br>sergey.kudriakov@cea.fr | **Combustion/structure interaction**<br><br>O. Halim, E. Studer, S. Koudriakov, B. Cariteau, A. Beccantini, Detailed examination of deformations induced by internal hydrogen explosions: part 2 models. Int. Conf. On Hydrogen Safety, Sep. 2019, Adelaide, Australia |
| GASFLOW<br><br>Commercial code<br><br>gasflow-mpi.com | Karlsruhe Institute of Technology<br><br>www.kit.edu<br><br>Dr. Jianjun Xiao<br><br>jianjun.xiao@kit.edu<br><br>Prof. Dr. Thomas Jordan<br><br>thomas.jordan@kit.edu | **Heat and Mass Transfer of Hydrogen Combustion Product (Validation of Heat and Mass Transfer of Steam**<br><br>Han Zhang, Yabing Li, Jianjun Xiao, Thomas Jordan, Uncertainty Analysis of Condensation Heat Transfer Benchmark Using CFD Code Gasflow-MPI, Nuclear Engineering And Design, Volume 340, 2018. |
| HyFOAM<br><br>Developed within the frame of OpenFOAM www.openfoam.com<br><br>for hydrogen safety applications | Centre for Energy Resilience, University of Surrey. Modified in-house version.<br><br>www.surrey.ac.uk/Centre for energy resilience<br><br>Prof. Jennifer X .Wen<br><br>j.wen@surrey.ac.uk | **Effect of fire attack on hydrogen cylinders**<br><br>Xu, B. P., Cheng, C. L. and Wen, J. X. (2019) Numerical modelling of transient heat transfer of hydrogen composite cylinders subjected to fire impingement. International Journal of Hydrogen Energy, 44 (21). pp. 11247-11258. doi:10.1016/j.ijhydene.2019.02.229 |
| Sierra Code Suite<br><br>Sandia National Laboratories www.sandia.gov | In-house code suite for Sandia National Labs. Dr. Myra Blaylock mlblayl@sandia.gov | **Heating of solids**<br><br>Chris LaFleur, Gabriela Bran-Anleu, Alice B. Muna, Brian D. Ehrhart, Myra Blaylock, William G. Houf. Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study. Sandia Report: SAND2017-11157. www.osti.gov/servlets/purl/1761273 |

### 5.6 Summary

As part of the remit of EHSP to collect and disseminate information related to hydrogen safety, invitations have been sent to stakeholders to collect information about CFD based models, which have been developed, validated, and applied to different LOC scenarios by the international hydrogen safety community. The chapter is compiled from the information submitted by the organisations which nominated the models for inclusion. It does not to make specific recommendations on the codes or models included. Readers who are interested in any particular code/model should use the contact information provided to contact the relevant organisation. This chapter can serve the purpose to point relevant stakeholders in the right direction to seek additional information, to discussion collaboration or consultancy services as well as seek expert advice subject to mutual agreement of both sides.

If any stakeholders would like to suggest additional models to be included in the future update of the chapter, they should contact the EHSP to supply the relevant information, using the listing in current report as examples.

## 6. PREVENTION AND MITIGATION STRATEGIES

This chapter provides an overview of the prevention and mitigation strategies which can potentially be used to deal with various consequences of liquid and gaseous hydrogen leaks due to unintentional leakages. They can be considered for implementation as part of the hydrogen infrastructure design.

### 6.1 Summary of prevention and mitigation strategies

A prevention measure or barrier is defined as a safeguard that stops the causes that result in the top event [1] for example loss of containment of hydrogen. It must have the capability to completely terminate a threat sequence on its own. A mitigation barrier or measure on the other hand is a safeguard that stops the scenario before the consequence occurs or reduces the severity of the consequence. The mitigation and prevention strategies are presented based on the consequences, e.g., release, spill, cryogenic exposure, fire and explosion, etc.

It should be noted the scope of this chapter does not cover intentional releases to remove excess hydrogen from liquid hydrogen tanks or relieve excess overpressure from the relief vent. Both measures would lead to the release of hydrogen from the storage tanks. Furthermore, any measures used to minimize and control potential ignition sources is also not covered in this chapter.

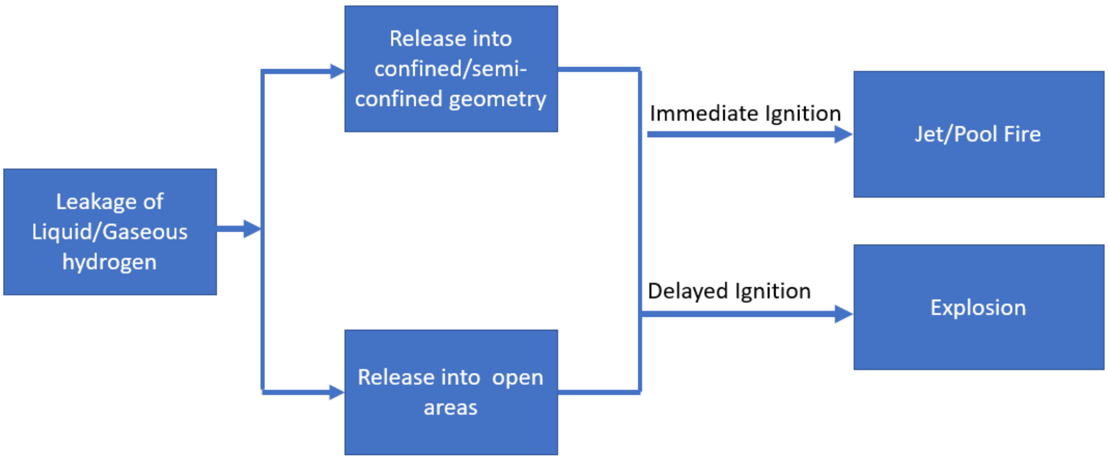


*Figure 1: Phenomena and consequences diagram for indoor use of hydrogen.*

#### 6.1.1 Release

Table 8 summarizes prevention and mitigation measures which can be used in relation to liquid/gaseous hydrogen release.

*Table 8:* Prevention/mitigation measures

| **Prevention/ Mitigation Strategies** | **Description** | **References** |
|---|---|---|
| Cryogenic spill protection (CSP) | CSP is used when there is a risk of cryogenic exposure to the structures leading to its damage. It is well known to be used in the LNG shipping industry. | J. Moorhouse, P. Roberts, Cryogenic spill protection and mitigation, Cryogenics, Volume 28, Issue 12, 1988, Pages 838-846, ISSN 0011-2275. |
| Bunds/impounding basin or spill containment system | Bunds or impounding basins can be used to collect liquid hydrogen leakages. The bunds are typically made of low thermally conductive material e.g., FOAMGLAS or lower thermal conductivity concrete therefore any liquid hydrogen material collected in the sump/basin evaporates slowly thereby limiting the amount of flammable hydrogen-air mixture formed. | *1.* www.law.cornell.edu/cfr/text/49/193.2181<br>*2.* www.foamglas.com/en/advice-center/general-advice/passive-fire-protection-for-lng-impounding-basins#:~:text=Most%20emergency%20incidents%20in%20an,via%20a%20spill%20containment%20system |
| Using gravels | Alternate mitigation measure which can be used for liquid hydrogen release is to have gravel on the ground underneath the liquid hydrogen tank or other liquid hydrogen leakage points. A gravel can significantly increase the evaporation of liquid hydrogen leading to quick dispersion of hydrogen in air. Thereby, limiting the consequence in case of delayed ignition of hydrogen-air mixture | Safety and Security Analysis: Investigative Report by NASA on Proposed EPA Hydrogen-Powered Vehicle Fueling Station, EPA420-R-04-016 October 2004 |
| An automatic shut-off valve | A valve to shut of the flow of hydrogen. An automatic shut-off valve shuts-off the flow when de-energized | *1.* https://fluidhandlingpro.com/fluid-process-technology/fluid-process-control-valves/special-ball-valves-for-safe-hydrogen-oxygen-shut-off/<br>*2.* https://apps.dtic.mil/sti/citations/AD0259087 |

### 6.1.2 Formation of a flammable hydrogen-air mixture

Following liquid/gaseous hydrogen release, a flammable hydrogen-air mixture can be formed. Delayed ignition of such a mixture could lead to possibility of vapour cloud explosion regardless of whether the hydrogen is released in confined, semi-confined, or non-confined environment. In case of release of hydrogen in confined environment, e.g., hydrogen release inside a fuel cell compartment, underground car park, car/bus garages and electrolysis containers, the formation of the large flammable hydrogen-air mixture can be prevented by using different mitigation strategies.

Some of these are presented below in Table 9. These measures could also be considered with caution for releases in semi-confined but highly congested geometries.

