EHSP
EUROPEAN HYDROGEN SAFETY PANEL

Clean Hydrogen Partnership

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EHSP GUIDANCE ON HYDROGEN SAFETY ENGINEERING

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- **Nature of Guidance:** This document is intended to provide general guidance and initial orientation for readers. It is not designed to offer an exhaustive or all-inclusive methodology, which falls outside the mandate and scope of the EHSP.
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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
CHP	Clean Hydrogen 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
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
MAWP	Maximum allowable working pressure

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. The first version was published at the Clean Hydrogen Partnership website in May 2023. Since the relaunch of the EHSP in 2025, experts have updated the report. Considerable changes have been made in this new version, which have focused more on providing guidance, and make cross referencing to other documents of EHSP as well as more references, etc. to the Appendices to make the core documents more compact and easier to follow.

While there are many publications in the public domain, which cover some topics addressed in this document, many stakeholders need orientation to navigate through the vast amount of information out there and guidance on applying the various methodologies to safety engineering design and practices, which is the main motivation for producing and updating this Guidance document.

Following the Introduction, Chapter 2 gives exemplar parameters to consider for hydrogen system risk assessment and industry guidelines for siting. This supplements the rest of the chapters, for which guidance is provided for other cases which require more analysis to inform the design and facility siting. Chapter 3 is focused on risk assessment methods and tools. Considering that for 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 organizations would really benefit from some assistance. Chapter 4 is hence dedicated to addresses this topic. Chapter 5 is focused on guidance for engineering models and tools; Chapter 6 provides guidance on applying computational fluid dynamics (CFD) models/tools. The newly added Chapter 7 provides guidance on using prevention and mitigation barriers. Regarding Regulations, Code and Standards (RCS), readers should consult the separate document, jointly compiled by EHSP Task Force 1 and 3, which provides an updated list of RCS.

The current document is organized 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.

2. INSTALLATION AND WORK PROCESS PARAMETERS

When the design and application of a hydrogen system are standardized, and established regulations, codes, standards, and industry guidelines exist, these resources can be applied. Such publications often provide specific requirements for mitigation barriers and separation distances, which are determined by factors like equipment size, complexity, and risk exposure.

For simpler, standard, or previously successful hydrogen system designs, relying on these applicable regulations, codes, standards, or industry guidelines for siting is often the most straightforward approach.

In other scenarios, a dedicated risk assessment is necessary to determine appropriate safety measures and requirements.

The following elements of hydrogen installation and process knowledge are needed for performing the risk assessment:

- The fundamental design-specific parameters for a system are meticulously documented in both the Piping and Instrumentation Diagram (P&ID) and the overall site layout drawings. These crucial documents collectively define the physical and operational characteristics of the process system.
    - **Pipe Size and Specifications**: The nominal diameter and wall thickness of the piping, which are critical for determining flow rate, fluid velocity, and structural integrity under pressure and temperature conditions. This also encompasses material specifications. Piping size (diameter/schedule) affects performance and leak-related safety risk. Mitigations such as breakaway devices, restricted orifices, and automatic isolation valves can limit hydrogen release, substantially reducing separation distances. Mitigations must be appropriate to the affected operation area (e.g., flow limits shouldn't apply upstream of the valve).
    - **Fluid Density** at operating conditions is essential for calculating pressure drop, flow rates etc. Fluid density directly impacts release rates; therefore, the range of potential densities must be considered to make reasonable assumptions.
    - **Pressure**: The operating and design pressures within the system. This includes maximum allowable working pressure (MAWP) for safety.
    - **Temperature**: The operating and design temperatures of the process fluid. This directly influences the selection of materials (due to thermal expansion and material strength degradation) and the requirements. The temperature of the fluid, in combination with the pressure, defines the fluid density and other properties that influence the release rate.
    - **Fluid Phase**: Whether the fluid is a liquid, gas, vapor, or a two-phase mixture. This parameter fundamentally dictates the type of equipment, piping design, and flow calculations necessary. For a cryogenic fluid, thermodynamic equilibrium between liquid and gas creates a two-phase flow, and determining the liquid fraction is crucial as it increases the mass of released hydrogen.
    - **Equipment** Count and Inventory: The total number and detailed inventory of all major and minor mechanical components within the system, such as pumps, compressors, control valves, and relief devices etc..Risk-based analysis (for example QRA) should consider each component's type, size, and quantity. More

equipment means more potential leak points. Components with lower reliability or high leak potential increase the risk impact.