*Table 9: Prevention/mitigation measures to limit flammable cloud for indoor release.*

| Prevention/Mitigation Strategies | Description | References |
|---|---|---|
| Forced and natural ventilation | Forced ventilation increases the airflow in areas where there is a possibility of hydrogen leak/release and substantial accumulation. | 1. Jaewon Lee, Sunghyun Cho, Hyungtae Cho, Seungsik Cho, Inkyu Lee, Il Moon, Junghwan Kim, CFD modeling on natural and forced ventilation during hydrogen leaks in a pressure regulator process of a residential area, Process Safety and Environmental Protection, Volume 161, 2022, Pages 436-446, ISSN 0957-5820.<br>2. M.R. Swain, M.N. Swain, Passive ventilation systems for the safe use of hydrogen, International Journal of Hydrogen Energy, Volume 21, Issue 10, 1996, Pages 823-835, ISSN 0360-3199.<br>3. Effect of Mechanical Ventilation on Accidental Hydrogen Releases—Large-Scale Experiments Agnieszka W. Lach and André V. Gaathaug, Energies 2021, 14, 3008. https://doi.org/10.3390/en14113008<br>4. Kuldeep Prasad, High-pressure release and dispersion of hydrogen in a partially enclosed compartment: Effect of natural and forced ventilation, International Journal of Hydrogen Energy, Volume 39, Issue 12, 2014, Pages 6518-6532, ISSN 0360-3199, |
| Inerting | Injection of inerting agent e.g., nitrogen or carbon dioxide etc to make sure that the flammable hydrogen-air mixture is not formed in large volume. In case it is formed the volume of the flammable hydrogen-air mixture is quite low. | 1. Investigation into the effects of carbon dioxide and nitrogen on flammability limits of gas mixtures, IChemE Symposium Series No. 155<br>2. Hydrogen: Air: Steam Flammability Limits and Combustion Characteristics in the FITS Vessel, NUREG/CR-3468 SAND84 -0383 R3 Printed December 1986, Billy W. Marshall, Jr.<br>3. Battersby, P., Holborn, P.G., Ingram, J.M., Averill, A.F. and Nolan, P.F. The mitigations of hydrogen explosions using water fog, nitrogen dilution and chemical additives, International Conference of hydrogen Safety,<br>4. Mitigation of hydrogen hazards in water-cooled power reactors, IAEA-TECDOC-1196<br>5. Malet, J., Porcheron, E., and Vendel, J., OECD International Standard Problem ISP-47 on Containment ThermalHydraulics— |

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| | | Conclusions of the TOSQAN part, Nuclear Engineering and Design, vol. 240, no. 10, pp. 3209–3220, 2010.<br>6. Jaewon Lee, Sunghyun Cho, Hyungtae Cho, Seungsik Cho, Inkyu Lee, Il Moon, Junghwan Kim, CFD modeling on natural and forced ventilation during hydrogen leaks in a pressure regulator process of a residential area, Process Safety and Environmental Protection, Volume 161, 2022, Pages 436-446, ISSN 0957-5820 |
| Ignitors | Igniters are typical of spark and catalytic igniter types. They are included to ensure that gas clouds are ignited (deliberate ignition of hydrogen at the lowest possible concentration) before they grow too large to limit the consequences. | 1. Jianjun Xiao, Zhiwei Zhou, Xingqing Jing, Safety Implementation of Hydrogen Igniters and Recombiners for Nuclear Power Plant Severe Accident Management, Tsinghua Science & Technology, Volume 11, Issue 5, 2006, Pages 549-558, ISSN 1007-0214<br>2. https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a0641-p-ge-g-en-0641-201811-cati-1.pdf?sfvrsn=aca2091f_2<br>3. https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a1737-p-ge-g-en-0641-201902-spark-igniter.pdf?sfvrsn=8895fec4_2<br>4. http://knt.re.kr/business/hydrogen-igniter/<br>5. Mitigation of hydrogen hazards in water-cooled power reactors, IAEA-TECDOC-1196<br>6. Catalytic and spark hydrogen igniters, R. Heck, doi.org/10.1515/kern-1988-530122 |
| Partial Autocatalytic Recombination Systems (PARs) | PARs are used to remove unwanted hydrogen. Typically used in the nuclear industries in order to avoid the build-up of the hydrogen-air flammable mixture inside the Containment. | 1. Y. Halouane, A. Dehbi, CFD simulation of hydrogen mitigation by a passive autocatalytic recombiner, Nuclear Engineering and Design, Volume 330, 2018, Pages 488-496, ISSN 0029-5493<br>2. Hydrogen hazard passive autocatalytic recombiners state of the art. https://cordis.europa.eu/project/id/FIKS-CT-1999-20002<br>3. Mitigation of hydrogen hazards in water-cooled power reactors, IAEA-TECDOC-1196<br>4. Mahdi Saghafi, Faramarz Yousefpour, Kaveh Karimi, Seyed Mohsen Hoseyni, Determination of PAR configuration for PWR containment design: A hydrogen mitigation |

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| | | strategy, International Journal of Hydrogen Energy, Volume 42, Issue 10, 2017, Pages 7104-7119, ISSN 0360-3199.<br>5. L. Gardner, Z. Liang, T. Clouthier, R. MacCoy, A large-scale study on the effect of ambient conditions on hydrogen recombiner-induced ignition, International Journal of Hydrogen Energy, Volume 46, Issue 23, 2021, Pages 12594-12604, ISSN 0360-3199, |
| Catalytic Recombination | Catalytic recombination is used in Automotive industries. | 1. https://www.kiwa.com/nl/en/products/hydrogen-combustion/<br>2. Catalytic hydrogen recombination for nuclear containments, G.W. Koroll, D.W.P. Lau, W.A. Dewit and W.R.C. Graham. |
| Reducing the confinement | Modification of geometry such that it reduces the confinement is reduced in order to prevent stagnant zones of the hydrogen-air mixture. It will also aid in increasing in the mixing of the hydrogen-air mixture due to buoyancy. | Not applicable |
| Hydrogen mixing dampers | Hydrogen mixing dampers can drastically reduce locally high hydrogen concentrations during hydrogen leakage. It enables the gas to spread homogenously within the confinement, therefore dangerous gas concentrations can be avoided preventing fast combustion which could be critical to the integrity of the containment. | https://1www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a1711-p-ge-g-en-1711-201901-hydrogen-mixing-dampers.pdf?sfvrsn=1e8754f4_2 |

For release in open or semi-confined environment, e.g., the release of hydrogen from a hydrogen pipeline, the release of hydrogen from a leak in gaseous hydrogen storage or the release of liquid hydrogen during refuelling from liquid hydrogen trailer on to a stationary tank or during bunkering etc. In this case, inerting agents, and forced and natural convection mitigation presented in Table 9 are less likely to be effective anymore. The following strategies, summarized in Table 10, should be considered.

*Table 10: Prevention/mitigation measures to limit flammable cloud in open environment.*

| Prevention/ Mitigation Strategies | Description | References |
|---|---|---|
| Vapour barrier | Vapour barriers are commonly used to control the dispersion of flammable vapour clouds which form in the event of an accidental release. Vapour barriers are typically used for LNG release. They are able to reduce the spread of LNG therefore reduce the overall size of the flammable cloud footprint. | 1. B. Hendrickson, C. Marsegan, F. Gavelli, where to begin – A parametric study for vapor barriers at LNG export facilities, Journal of Loss Prevention in the Process Industries, Volume 44, 2016, Pages 573-582, ISSN 0950-4230.<br>2. LNG vapor barrier and obstacle evaluation: Wind-tunnel simulation of 1987 Falcon Spill Series. Final report, July 1987-February 1991 Shin, S.H.; Meroney, R.N.; Neff, D.E. Colorado State Univ., Fort Collins, CO (United States). Dept. of Civil Engineering.<br>3. Rana, Morshed. (2009). Forced Dispersion of Liquefied Natural Gas Vapor Clouds with Water Spray Curtain Application. |
| Water sprinklers etc | Fine water-mist dilution to reduce flammability, or sprinklers to improve mixing/dilution. Note that this strategy can also be used reduction in flammable concentration volume in case of confinement. | 1. S.E.Gant, CFD Modelling of Water Spray Barriers HSL/2006/79.<br>2. Rana, Morshed. (2009). Forced Dispersion of Liquefied Natural Gas Vapor Clouds with Water Spray Curtain Application.<br>3. Rana, Morshed & Guo, Yuyan and Mannan, M. Sam. (2010). Use of water spray curtain to disperse LNG vapor clouds. Journal of Loss Prevention in The Process Industries - J LOSS PREVENT PROC IND. 23. 77-88. 10.1016/j.jlp.2009.06.003. |

### 6.1.3 Fire

In case of immediate ignition of hydrogen, there is a possibility of a jet or pool fire. Direct fire impingement or engulfment and the thermal heat flux can have an impact on people and surrounding structures. For example, leak from a gaseous hydrogen pipe can lead to a jet fire, which could potentially injure people within the vicinity. The heat flux and fire exposure to the gaseous hydrogen storage tank can lead to over pressurization of gaseous hydrogen storage tanks and boiling liquid expanding vapor explosion (BLEVE) of the liquid hydrogen storage tank. Potential prevention and mitigation measures are summarised in Table 11.

*Table 11: Prevention/mitigation measures related to hydrogen fires.*

| **Prevention/Mitigation Strategies** | **Description** | **References** |
|---|---|---|
| Firewall/ Fire barriers | A firewall is a passive structure often used in gaseous hydrogen refuelling stations to prevent personnel/objects from fire hazards and thermal radiation.<br><br>The use of firewall/fire barriers should also consider their effect of inhibiting the dispersion of the released hydrogen as well as creating congestion to increase explosion hazards. A balanced approach, taking into local environment and actual installation/facility, is recommended. | 1. Chen Wang, Long Ding, Huaxian Wan, Jie Ji, Yonglong Huang, Experimental study of flame morphology and size model of a horizontal jet flame impinging a wall, Process Safety and Environmental Protection, Volume 147, 2021, Pages 1009-1017, ISSN 0957-5820<br>2. W. Houf, R. Schefer, G. Evans, E. Merilo, M. Groethe, Evaluation of barrier walls for mitigation of unintended releases of hydrogen, Int. J of Hydrogen Energy, 35(10), 2010, Pages 4758-4775.<br>3. R.W. Schefer, M. Groethe, W.G. Hou f, G. Evans, Experimental evaluation of barrier walls for risk reduction of unintended hydrogen releases, International Journal of Hydrogen Energy, 34 (3) (2009), pp. 1590-1606<br>4. R.W. Schefer, E.G. Merilo, M.A. Groe the, W.G. Houf Experimental investigation of hydrogen jet fire mitigation by barrier walls Int. J. Hydrog. Energy, 36 (3) (2011), pp. 2530-2537 |
| Water mist (active fire protection systems) | Water mist is used in partial suppression of the fire the impact on fire by absorbing some of the heat. It can effectively reduce the fire field temperature of hydrogen fires and prevent the fire from developing further. | 1. Zhenhua Tang, Kun Zhao, Zhirong Wang, Jizhe Wang, Yi Pan, Study on the extension length of horizontal hydrogen jet fires under the action of water curtain, Fuel, Volume 322, 2022, 124254, ISSN 0016-2361<br>2. Experimental and theoretical study on the suppression effect of water mist containing dimethyl methylphosphonate (DMMP) on hydrogen jet flame, Zhirong Wang, Hui Xu, Yawei Lu, Zhenhua Tang, Rujia Fan, Fuel ( IF 8.035 ) Pub Date: 2022-09-07, DOI:10.1016/j.fuel.2022.125813<br>3. Dembele, S. and Wen, J.X. (2014) Analysis of the screening of hydrogen flares and flames thermal |

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| | | radiation with water sprays. *International Journal of Hydrogen Energy*, 39(11), pp. 6146-6159. ISSN (print) 0360-3199<br>4. Palis, Stephan & Sträubig, Felix & Voigt, Sascha & Knaust, Christian. (2020). Experimental investigation of the impact of water mist on high-speed non-premixed horizontal methane jet fires. Fire Safety Journal. 114. 103005. 10.1016/j.firesaf.2020.103005.<br>5. Ming-Hui Feng, Quan-Wei Li, Jun Qin, Extinguishment of hydrogen diffusion flames by ultrafine water mist in a cup burner apparatus – A numerical study, Int. J of Hydrogen Energy, 40(39), 2015, Pages 13643-13652, ISSN 0360-3199,<br>6. R. Seiser, K. Seshadri The influence of water on extinction and ignition of hydrogen and methane flames Proc Combust Inst, 30 (2005), pp. 407-414<br>7. C.C. Ndubizu, R. Ananth, P.A. Tatem , V. Motevalli On water mist fire suppression mechanisms in a gaseous diffusion flame Fire Saf J, 31 (1998), pp. 253-276 |
| Sprinkler system (active fire protection systems[6]) | Sprinkler systems are used to provide cooling to the tanks and other structures in case of fire exposure. It is intended to cool the tank and its contents to prevent tank rupture/explosion. It can also be installed onto the surface of hydrogen storage tanks. Sprinkler systems are used in the building containing hydrogen storage tanks.<br><br>Sprinkler systems or water spray can also be used | 1. Jet diffusion flame suppression using water sprays AN INTERIM REPORT, NBSIR84-2812, B.J.McCaffrey<br>2. Zhanjjie Xu, Fan Jiang and Thomas Jordan, Investigation on Cooling Effect of Water Sprays on Tunnel Fires of Hydrogen, International Conference on Hydrogen Safety |

[6] Active fire protection systems - Active fire protection is a safety provision which requires action to be taken to detect and alert, stop or contain a fire. For example, Fire alarm systems, Emergency escape lighting, Fire suppression and sprinkler systems, and dry and wet risers.

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| | externally on the surfaces of hydrogen tanks. | |
| Passive Fire coatings (passive fire protection systems[7]) | Passive fire protection systems work by a process of heat absorption and/or thermal insulation. Thereby, reducing the rate of temperature rise of the item being protected. | 1. *www.hse.gov.uk/comah/sragtech/techmeasfire.htm*<br>2. A review of the applicability of the jet fire resistance test method to severe release scenarios, *https://www.hse.gov.uk/research/rrpdf/rr1120.pdf* |
| Design of structure against heat load | The exposed structure is designed to make sure that it withstands impact of fire. | Thermal Protection and Fire Resistance of High-Pressure Hydrogen Storage D. Makarov, Y. Kim, S. Kashkarov, V. Molkov., Proc. of the Eighth International Seminar on Fire and Explosion Hazards (ISFEH8) |
| Inert gas injection | Inert gas systems or fine water mist are injected into the fire to dilute oxygen and reduce heat generation. | 1. Yue Wu, Xing Yu, Zongcheng Wang, Hao Jin, Yanqiu Zhao, Changjian Wang, Zhihe Shen, Yi Liu, Wei Wang, The flame mitigation effect of N2 and CO2 on the hydrogen jet fire, Process Safety and Environmental Protection, Volume 165, 2022, Pages 658-670, ISSN 0957-5820<br>2. Shmakov, Andrey & Kozlov, Victor & Litvinenko, Maria & Litvinenko, Yu. (2020). Effect of inert and reactive gas additives to hydrogen and air on blow-off of flame at hydrogen release from microleakage. International Journal of Hydrogen Energy. 46. 10.1016/j.ijhydene.2020.10.088. |

### 6.1.4 Explosion

In case of delayed ignition of flammable hydrogen-air mixture formed inside the confinement, e.g., fuel cell and electrolysis compartment, there is a possibility of generating high explosion overpressure or deflagration to detonation transition. This can be possibly mitigated by following prevention and mitigation strategies summarized in Table 12.

[7] Passive fire protection systems - Passive fire protection (PFP) is a form of fire safety provision that remains dormant during normal conditions but becomes active during a fire situation. For example, passive fire protection coatings are thin film intumescent, thick film intumescent (epoxy) and Lightweight cementitious.

*Table 12: Prevention/mitigation measures related to hydrogen explosion.*

| Prevention/Mitigation Strategies | Description | References |
|---|---|---|
| Pressure relief vents or pressure relief devices<br>Rupture disks | Pressure relief allows overpressure to be vented. Typically used in liquid/gaseous hydrogen storage tanks. | 1. Pressure Relief Devices for High-Pressure Gaseous Storage Systems: Applicability to Hydrogen Technology A. Kostival, C. Rivkin, W. Buttner, and R. Burgess National Renewable Energy Laboratory<br>2. *https://www.airproducts.com/-/media/airproducts/files/en/900/900-13-106-us-cylinder-pressure-relief-devices-safetygram-15.pdf?la=en&hash=D770F8F6F3DE50DCCEDE614BB7F5B519*<br><br>*https://www.airproducts.com/-/media/airproducts/files/en/900/900-13-106-us-cylinder-pressure-relief-devices-safetygram-15.pdf?la=en&hash=D770F8F6F3DE50DCCEDE614BB7F5B519* |
| Vents | Explosion vent is a safety device used to protect against excessive internal overpressure generated in case of internal explosion. These contain membrane which burst at low pressure typically fixed over an opening on the structure to be protected. In the event of an internal explosion the vents provide a rapid and unrestricted opening at a predetermined burst pressure allowing combustion burned gases to expand and flow through the open vent. | 1. Explosion venting of rich hydrogen-air mixtures in a cylindrical vessel with two symmetrical vents, Guo, J., Shao, K., Rui, S.H., Sun, X.X., Cao, Y., Hu, K.L. and Wang, C.J, ICHS.<br>2. Hongwei Li, Jin Guo, Fuqiang Yang, Changjian Wang, Jiaqing Zhang, Shouxiang Lu, Explosion venting of hydrogen-air mixtures from a duct to a vented vessel, Int. J of Hydrogen Energy, 43(24), 2018, Pages 11307-11313, ISSN 0360-3199.<br>3. Kai Zhang, Saifeng Du, Hao Chen, Jingui Wang, Jiaqing Zhang, Yi Guo, Jin Guo, Effect of hydrogen concentration on the vented explosion of hydrogen–air mixtures in a 5-m-long duct, Process Safety and Environmental Protection, Volume 162, 2022, Pages 978-986, ISSN 0957-5820. |