- **Equipment Layout and Spatial Arrangement**: The precise physical location, elevation, and orientation of all equipment and piping runs within the facility or site. This is critical for maintenance periodicity and safety. Equipment layout affects risk profiles. Placing components with high leak potential close together increases local separation distance. Moving them apart reduces this. Equipment congestion and confinement also influence blast loads from an accidental hydrogen VCE.
- **Mitigations and Safety Systems**: The engineering controls and protective measures incorporated into the design to manage identified hazards. Reduce risk by lowering the probability and/or consequences of an event.
    - Examples of prevention barriers reducing the probability of an event (for more detailed list, please see Chapter 7 for more details):
        - Welded connections instead of flanges.
        - Redundant components, for example the use of two safety valves or of a safety valve and a bursting disk, the use of two quick-acting shutoff valves.
        - Check valves to prevent the backflow.
        - Anti-tow-away devices.
        - Grounding.
        - Break-away devices to reduce the loss of containment or restricted flow orifice to mitigate consequences.
        - Physical protection such as bollards to prevent damage to the system.
        - Gas detectors, including but not limited to concentration, acoustic, thermal, coupled with hydrogen system isolation and shut down.
        - Exhaust ventilation to prevent potential hydrogen accumulation.
        - Anti-whip protection to hoses.
    - Examples of mitigation barriers reducing the consequences of an event (for more detailed list, please see for more details Chapter 7) include:
        - Remote controlled, automatic or manual quick-acting emergency isolating valves;
        - Flow rate limiters;
        - Ventilation;
        - Deflagration vent panels;
        - Fire-resistant walls; and
        - Barrier that provides protection from fragment hazards.

The following information also is needed:

- Pressure Relief: Sizing and setpoints for pressure relief valves (PRVs) and rupture discs.
- Emergency Shutdown (ESD) Systems: Location and logic for critical automated and manual shutdown points.
- Fire Protection: Location of fire monitors, sprinklers, and fireproofing specifications, etc.
- Risk receptors (persons in affected range):
    - Level of exposure (probability of the person in harm's way),
    - Population density,

- Receptor knowledge (the skill of the receptor to assess potential risk, and/or use personal protective equipment), and
- Assessment of avoidance or escape (the reasonable chance for a person to escape harm, emergency procedures in place).

- Size of hydrogen inventory:
  - Stored or produced volume or mass,
  - Process piping size,
  - Maximum operating pressure and temperature, and
  - State (e.g., gaseous, liquid, two-phase).

3. RISK ASSESSMENT METHODS AND TOOLS

The purpose of risk assessment is to proactively identify hazards, to quantify potential risks, and to implement preventive or mitigative measures. Numerous risk assessment methods exist to address varying needs for detail (e.g. qualitative vs. quantitative risk assessment), to meet specific country-dependent regulatory standards, and to align with specific objectives defined by the respective organization.

Performing a risk assessment according to a specific method often requires a quantitative estimation of potential hazards and their consequences. The use of specific tools plays an important role in determining concrete numerical values.

The next sub-chapter gives an overview of established risk assessment methods. Risk assessment tools are next presented, which offer support in implementing specific risk assessment methods.

For more detailed information on how to perform a risk assessment on a specific application, Appendix 1 provides a list of key references with risk assessment methods applied to hydrogen safety applications. References for the use of risk assessment tools are provided in Appendix 2.

3.1. Overview of risk assessment methods

A risk assessment may be required to supplement published methods and guidance when standard requirements are unmet, ambiguous, or missing, or when the system is complex, involves new technology, needs additional safeguards, or is near a sensitive receptor (for example school and hospital). A qualitative risk ranking method can identify major hazards and necessary safeguards and operational procedures.