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| Water mist and deluge | Water deluge or water mist generated ahead of flames when comes in contact with the flame cools the flame thereby generating lower flame speeds and lower overpressure. They are typically used explosion mitigation in offshore platforms. | 1. www.nist.gov/document/r9302947pdf<br>2. Butz, J.R., French, P. and Plooster, M., "Application of Fine Water Mists to Hydrogen Deflagrations," Proceedings: Halon Alternatives Technical Working Conference, 1994, p. 345.<br>3. Yong Xu, Huangwei Zhang. (2022) Pulsating propagation and extinction of hydrogen detonations in ultrafine water sprays. Combustion and Flame 241, 112086.<br>4. Mitigation of hydrogen-air explosions using fine water mist sprays, SYMPOSIUM SERIES NO. 151, 2006 IChemE<br>5. Xingyan Cao, Yangqing Zhou, Zhirong Wang, Longtao Fan, Zhi Wang, Experimental research on hydrogen/air explosion inhibition by the ultrafine water mist, Int. J of Hydrogen Energy, 47(56), 2022, Pages 23898-23908, ISSN 0360-3199.<br>6. Cheikhravat, H., Goulier, Jules & Bentaib, Ahmed & Meynet, Nicolas & Chaumeix, Nabiha & Paillard, Claude. (2014). Effects of water sprays on flame propagation in hydrogen/air/steam mixtures. Proceedings of the Combustion Institute. https://doi.org/10.1016/j.proci.2014.05.102<br>7. Mitigation of gas explosions using water deluge, Kees Van Wingerden, 2004 https://doi.org/10.1002/prs.680190309 |
| Proper design of the occupied buildings against pressure loads. | Designing the building to account for pressure loads (overpressure and impulse) generated in case of credible explosion scenario. | 1. Paola Russo, Alessandra De Marco, Fulvio Parisi, Failure of reinforced concrete and tuff stone masonry buildings as consequence of hydrogen pipeline explosions, Int. J of Hydrogen Energy, 44(38), 2019, Pages 21067-21079, ISSN 0360-3199 |

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| | | 2. Analysis and Design of Profiled Blast Walls, RESEARCH REPORT 146, Dr L A Louca and J. W. Boh, Health and Safety Executive 2004 |
| Chemical inhibition | Chemical inhibition systems contain chemical (NaHCO3 , HBr and NaCl etc) when injected quickly supress the combustion and stopping the flame propagation. | 1. Mitigation of vapour cloud explosion by chemical inhibition, Dirk Roosendans, Pol Hoorelbeke, Kees van Wingerden, 2012 IChemE, Symposium series number. 158<br>2. Chemical Inhibition of Premixed Hydrogen-air Flames: Experimental Investigation using a 20-litre Vessel,  M. van Wingerden, Trygve Skjold, D. Roosendans, A. Dutertre and A. Pekalski, International Conference on Hydrogen Safety, Edinburgh, 2021.<br>3. Industrial System for Chemical Inhibition of Vapor Cloud Explosions, Dirk Roosendans, Pol Hoorelbeke, Chemical Engineering Transactions, Volume 77, 2019<br>4. Rujia Fan, Zhirong Wang, Wenjie Guo, Yawei Lu, Experimental and theoretical study on the suppression effect of CF3CHFCF3 (FM-200) on hydrogen-air explosion, Int. J of Hydrogen Energy, 47(26), 2022, Pages 13191-13198, ISSN 0360-3199. |
| Separation distances | Separation distance is used to avoid incidents to escalate to other parts of plant or to protect neighbours. | 1. Lachance, J. (2009). Risk-informed separation distances for hydrogen refueling stations. Int. J of Hydrogen Energy, 34. 10.1016/j.ijhydene.2009.02.070.<br>2. Analysis to support revised distance between bulk liquid hydrogen systems and exposure, Hecht, E.S, and Ehrhart, B.D, ICHS. |

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| Flame arrestors or flame flash back arrestors or detonation arrestors | A flame arrester is designed to prevent the propagation of flame in a pipe. It typically contains an assembly of perforated plates, slots, screens etc typically enclosed in a case or frame that will absorb the heat of a flame. Thereby completely stopping the flame propagation and quenching it completely. A Detonation arrestor on the other hand is designed to extinguish a flame front resulting from a detonation of a gas in a piping system. In addition to extinguishing the flame, it is capable of dissipating (attenuating) the pressure front that precedes the flame front. | 1. Performance requirements of flame arrestors in practical applications , I.CHEM.E. SYMPOSIUM SERIES NO. 97, H Phillips and D K Pritchard<br>2. Handbook of Fire and Explosion Protection Engineering Principles, For Oil, Gas, Chemical and Related Facilities Book, Second Edition, 2011 |
| Similar “soft barriers” could be used to limit combustion near ceiling (in flame accelerating beams) or other places with significant congestion.<br><br>The use of large balloons to prevent flammable mixtures in certain regions, but still give volume for gas expansion during explosion. | | Tam V (2000), Barrier Method: An Alternative Approach to Gas Explosion Control, FABIG Newsletter, R372, The Steel Construction Institute, UK |
| Modification of geometry | Layout/geometry optimisation (e.g., limiting the obstacles and limit the confinement) to limit turbulence generation and thereby reducing the maximum flame speed and maximum overpressure | Not applicable |

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| | produced in case ignition of hydrogen-air mixtures. | |
| Blast dampers | Blast dampers are designed to provide protection to persons and equipment during blast events, mitigating the passage of blast pressure along a ventilation system. | 1. https://wozair.com/products/blast-dampers/<br>2. www.nsv.co.uk/index.php/products/dampers.html |
| Blast walls | A blast wall is simply a barrier used to protect the vulnerable structure and its occupants from explosion overpressure, fire and debris. | 1. T. Nozu; R. Tanaka; T. Ogawa; K. Hibi; Y. Sakai , Numerical simulations of hydrogen explosions © blast mitigation, International Conference of hydrogen safety, 2005.<br>2. Vyazmina, E., Jallais, S., Beccantini, A., & Trélat, S. (2018). Protective walls against effects of vapor cloud fast deflagration: CFD recommendations for design. Process Safety Progress, *37*.<br>3. Suwa, Y. (2011). Influence of hydrogen-gas explosion on peripheral structures - Blast wave characteristics and the response of RC walls subjected to the explosive load. In *Proceedings of the 9th International Conference on Shock and Impact Loads on Structures* (pp. 625-634). (Proceedings of the 9th International Conference on Shock and Impact Loads on Structures). |
| Blast Resistant Building | Blast resistant buildings are modular buildings that are designed to withstand significant explosions overpressure. Therefore, they are suitable to keep personnel occupying them | 1. https://modulexsolutions.com/what-is-a-blast-resistant-modular-building/<br>2. Paola Russo, Alessandra De Marco, Fulvio Parisi, Failure of reinforced concrete and tuff stone masonry buildings as consequence of |

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| | safe, and/or protect valuable or safety critical equipment. | hydrogen pipeline explosions, Int. J of Hydrogen Energy, 44(38), 2019, Pages 21067-21079, ISSN 0360-3199<br>3. Handbook for blast-resistant design buildings, Edited by Donald O. Dusenberry, John Wiley and Sons, Inc. |

It is to be recommended that mitigation measures or barriers mentioned above should not be used blindly. It must be considered as part of the design by a competent person/team after discussion. Since it is always possible that mitigation measures used for certain consequence might have opposite effects i.e., enhance the consequences instead of limiting it. For example, the firewalls (see Section 7.2) present in the hydrogen refuelling station will be needed to limit the consequence of hydrogen jet fire in case of immediate ignition. However, if the number of firewalls is more than 2 or 3 it is possible that it will confine the hydrogen gas which has potential to increase the consequence of delayed ignition of hydrogen-air mixture. Another example is injection of water sprays (typically used for enhancing dispersion of hydrogen-air mixture) into liquid hydrogen pool can result in substantial evaporation of liquid hydrogen generating large quantity of flammable hydrogen-air mixture. Delayed ignition of hydrogen-air mixture can result in explosion. Therefore, instead of mitigating effect of water sprays or firewall, depending on how it is used it can enhance the consequences. It is therefore recommended that a balanced approach considering their conflicting effects should be considered with the support of consequence analysis to evaluate and compare the options and their effects on the resulting consequences.

It is recommended that Computational Fluid Dynamics based tools [1-3] are used to investigate the effects of prevention and mitigation systems on the consequences. These tools can also be used for design of the mitigations.

### 6.2 Summary

This chapter summarizes mitigation measures which can be used as part of the hydrogen systems. It is recommended mitigation measures provided is a guidance not be used in all the cases. It is therefore recommended that before a particular mitigation/prevention measure is included as part of the hydrogen system is discussed within the team.

# 7. REGULATIONS, CODES, AND STANDARDS FOR HYDROGEN SAFETY

This chapter gives an overview of the various regulations, codes and standards (RCS) used to address hydrogen safety. This is presented below. It is to be noted that the purpose of the chapter is not to provide an exhaustive and updated overview of all international and national RCS related to hydrogen but rather just some selected ones which are thought to be most relevant to stakeholders of Clean Hydrogen JU. It provides links to some of the most relevant standardisation organisations etc.

## 7.1 Summary of existing RCS

The codes, regulations and standards are mainly divided into those provided by International Organization for Standardization (ISO), Society of Automotive Engineers (SAE), Compressed Gas Association (CGA), European Industrial Gases Association (EIGA), International Electrotechnical Commission (IEC), National Fire Protection Association (NFPA), Publication Series on Hazardous Substances (PGS), American Society Of Mechanical Engineers (ASME) and American Institute of Aeronautics and Astronautics (AIAA) etc. It is to be noted this chapter does not include country-specific RCS.

### 7.1.1 International Organization for Standardization (ISO)

13. ISO 13984: 1999 Liquid hydrogen – Land vehicle fueling system interface. ISO, 1999.
14. ISO 13985: 2006 Liquid hydrogen – Land vehicle fuel tanks. ISO, 2006.
15. ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems, ISO 2015.
16. ISO/TC 220 Cryogenic vessels
17. ISO 21009-1:2008 Cryogenic vessels — Static vacuum-insulated vessels — Part 1: Design, fabrication, inspection, and tests
18. ISO 21009-2:2006 Cryogenic vessels — Static vacuum insulated vessels — Part 2: Operational requirements
19. ISO 21010, Cryogenic vessels — Gas/material compatibility
20. ISO 21011 Cryogenic vessels - Valves for cryogenic service
21. ISO 21012 Cryogenic vessels – Hoses
22. ISO 21013-1:2008 Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 1: Reclosable pressure-relief valves. This standard has been revised by ISO 21013-1:2021.
23. ISO 21013-2:2018, Cryogenic vessels - Pressure-relief accessories for cryogenic service - Part 2: Non-reclosable pressure-relief devices
24. 21013-3:2016 Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 3: Sizing and capacity determination
25. ISO 21014:2019 Cryogenic vessels: Cryogenic Insulation performance
26. ISO 21028-1:2016 Cryogenic vessels — Toughness requirements for materials at cryogenic temperature — Part 1: Temperatures below -80 degrees C
27. ISO 21029-1:2018 Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 1: Design, fabrication, inspection and tests (corresponding to the EN 1251-1,)

28. ISO 20421-1:2019 Cryogenic vessels — Large transportable vacuum-insulated vessels — Part 1: Design, fabrication, inspection and testing
29. ISO 24490: 2016 Cryogenic vessels — Pumps for cryogenic service
30. ISO 14687:2019(en); Hydrogen fuel quality — Product specification
31. ISO 14687:2019 HYDROGEN FUEL QUALITY — PRODUCT SPECIFICATION
32. ISO 15869 Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks (Technical Specification) International 2009
33. ISO 23273:2013 Fuel cell road vehicles -- Safety specifications -- Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen
34. ISO 23828 Fuel Cell Road Vehicle- Energy Consumption Measurement Part 1: Vehicles fuelled with compressed hydrogen
35. ISO/TR 11954:2010 Fuel Cell Road Vehicles- Road Maximum Speed Measurement
36. ISO 6469-1 Electrically propelled road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage systems (RESS)
37. ISO 6469-2 Electrically propelled road vehicles – Safety specifications – Part 2: Vehicle operational safety
38. ISO 6469-3 Electrically propelled road vehicles – Safety specifications – Part 3: Protection of persons against electric shock
39. ISO 6469-4 Electrically propelled road vehicles – Safety specifications – Part 4: Post crash electrical safety requirements
40. ISO/TR 8713 Electrically propelled road vehicles — Vocabulary
41. ISO 12619-1 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 1: General requirements and definitions
42. ISO 12619-2 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 2: Performance and general test methods
43. ISO 12619-3 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 3: Pressure regulator
44. ISO 12619-4 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 4: Check Valve
45. ISO 12619-5 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 5: Manual Cylinder Valve
46. ISO 12619-6 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 6: Automatic Valve
47. ISO 12619-7 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 7: Gas Injector
48. ISO 12619-8 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 8: Pressure Indicator
49. ISO 12619-9 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 9: Pressure Relief Valve
50. ISO 12619-10 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 10: Pressure Relief Device
51. ISO 12619-11 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 11: Excess Flow Valve
52. ISO 12619-12 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 12: Gas-Tight Housing & Ventilation Hoses

53. ISO 12619-13 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 13: Rigid Fuel Line in Stainless Steel
54. ISO 12619-14 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 14: Flexible Fuel Line
55. ISO 12619-15 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 15: Filter
56. ISO 12619-16 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components Part 16: Fittings
57. ISO 11114-1 Gas Cylinders - Compatibility of cylinder and valve materials with gas contents Part 1: Metallic materials
58. ISO 11114-2 Gas Cylinders - Compatibility of cylinder and valve materials with gas contents Part 2: Non-Metallic materials
59. ISO 11114-3 Gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 3: Autogenous ignition test for non-metallic materials in oxygen atmosphere
60. ISO 11114-4 Gas Cylinders - Compatibility of cylinder and valve materials with gas contents Part 4: Test methods for selecting metallic materials resistant to hydrogen embrittlement
61. ISO 21087 Gas analysis — Analytical methods for hydrogen fuel — Proton exchange membrane (PEM) fuel cell applications for road vehicles
62. ISO 16110-1 Hydrogen Generators Using Fuel Processing Technologies - Safety
63. ISO 16110-2 Hydrogen Generators Using Fuel Processing Technologies - Test Method for Performance
64. ISO 16111 Transportable Gas Storage Devices - Hydrogen Absorbed in Reversible Metal Hydrides
65. ISO 17268 Gaseous Hydrogen Land Vehicle Refueling Connection Devices
66. ISO 19880-1 Gaseous Hydrogen Fueling Station - General Requirements
67. ISO 19880-2 Gaseous Hydrogen Fueling Station Dispensers
68. ISO 19880-3 Gaseous hydrogen -- Fueling stations -- Part 3: Valves
69. ISO 19880-4 Gaseous Hydrogen Fueling Station - Compressors
70. ISO 19880-5 Gaseous Hydrogen - Fueling Station – Part 5: Hoses
71. ISO 19880-8 Gaseous Hydrogen Fueling Station - Part 8: Hydrogen Quality Control
72. ISO 19881 Gaseous hydrogen -- Land vehicle fuel containers
73. ISO 19882 Gaseous hydrogen -- Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers
74. ISO/TS 19883 Pressure swing adsorption system for hydrogen separation and purification
75. ISO 19884 2000 GASEOUS HYDROGEN - CYLINDERS AND TUBES FOR STATIONARY STORAGE
76. ISO 22734 Hydrogen Generators Using Electrolysis Process
77. ISO 26142 Hydrogen Detection Apparatus – Stationary applications
78. ISO 19885-1 Gaseous Hydrogen – Fuelling protocols for hydrogen-fuelled vehicles Part 1: Design and development process for fuelling protocols
79. ISO 19885-2 Gaseous Hydrogen – Fuelling protocols for hydrogen-fuelled vehicles Part 2: Definition of communications between the vehicles and dispenser control systems.
80. ISO 19885-3 Gaseous Hydrogen – Fuelling protocols for hydrogen-fuelled vehicles Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles
81. ISO 19880-6 Gaseous Hydrogen Fueling Station - Fittings

82. ISO 20088-1:2016 Determination of the resistance to cryogenic spillage of insulation materials — Part 1: Liquid phase
83. ISO 20088-2:2020 Determination of the resistance to cryogenic spill of insulation materials — Part 2: Vapour exposure"
84. "ISO 20088-3:2018 Determination of the resistance to cryogenic spillage of insulation materials — Part 3: Jet release"
85. ISO TS 20100 Gaseous Hydrogen – Service Stations

### 7.1.2 European norms (CEN/CENELEC)

1. EN 1251-1 Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 1: Design, fabrication, inspection and tests; — Part 2:)
2. EN 17127 Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols.
3. EN 16942, Fuels — Identification of vehicle compatibility — Graphical expression for consumer information
4. EN ISO 4022, Permeable sintered metal materials — Determination of fluid permeability (ISO 4022:2018)
5. EN ISO 17268 Gaseous hydrogen land vehicle refuelling connection devices.
6. EN 17124, Hydrogen fuel — Product specification and quality assurance — Proton exchange membrane (PEM) fuel cell applications for road vehicles
7. EN ISO 4022 Permeable sintered metal materials
8. EN 60204-1 Safety of machinery - Electrical equipment of machines - Part 1 : general requirements.
9. ATEX 114 "equipment" Directive 2014/34/EU - Equipment and protective systems intended for use in potentially explosive atmospheres.
10. ATEX 137 "workplace" Directive 1999/92/EC - Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.
11. ATEX 2014/34/EU: Equipment intended for use in Potentially Explosive Atmospheres
12. ATEX 1999/92/EC: Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.
13. EN 14373, Explosion suppression systems, 2021
14. EN 14460, Explosion resistant equipment, 2018
15. EN 14797, Explosion venting devices, 2006
16. EN 15089, Explosion isolation systems, 2009
17. EN 15233, Methodology for functional safety assessment of protective systems for potentially explosive atmospheres, 2007
18. EN 16020, Explosion diverters, 2011
19. EN 16009, Flameless explosion venting devices, 2011
20. EN 16447, Explosion isolation flap valves, 2014
21. CEN/TR 15281, Guidance on inerting for the prevention of explosions, 2006
22. EN ISO 16852, Flame arresters. Performance requirements, test methods and limits for use, 2016
23. CEN TC 305: "Potentially explosive atmospheres - Explosion prevention and protection", including the various working groups:
24. CEN TC 305 WG1: Test methods for determining the flammability characteristics of substances in potentially explosive atmospheres.