A quantitative risk approach is needed for higher precision. Risk is defined by consequence and likelihood. Risk-based studies aggregate total system risk to provide granular profiles relative to sensitive receptors. Details of the study are determined by system complexity and the history of similar systems.

Quantitative Risk Assessment (QRA) is more comprehensive than Qualitative Risk Assessment, which uses inherent conservative simplifications and assumptions for easier analysis.

A QRA begins by defining design assumptions, including fluid properties (temperature, pressure, state), pipe sizes, locations, equipment, and mitigations. It assigns assumed hole sizes to credible leak points, then uses physical models to predict the fluid flow from each leak. This flow data is then used in further physical models to study potential consequences. The QRA combines hole size, mitigations, atmospheric conditions, release direction, probability of ignition, and probits to determine a frequency for each potential leak.

A QRA evaluates potential leaks using two methods: societal risk and individual risk. Societal risk analysis rank-orders leaks by the number of affected persons, considering the area at risk and population density. Frequencies are aggregated and plotted against societal risk limits to determine design acceptability. Individual risk analysis uses the same data, but rank-orders the consequence range. The aggregate frequency is plotted over a site plan, which directly shows exclusion zones and property lines. If risk is unacceptable, the results indicate the drivers, but the solution requires a design modification and re-assessment. Due to their site-specific nature, full QRAs must be performed for every installation.

This chapter gives an overview of established risk assessment methods. The methods are divided into quantitative, semi-quantitative, and qualitative categories.

3.1.1. Qualitative risk assessment methods

This section briefly describes the established qualitative risk assessment methods. For further reading, readers should see Appendix 1.

Hazard Identification (HAZID)

Hazard Identification Methods, F. Crawley and B. Tyler, IChemE, 2003, ISBN: 978-0852954577

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.

Hazard and Operability Analysis (HAZOP)

HAZOP – Guide to Best Practice, 3rd Edition, F. Crawley and B. Tyler, Elsevier, 2015, ISBN: 978-0-323-39460-4
Hazard and operability (HAZOP) analysis. A literature review, J. Dunjó et al., 2009, https://doi.org/10.1016/j.jhazmat.2009.08.076

HAZOP is 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.

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.

Event Tree Analysis (ETA)

Event Tree Analysis of Lock Closure Risks, G.K. Beim and B.F. Hobbs, 1997, https://doi.org/10.1061/(ASCE)0733-9496(1997)123:3(169)
Quantitative risk analysis of gaseous hydrogen storage unit, A.E.P. Brown et al., 2005, http://conference.ing.unipi.it/ichs2005/Papers/220003.pdf

ETA is an inductive approach used to identify and quantify a set of possible consequences resulting from a specific initiating event. The analysis starts with an initiating event or initial condition and includes the identification of a set of success and failure events that are combined to produce various outcomes.

This quantitative method identifies the spectrum and severity of possible outcomes and determines their likelihood.

Probabilistic Risk Assessment (PRA)

Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety, 2nd Edition, AIChE, 1999, ISBN: 978-0-8169-0720-5
Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High Temperature Electrolysis Hydrogen Production Plant, K.G. Vedros et al., 2020, https://doi.org/10.2172/1691486

PRA is a systematic and comprehensive methodology to evaluate risks associated with a complex engineered technological entity. Risk is characterized by two quantities, the severity of the possible consequences, and the probability of occurrence of each consequence. It is organized as a process to answer the following three questions:

- What can go wrong?
- How severe are the consequences?
- How likely are these consequences to occur?

Checklist Analysis

Risk analysis of six potentially hazardous industrial objects in the Rijnmond area - a pilot study, Rijnmond Public Authority, Springer, 1982, https://doi.org/10.1007/978-94-017-2907-9

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.

"What If" Analysis, Structured "What If" Technique (SWIFT)

Beyond FMEA: the structured what-if technique (SWIFT), A.J. Card et al., 2012, https://doi.org/10.1002/jhrm.20101

The Structured What-If Technique (SWIFT) is a flexible, team-based, qualitative risk assessment method designed as a faster, more flexible alternative to traditional Failure Mode and Effects Analysis (FMEA). It is built on a speculative process where questions of the form "What if [hardware, software, instrumentation, or operators] [fail, breach, break, lose functionality, reverse, etc.]?" are formulated and reviewed.