25. CEN TC 305 WG2: Equipment for use in potentially explosive atmospheres
26. CEN TC 305 WG3: Devices and systems for explosion prevention and protection
27. CEN TC 305 WG4: Terminology and methodology
28. CEN TC 305 WG5: Equipment and protection systems for mining
29. CEN TC 305 WG6: Flame arresters
30. Inland transport of dangerous goods Directive, 2008/68/EC: http://europa.eu/legislation_summaries/transport/rail_transport/tr0006_en.htm
31. Dangerous Substances Directive: 67/548/EEC
32. Low Voltage Directive (LVD) 2006/95/EC
33. Electromagnetic Compatibility Directive (EMC) 2004/108/EC
34. Pressure Equipment Directive (PED) 97/23/EC
35. Simple Pressure Vessels Directive (SPVD) 2009/105/EC
36. Transportable Pressure Equipment Directive (TPED) 1999/36/EC
37. Gas Appliances Directive 2009/142/EC Includes fuel cells (where the primary function is heating)
38. Equipment and protective systems for potentially explosive atmosphere Directive (ATEX 95) 94/9/EC
39. Directive on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (ATEX 137) 99/92/EC
40. Machinery Directive (MD) 2006/42/EC
41. Seveso II Directive
42. Directive ATEX 2014/34/E
43. EU directive on Alternate fuels infrastructure, 2014
44. The Electromagnetic Compatibility Directive: EMC 2014/30/EU
45. Commission Regulation (EU) No 406/2010 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.
46. EU regulation 406/2010 Implementing EC Regulation 79/2009 on type-approval of hydrogen-powered motor vehicles EU 2010
47. Measures to encourage improvements in the safety and health of workers 89/391/EEC
48. Personal protective equipment Directive 89/686/EEC

#### 7.1.3 Society of Automotive Engineers (SAE)

1. SAE J2579: Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
2. SAE J2578: General fuel cell vehicle safety U.S., 2009 re-published
3. SAE AIR 6464 EUROCAE Working Group 80 / SAE AE-7AFC Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines
4. SAE AS 6858 Installation of Fuel Cell Systems in Large Civil Aircraft
5. Fuel Cell Standards Committee - Safety Working Group
6. SAE J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
7. SAE J2760 Pressure Terminology Used in Fuel Cells and Other Hydrogen Vehicle Applications
8. SAE J2990/1 Hydrogen and Fuel Cell Vehicle First and Second Responder Recommended Practice

9. SAE J3089 Vehicular Hydrogen Sensor Test Method
10. SAE J3219 Hydrogen Fuel Quality Screening Test of Chemicals for Fuel Cell Vehicles
11. SAE J2572 Measuring the Exhaust Emissions, Energy Consumption and Range of Fuel Cell Powered Electric Vehicles Using Compressed Hydrogen
12. SAE J2574 Fuel Cell Electric Vehicle Terminology
13. SAE J2594 Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems
14. Fuel Cell Standards Committee - Interface Working Group
15. SAE J2600 Compressed Hydrogen Vehicle Fueling Connection Devices (defines geometries of receptacles for different pressure levels)
16. SAE J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles
17. SAE TIR J2601/2 Fueling Protocols for Heavy Duty Gaseous Hydrogen Surface Vehicles (buses)
18. SAE TIR J2601/3 Fueling Protocols for Gaseous Hydrogen Powered Industrial Trucks (forklifts)
19. SAE J2601/4 Ambient Temperature Fixed Orifice Fueling
20. SAE J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles
21. SAE J2719/1 Application Guideline for Use of Hydrogen Fuel Quality Specification
22. SAE J2799 70 MPa Compressed Hydrogen Surface Vehicle Refueling Connection Device and Optional Vehicle to Station Communication
23. SAE J2615 Performance Test Procedures of Fuel Cell Systems For Automotive Applications
24. SAE J2616 Performance Test Procedures for the Fuel Processor Subsystem of Automotive Fuel Cell System.
25. SAE J2617 Performance Test Procedure of PEM Fuel Cell Stack Subsystem for Automotive application.
26. SAE J2719:201109 Hydrogen Fuel Quality for Fuel Cell Vehicles
27. SAE AS 7373 Gaseous Hydrogen for Storage for General Aviation
28. SAE AS 6679 Liquid Hydrogen for Storage for Aviation
29. European Organization for Civil Aviation Equipment (EUROCAE) / Society of Automotive Engineers (SAE)
30. EUROCEA / AIR 6464 SAE AIR 6464 EUROCAE WG80 / SAE AE-7AFC Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines
31. EUROCEA / AS 6858 SAE AS 6858 EUROCAE / SAE Installation of Fuel Cell Systems in Large Civil Aircraft

#### 7.1.4 Compressed Gas Association (CGA)

1. CGA C-6.4: Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Vehicle (HV) Fuel Containers and Their Installation
2. CGA C-21: Design, Qualification and Testing for Pressure Vessels for Portable, Reversible Metal Hydride Systems
3. CGA G-5: Hydrogen
4. CGA G-5.3: Commodity Specification for Hydrogen
5. CGA G-5.4: Standard for Hydrogen Piping Systems at Consumer Sites
6. CGA G-5.5: Hydrogen Vent Systems, Third Edition, 2014.
7. CGA G-5.6: - Hydrogen Pipeline Systems
8. CGA G-4.15: Vacuum-Jacketed Piping in Liquid Oxygen Service standard by Compressed Gas Association, 01/25/2019

9. CGA H-1: Service Conditions for Portable, Reversible Metal Hydride Systems
10. CGA H-2: Guidelines for the Classification and Labeling of Hydrogen Storage Systems with Hydrogen Absorbed in Reversible Metal Hydrides
11. CGA H-3: Cryogenic Hydrogen Storage
12. CGA H-4: Terminology Associated with Hydrogen Fuel Technologies
13. CGA H-5: Installation Standard for Bulk Hydrogen Supply Systems
14. CGA H-10: Combustion Safety for Steam Reformer Operation
15. CGA H-11: Safe Start up and Shutdown Practices for Steam Reformers
16. CGA H-12: Mechanical Integrity of Syngas Outlet Systems
17. CGA H-13: Safe Start up and Shutdown Practices for Steam Reformers Hydrogen Pressure Swing Adsorber (PSA) Mechanical Integrity Requirements
18. CGA H-14: HYCO Plant Gas Leak Detection and Response Practices
19. CGA H-15: Safe Catalyst Handling in HYCO Plants
20. CGA P-6: Standard Density Data, Atmospheric Gases and Hydrogen
21. CGA P-8.3:1999 Perlite Management
22. CGA P-12: Safe Handling of Cryogenic Liquids
23. CGA P-28: Risk Management Plan Guidance Document For Bulk Liquid Hydrogen Systems
24. CGA P-30: Guideline for portable cryogenic liquid containers – Use, care and disposal.
25. CGA P-31: Liquid Oxygen, Nitrogen, and Argon Cryogenic Tanker Loading System Guide
26. standard by Compressed Gas Association, 02/02/2021
27. CGA P-35: Guidelines for Unloading Tankers of Cryogenic Oxygen, Nitrogen, and Argon
28. CGA P-40: Calculation Method for the Analysis and Prevention of Overpressure During Refilling of Cryogenic Tanks with Rupture Disk(s)
29. CGA P-41: Locating Bulk Liquid Storage Systems in Courts
30. CGA P-48: Reciprocating Cryogenic Pumps and Pump Installations for Oxygen, Argon, and Nitrogen
31. CGA P-56: Cryogenic Vaporization Systems-Prevention Of Brittle Fracture Of Equipment And Piping (EIGA Doc 133/05)
32. CGA P-59: Prevention of Excessive Pressure During Filling of Cryogenic Vessels
33. CGA P-75: Standard for Proper Handling of Insulated Tanks that are in Obvious Signs of Loss of Vacuum
34. CGA PS-31: Cleanliness for PEM Hydrogen Piping / Components
35. CGA PS-33: CGA Position Statement on Use of LPG or Propane Tank as Compressed Hydrogen Storage Buffers
36. CGA PS-46: Position Statement - Roofs Over Hydrogen Storage Systems
37. CGA PS-48: CGA Position Statement On Clarification Of Existing Hydrogen Setback Distances And Development Of New Hydrogen Setback Distances In NFPA 55
38. CGA P-8.7: Safe Location of Oxygen and Inert Gas Vents
39. CGA S-1. 1-1.3: Pressure relief device design
40. CGA C-6.4 Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Vehicle (HV) Fuel Containers and Their Installation
41. CGA C-21 Design, Qualification and Testing for Pressure Vessels for Portable, Reversible Metal Hydride Systems
42. CGA P-28 Risk Management Plan Guidance Document For Bulk Liquid Hydrogen Systems
43. CGA V-6:1993 Standard Cryogenic Liquid Transfer Connections

### 7.1.5 European Industrial Gases Association (EIGA)

1. 75/21: Determination of safety distances methodology for determination of safety and separation distances.
2. 211/17: Hydrogen Vent Systems for Customer Applications
3. 13: Oxygen Pipeline and Piping Systems
4. 33: Cleaning of Equipment for Oxygen Service
5. 6/02/E: Safety in storage, handling and distribution of liquid hydrogen
6. 7/03: Metering of cryogenic liquids
7. 24/02: Vacuum insulated cryogenic storage tank systems pressure protection devices
8. 41/89/E: Guidelines for transport of vacuum insulated tank containers by sea
9. 59/98/E: Prevention of excessive pressure in cryogenic tanks during filling
10. 77/01/E: Protection of cryogenic transportable tanks against excessive pressure during filling
11. 93/03/E: Safety features of portable cryogenic liquid containers for industrial and medical gases
12. 103/03/E: Transporting gas cylinders or cryogenic receptacles in "enclosed vehicles"
13. 114/03/E: Operation of static cryogenic vessels
14. 119/04 E: Periodic inspection of static cryogenic vessels