3.1.2. Semi-quantitative risk assessment methods

This section briefly describes the established semi-quantative risk assessment methods. For further reading, readers should see Appendix 1.

Failure Mode and Effects Analysis (FMEA)

Procedure for failure mode, effects, and criticality analysis (FMECA), NASA, 1966, https://ntrs.nasa.gov/api/citations/19700076494/downloads/19700076494.pdf

FMEA is a tool to systematically analyse all contributing component failure modes and identify the resulting effect on the system. It provides a structured, proactive approach to identify, prioritize, and mitigate potential failures in designs, manufacturing processes, or products before they occur. The semi-quantitative method involves

- Identification of hazards and events (potentially with an advanced HAZOP) for related equipment, components, and processes
- Identification of failure modes and effects for all components and equipment
- Determination of a risk priority number (RPN). Agree on acceptable limits for the RPN

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.

Layer of Protection Analysis (LOPA)

Layer of Protection Analysis: Simplified Process Risk Assessment, Center for Chemical Process Safety (CCPS). 1999, ISBN: 978-0-816-90811-0

LOPA is a semi-quantitative risk assessment method used to estimate the frequency of hazardous events by evaluating the effectiveness of independent protective layers (IPLs). It bridges qualitative hazard identification (like HAZOP) and full quantitative risk assessment (QRA) by calculating if a scenario meets risk tolerance criteria. Properly applied, LOPA provides a consistent basis for assessments within a company or organisation. However, LOPA is a simplified form of numerical risk analysis and hence has significant limitations. Also, from auditing and reviewing LOPA studies, there are concerns regarding the level of mistakes being made using the technique.

3.1.3. Quantitative risk assessment methods

This section briefly describes the established quantitative risk assessment methods. For further reading, readers should see Appendix 1.

Quantitative Risk Assessment (QRA)

Guidelines for Chemical Process Quantitative Risk Analysis, 2nd Edition, AIChE, 1999, ISBN 978-0-8169-0720-5

Quantifying and Controlling Catastrophic Risks, G.E. Apostolakis, 2008, https://doi.org/10.1016/B978-0-12-374601-6.00014-5

QRA is a method to quantify 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 health of people or damage to property or the environment.

Fault Tree Analysis (FTA)

Fault Tree Analysis: For Reliability and Risk Assessment, J. Andrews and J. Dugan, Quality and Reliability Engineering Series, John Wiley & Sons Inc., 1998, ISBN 978-0-471-98279-1

FTA is a quantitative (regarding 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. It addresses multiple failures, events, and conditions. By visually mapping relationships using logic gates (AND/OR), it helps calculate risk probabilities, identify critical failure paths, and calculate the overall system reliability.

3.2. Overview of risk assessment tools

Risk assessment tools have generally been developed based on the aforementioned risk assessment methodologies as well as on 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.

Risk assessment tools require users to be familiar with the installation and work process described in Chapter 2, as well as to understand assumptions and provide source terms as input, for which some guidance is provided in Chapter 4.

Some of the established risk assessment tools have been used in the process industry for quite some time, while others have been developed specifically for hydrogen safety over the last decade. While HyRAM is available as open source, all other tools listed are commercially available. This section provides an overview of the established risk assessment tools, interested readers should use the web link and or follow the references listed in the Appendix 2 for further details and information on accessing these tools.

3.2.1 Hazard and Operability Analysis (HAZOP)

Open-PHA

Kenexis

https://www.kenexis.com/software/openpha

Open-PHA is a specialized software developed by Kenexis for performing Process Hazard Analysis (PHA), specifically Hazard and Operability (HAZOP) and Layer of Protection Analysis (LOPA) studies, designed to identify and mitigate safety risks in industrial processes.

It is available as a free, offline, standalone desktop application or a cloud-based premium version.

HAZOP Manager

Lihoutech

https://www.lihoutech.com

HAZOP Manager is a specialized, PC-based software application designed to facilitate and document Hazard and Operability Studies (HAZOP) and other risk assessment methodologies like PHA, HAZID, and FMEA. It enables structured risk identification, generates standardized reports, and aids in tracking safety actions.

PHA-Pro

Sphera

PHA-Pro is a specialized software tool designed for conducting Process Hazard Analysis (PHA) and Hazard and Operability studies (HAZOP) in asset-intensive industries. It helps identify, assess, and mitigate risks through structured, collaborative workflows, ensuring compliance with safety regulations. The software streamlines the entire risk management process, from analysis to reporting.

3.2.2 Failure Mode and Effects Analysis (FMEA)

FMEA-Pro

Sphera

https://sphera.com/solutions/process-safety-management/advanced-risk-assessment-software-and-services/failure-mode-effects-analysis-fmea-pro/

FMEA-Pro is a desktop application used to conduct Failure Mode and Effects Analysis (FMEA), enabling proactive risk management, enhanced safety, and regulatory compliance for product designs and manufacturing processes. It streamlines risk assessment, shortens analysis times, and ensures consistency in identifying, evaluating, and mitigating potential failures.

3.2.3 Quantitative Risk Assessment (QRA)

HyRAM

Sandia National Laboratories

https://h2tools.org/hyram

HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models), Version 4.1., Sandia National Laboratories, 2022

B.D. Ehrhart and E.S. Hecht, Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+), Version 4.1, Technical Reference Manual. SAND2022-5649, April 2022.

B.D. Ehrhart et al., Validation and Comparison of HyRAM Physics Models. SAND2021-5811, May 2021.

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is a software toolkit that integrates publicly available data and models relevant to assessing the safety in the use, delivery, and storage infrastructure of hydrogen and other alternative fuels (i.e., methane and propane). 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. HyRAM+ also incorporates experimentally validated models of various aspects of release behavior and flame physics. The HyRAM+ toolkit can be used to support multiple types of analysis, including code and standards development, safety basis development, facility safety planning, and stakeholder engagement.

Shell Shepherd

Shell (distributed by Gexcon)

Shell Shepherd is a specialized Quantitative Risk Assessment (QRA) software tool developed by Shell and licensed through Gexcon. It is designed to assess risks in onshore facilities, helping operators and safety

https://www.gexcon.com/software/shell-shepherd	professionals predict and manage the impact of hazardous incidents such as fires, explosions, and the release of toxic or flammable materials. It enables rapid, probabilistic modeling of risk scenarios, including dispersion, fires, BLEVE (Boiling Liquid Expanding Vapor Explosion), and explosions.
Phast (Safeti Platform) DNV *https://www.dnv.com/services/phast* *https://www.dnv.com/software/services/plant/quantitative-risk-analysis*	Phast (Process Hazard Analysis Software Tool), often used for "Phast Risk" analysis, is a specialized, industry-standard software package developed by DNV for safety and risk management, particularly in the chemical, petrochemical, and oil & gas industries. It is designed to model the consequences of potential hazardous incidents - such as fires, explosions, and toxic releases - to assess risks and inform safety measures.
RISKCURVES TNO (distributed by Gexcon) *https://www.gexcon.com/software/riskcurves/* *Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) - 'Yellow Book', Committee for the Prevention of Disasters, CPR 14E/PGS2, 2nd rev. print, 2005* *Guidelines for quantitative risk assessment - 'Purple Book', National Institute of Public Health and the Environment (RIVM), CPR 18E, 1st edition, 1999/2005*	RISKCURVES is a specialized, industry-standard software tool developed by TNO and currently managed by Gexcon used to perform Quantitative Risk Analyses (QRA) to evaluate safety risks related to the storage, transport, and processing of hazardous materials. It is used to quantify the risk posed to surrounding populations and infrastructure, helping companies comply with safety regulations and supporting urban spatial planning. It calculates risks to human life (individual and societal risk) and assesses the consequences of major accidents, such as explosions, fires, and toxic releases. The software is based on internationally recognized methods and models, specifically the "Coloured Books" (e.g., Yellow Book for effects, Purple Book for QRA procedures).