### 7.1.6 International Electrotechnical Commission (IEC)

1. IEC 60079-10-1: Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres
2. IEC 60079-10.2: Classification of areas - Combustible dust atmospheres
3. IEC 63341-1 Railway applications – Rolling stock – Fuel cell systems for propulsion -Part 1: Fuel cell power system
4. IEC 63341-2 Railway applications – Rolling stock – Fuel cell systems for propulsion -Part 2: Hydrogen storage system
5. IEC 62282-6-401 Micro Fuel Cell Power Systems – Power, data, interchangeability and performance test methods for laptop computers
6. IEC/TS 62282-8-301 Energy storage systems using fuel cell modules in reverse mode – Power to methane energy systems based on solid oxide cell including reversible operation – Performance test method
7. IEC 62282-2-100 Fuel Cell Modules
8. IEC 62282-3-100 Stationary Fuel Cell Power Systems - Safety
9. IEC 62282-3-200 Test Method for the Performance of Stationary Fuel Cell Power Plants
10. IEC 62282-3-201 Small stationary polymer electrolyte fuel cell power system – Performance test method
11. IEC 62282-3-300 Stationary Fuel Cell Power Systems - Installation
12. IEC 62282-3-400 Stationary fuel cell power systems - Small stationary fuel cell power systems with combined heat and power output
13. IEC 62282-4-101 Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU) - Safety of electrically powered industrial trucks
14. IEC 62282-4-102 Fuel cell power systems for industrial electric trucks - Performance test methods
15. IEC 62282-4-202 Fuel Cell Power System for Unmanned Aircraft Systems –Performance test method

16. IEC 62282-4-600 Fuel cell and battery hybrid power pack systems for excavators - Performance test methods
17. IEC 62282-5-100 Portable Fuel Cell Appliances - Safety
18. IEC 62282-6-100 Micro Fuel Cell Power System - Safety
19. IEC/PAS 62282-6-150 Micro Fuel Cell Power Systems – Safety – Water reactive (UN Division 4.3) compounds in indirect PEM fuel cells
20. IEC 62282-6-200 Micro Fuel Cell Power Systems - Performance
21. IEC 62282-6-300 Micro Fuel Cell Power System - Fuel Cartridge Interchangeability
22. IEC TS 62282-7-2 Single Cell and Stack Performance Test Methods for Solid Oxide Fuel Cells
23. IEC/TS 62282-8-102 Energy storage systems using fuel cell modules in reverse mode – PEM single cell and stack performance including reversing operation
24. IEC/TS 62282-8-201 Energy storage systems using fuel cell modules in reverse mode – Power to power systems - Performance
25. IEC/TS 62282-9-101 Evaluation methodology for the environmental performance of fuel cell power systems based on life cycle thinking – Streamlined life cycle considered environmental performance characterization of...
26. IEC/TS 62282-9-102 Evaluation methodology for the environmental performance of fuel cell power systems based on life cycle thinking – Product category rules for environmental product declarations of stationary fuel...
27. IEC 62282-6-401
28. IEC 62282-4-1000 Fuel Cell Power Systems for Rolling Stock - Performance Requirements and Test Methods
29. IEC/TS 62282-1 Terminology
30. IEC 62282-6-400 Micro Fuel Cell Power Systems – Power and Data Interchangeability
31. IEC/TS 62282-7-1 Single Cell Test method for Polymer Electrolyte Fuel Cells
32. IEC/TS 62282-8-101 Energy storage systems using fuel cell modules in reverse mode – Solid oxide single cell and stack performance including reversing operation
33. IEC 62932-1 Flow Battery Systems for Stationary Applications – Part 1: Terminology and general aspect
34. IEC 62932-2-1 Flow Battery Systems for Stationary Applications – Part 2-1 Performance, general requirements and method of test
35. IEC 62932-2-2 Flow Battery Systems for Stationary Applications – Part 2-2 Safety Requirements
36. IEC 62932-2-3 Flow Battery Systems for Stationary Applications – Installation requirements
37. IEC 60079-29-1 Explosive atmospheres – Part 29-1: Gas detectors- Performance requirements of detectors for flammable gases
38. IEC 60079-29-2 Explosive atmospheres – Part 29-2: Gas detectors- Selection, installation, use and maintenance of detectors for flammable gases and oxygen

#### 7.1.7 National Fire Protection Association (NFPA)

1. NFPA 55: Compressed Gases and Cryogenic Fluids Code
2. NFPA 2: Hydrogen Technologies Code
3. NPR 8099:2010 on Hydrogen fuelling stations – Guide for safe application of installations for delivery of hydrogen to vehicles and boats with respect to fire, workplace and environment.
4. NFPA 67: Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems
5. NFPA 68: Standard on Explosion Protection by Deflagration Venting

6. NFPA 69: Standard on Explosion Prevention Systems
7. NFPA 30A: Code for Motor Fuel Dispensing Facilities and Repair Garages (National Fire Protection Association, 2003)
8. NFPA 497: Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas Deflagration Venting
9. NFPA 70 Article 692 National Electrical Code - Fuel Cell Systems
10. NFPA 110 Emergency and Standby Power Systems
11. NFPA 853 Installation of Stationary Fuel Cell Power Plants
12. NFPA 855 Standard for the Installation of Stationary Energy Storage Systems

#### 7.1.8 Publication Series on Hazardous Substances (PGS)-35

1. PGS 35 Guidelines “Hydrogen: installations for delivery of hydrogen to road vehicles”. Hazardous Substances Publication Series 35, version 1.0 (April 2015).

#### 7.1.9 American Society Of Mechanical Engineers (ASME)

1. ASME Boiler and Pressure Vessel Code, Section
2. ASME STP-PT-006 Design Guidelines for Hydrogen Piping and Pipelines
3. ASME B31.12, Hydrogen Piping and Pipelines (American Society of Mechanical Engineers, 2012)
4. ASME B31.3, Process Piping (American Society of Mechanical Engineers, 2006)
5. American Society of Mechanical Engineers
6. ASME B31.1 Power Piping
7. ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids
8. ASME B31.8 Gas Transmission and Distribution Piping Systems
9. ASME B31.8S Managing System Integrity of Gas Pipelines
10. ASME STP-PT-006 Design Guidelines for Hydrogen Piping and Pipelines
11. ASME BPVC Section VIII, Division 1 Rules for Construction of Pressure Vessels Division 1
12. ASME BPVC Section VIII, Division 2 Rules for Construction of Pressure Vessels Division 2, Alternate Rules
13. ASME BPVC Section VIII, Division 3 Rules for Construction of Pressure Vessels Division 3, Alternate Rules High Pressure Vessels Article KD-10 Special Requirements for Vessels in High Pressure Gaseous Hydrogen Transport and Storage...
14. ASME Code Case 2390 Composite Reinforced Pressure Vessels
15. ASME BPVC-Section X Fiber-Reinforced Plastic Pressure Vessels
16. ASME BPVC-Section XII Transportation Tanks
17. ASME PTC 50 Performance Test Code for Fuel Cell Power Systems Performance

### 7.2 American Institute of Aeronautics and Astronautics (AIAA)

1. AIAA G-095 Hydrogen and Hydrogen Systems, ANSI/AIAA G-095A-2017.

#### 7.2.1 Underwriters Laboratories (UL)

1. UL Subject 1741 Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
2. UL Subject 2075 Standard for Gas and Vapor Detectors and Sensors

3. UL Subject 2262 Fuel Cell Modules for Use in Portable and Stationary Equipment
4. UL Subject 2262A Borohydride Fuel Cartridges with Integral Fuel Processing for Use with Portable Fuel Cell Power Systems or Similar Equipment
5. UL Subject 2264 B Hydrogen Generators Using Water Reaction
6. UL Subject 2264 D Portable Water Electrolysis Type Hydrogen Generators
7. UL Subject 2265 A Micro Fuel Cell Power Systems Using Direct Methanol Fuel Cell Technology
8. UL Subject 2265 C Hand-Held or Hand-Transportable Alkaline (Direct Borohydride) Fuel Cell Power Units And Borohydride Fuel Cartridges For Use With Consumer Electronics or Information Technology Equipment
9. UL Subject 2266 Electromagnetic Compatibility, Electrical Safety, And Physical Protection of Stationary and Portable Fuel Cell Power Systems for Use with Commercial Network Telecommunications Equipment
10. UL 60079-29-1 Standard for Explosive Atmospheres

#### 7.2.2 American Society for Testing and Materials (ASTM)

1. ASTM D1945-14 Standard Test Method for Analysis of Natural Gas by Gas Chromatography
2. ASTM D7550-09 (Withdrawn 2017) Standard Test Method Standard for Determination of Ammonium, Alkali and Alkaline Earth Metals in Hydrogen and Other Cell Feed gases by Ion Chromatography
3. ASTM D7606 - 17 Standard Practice for Sampling of High-Pressure Hydrogen and Related Fuel Cell Feed Gases
4. ASTM D7634 - 10 (2017) Standard Test Method for Visualizing Particulate Sizes and Morphology of Particles Contained in Hydrogen Fuel by Microscopy
5. ASTM D7649-19 Standard Test Method for Determination of Trace Carbon Dioxide, Argon, Nitrogen, Oxygen and Water in Hydrogen Fuel by Jet Pulse Injection and Gas Chromatography/Mass Spectrometer Analysis
6. ASTM D7650-13 Standard Test Method for Sampling of Particulate Matter in High Pressure Hydrogen used as Gaseous Fuel with an In-Stream Filter
7. ASTM D7651 - 17 Standard Test Method for Gravimetric Measurement of Particulate Concentration of Hydrogen Fuel
8. ASTM D7652 - 11 (Withdrawn 2020) Standard Test Method for Determination of Trace Hydrogen Sulfide, Carbonyl Sulfide, Methyl Mercaptan, Carbon Disulfide and Total Sulfur in Hydrogen Fuel by Gas Chromatography and Sulfur.
9. ASTM D7653 - 18 Standard Test Method for Determination of Trace Gaseous Contaminants in Hydrogen Fuel by Fourier Transform Infrared (FTIR) Spectroscopy
10. ASTM D7676-18 Standard Practice for Screening Organic Halides Contained in Hydrogen or Other Gaseous Fuels
11. ASTM D7941/7941M-14 Standard Test Method for Hydrogen Purity Analysis Using a Continuous Wave Cavity Ring-Down Spectroscopy Analyzer
12. ASTM D7675-15 Standard Test Method for the Determination of Total Hydrocarbons in Hydrogen by FID Based Total Hydrocarbon (THC) Analyzer
13. ASTM D7892-15 Standard Test Method for Determination of Total Organic Halides, Total Non-Methane Hydrocarbons and Formaldehyde in Hydrogen Fuel by Gas Chromatography (GC) and Mass Spectrometry (MS)
14. ASTM Committee F07 on Aerospace and Aircraft / Committee F07.04 Hydrogen Embrittlement

15. ASTM F326-18 Standard Test Method for Electronic Measurement For Hydrogen Embrittlement from Cadmium-Electroplating Processes
16. ASTM F519-17 Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
17. ASTM F1113-87 (2017) Standard Test Method for Electrochemical Measurement of Diffusible Hydrogen in Steel
18. ASTM F1459-06 (2017) Standard Test Method for Determination of the Susceptibility of Metallic Materials to Hydrogen Gas Embrittlement
19. ASTM F1624-12 Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique
20. ASTM Committee F07 on Aerospace and Aircraft / Committee F07.04 Hydrogen Embrittlement
21. ASTM F2078-15 Standard Terminology Relating to Hydrogen Embrittlement Testing
22. ASTM WK17123 Test Method for Carbon Monoxide Chemisorption on Supported Platinum on Alumina Catalysts Using Dynamic Flow Method
23. ASTM Committee F38 on Unmanned Aircraft Systems / Committee F38.01 Airworthiness
24. ASTM WK 60937 Design of Fuel Cells for Use in Unmanned Aircraft Systems
25. ASTM A962/A962M-01a Standard Specification for Common Requirements for Steel Fasteners or Fastener Materials, or Both, Intended for Use at Any Temperature from Cryogenic to the Creep Range
26. ASTM C740-97 Standard Practice for Evacuated Reflective Insulation in Cryogenic Service

#### 7.2.3 CSA America

1. CSA HGV 19880-3 Gaseous Hydrogen – Fueling stations - Valves
2. CSA HGV 5.2 Compact Hydrogen Fueling Systems
3. CSA FC4 / CSA C22.2 No. 22734 Hydrogen Generators using Water Electrolysis - Industrial, Commercial and Residential Applications
4. ANSI/CSA CHMC 1 Test Method for Evaluating Material Compatibility in Compressed Hydrogen Applications – Phase I - Metals
5. CSA CHMC2 Test Method for Evaluating Material Compatibility in Compressed Hydrogen Applications – Phase 2 – Polymers
6. ANSI/CSA FC1-2014 (IEC 62282-3-100:2012,MOD)(formerly ANSI Z21.83) Fuel Cell Power Systems
7. ANSI/CSA FC3 Portable Fuel Cell Power Systems
8. CSA FC5 Hydrogen Generators Using Fuel Processing Technologies – Part 1: Safety
9. ANSI/CSA FC6 Fuel Cell Modules
10. CSA HGV2 Standards for Hydrogen Vehicle Fuel Containers
11. ANSI/CSA HGV3.1 Fuel System Components for Hydrogen Gas Powered Vehicles
12. CSA HGV4.1 Hydrogen Dispensers
13. CSA HGV4.2 Hose and Hose Assemblies for Hydrogen Vehicles and Dispensing Systems
14. CSA HGV4.3 Fueling Parameters for Hydrogen Dispensing System
15. CSA HGV4.4 Gaseous Hydrogen – Fueling Stations - Valves
16. CSA HGV4.6 Manually Operated Valves Used in Gaseous Hydrogen Vehicle Fueling Stations
17. CSA HGV4.7 Automatic Pressure Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations
18. CSA HGV4.8 Hydrogen Gas Vehicle Fueling Stations Compressor Guidelines
19. CSA HGV4.9 Fueling System Guideline

20. CSA HGV4.10 Performance of Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures
21. CSA HPIT1 Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components
22. CSA HPIT2 Dispensing systems and components for fueling hydrogen powered industrial trucks
23. CSA HPRD1 Basic Requirements for Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers
24. CSA SPE – 2.1.3 Best practices for defueling, decommissioning, and disposal of compressed hydrogen gas vehicle fuel containers

**7.2.4 Others**

1. International Fire code, 2018.
2. GTR 2013: Global Technical Regulation (GTR) on hydrogen and fuel cell vehicles. (ECE/TRANS/WP. 29/GRSP/2013/41). International 2013
3. OSHA: 29 CFR 1910.103 29 CFR 1910 Subpart H – Hazardous Materials
4. Code of Federal Regulations 49 CFR Parts 171, 173 and 175 Transport of Micro Fuel Cells on Passenger Aircraft
5. JARI S001: Technical standard for containers of compressed hydrogen vehicle fuel devices
6. EC No.79/2009 Type-approval of hydrogen-powered motor vehicles
7. IGF International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels: Part E
8. IGC Code, produced by the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) http://www.imo.org/environment/mainframe.asp?topic_id=995
9. ADR UN ECE Agreement concerning the International Carriage of Dangerous Goods by Road
10. http://www.unece.org/trans/danger/publi/adr/adr_e.html
11. RID is the European Agreement on the International Carriage of Dangerous Goods by Rail. The regulations appear as Appendix C to the Convention concerning International Carriage by Rail (COTIF) concluded at Vilnius on 3 June 1999, http://www.otif.org/en/law.html
12. ADN is the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways concluded at Geneva on 26 May 2000, http://www.unece.org/trans/danger/publi/adn/adn_e.html
13. The International Maritime Dangerous Goods (IMDG) Code covers the transport of dangerous goods by sea http://www.imo.org/safety/mainframe.asp?topic_id=158
14. UN Recommendations on the Transport of Dangerous Goods, Model Regulations. These are updated every two years. Recommendations relevant to hydrogen are UN 1049 (Hydrogen, Compressed), UN 1066 (Hydrogen, refrigerated liquid) and UN 3468 (hydrogen in a metal hydride storage system)
15. IEEE P1547.9 Guide to Using IEEE Standard 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems
16. ANSI/ISA-60078-29-1 (12.13.01) - 2003 Explosive Atmospheres Part 29-1: Gas detectors - Performance requirements of detectors for flammable Gases
17. UNECE R134, Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV)

18. ECE/TR ANS/WP.29/2014/78, Proposal for a new Regulation on hydrogen and fuel cell vehicles (HFCV) Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV), 26 August 2014 (legally binding document)
19. DI 99/92/CE DU PARLEMENT EUROPÉEN ET DU CONSEIL du 16 décembre 1999 Concernant les prescriptions minimales visant à améliorer la protection en matière de sécurité et de santé des travailleurs susceptibles d'être exposés au risque d'atmosphères explosives

### 7.3 Additional references

More comprehensive list of RCS is provided by FCHO standards database [1] and H2tools [2]. The FCHO database is structured along the different categories e.g., transport applications, stationary applications, portable applications, hydrogen generation and infrastructure hydrogen demand. These categories encompass a vast array of standards related to the fuel cell and hydrogen space. H2tools database on another hand provide various standards application types, e.g., electrical interfaces, embrittlement tests, fuel cell modules, fuel cell power systems, fuelling systems, fuelling station design and fuel specifications etc.

[1]. https://www.fchobservatory.eu/reports

[2]. https://h2tools.org/

## 8. CONCLUSIONS

This document is designed to take the readers through the most basic elements of consequence analysis to the consideration of prevention and mitigation measures as well as regulations, codes and standards. In practical design and preparation of safety case documents, it is likely that these two considerations may also necessitate the repeating of some of the earlier analysis. Hence, it is recommended that readers, who are new to consequence analysis, should consult all chapters of the documents before embarking on these activities. For those readers, who are familiar with the contents of some chapters, they can choose to focus on the chapters which they are relatively less experienced.

It should be noted that some of the risk analysis, engineering and CFD tools are freely available online, some others are not. Interested readers should contact directly the names listed for each tool.