3.2.4 Fault Tree Analysis (FTA)

FaultTree+ Isograph	FaultTree+ is a specialized software for performing Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Markov analysis, primarily used to assess system safety and reliability in high-risk industries. It is widely considered a leading tool for identifying root causes of system failures, evaluating safety-critical systems, and ensuring compliance with international safety standards. FaultTree+ serves as a deductive analysis tool that maps how specific combinations of hardware, software, or human errors can lead to an undesirable "top event" (e.g., an accident, explosion, or system shutdown).

4. ASSUMPTIONS AND SOURCE TERMS

Following the basic qualitative risk assessment, the next step is to define the source terms for the loss of containment and other scenarios (e.g. see Figure 1) that need to be considered for quantitative risk assessment depending on the hydrogen installation. This is required to quantify the level of the risk associated with loss of containment of hydrogen. As shown in Figure 1, scenarios outlined in red dashes have the potential to be hazardous; these releases of hydrogen can be gas or liquid, forming small leaks, jets or liquid pools. It should be noted that some of these scenarios have very low frequency of occurring or cannot happen for specific hydrogen installations.

In this step, it is not possible to consider all the detailed geometry and operating conditions. Therefore, some assumptions will need to be made. This Chapter will guide the reader in terms of how 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 3), 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 quantitative risk assessment. These recommendations should be considered with care and in combination with the local regulations, environment, and geometrical conditions.

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

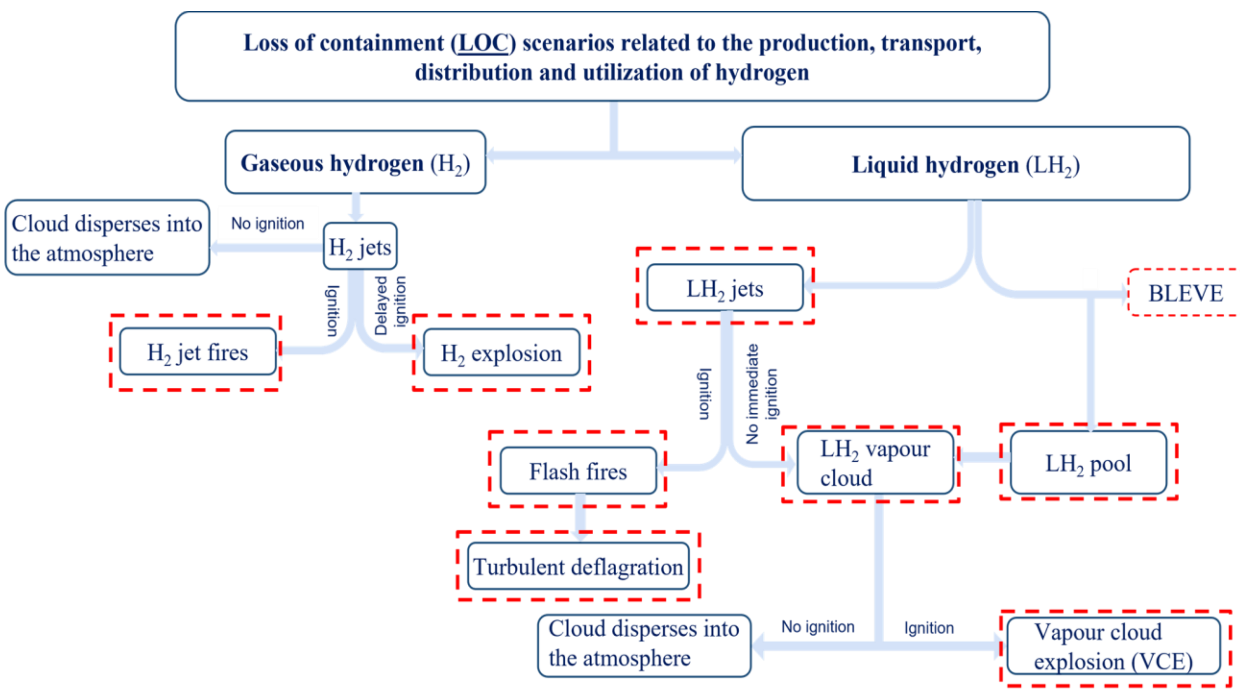

Figure 1. Loss of containment (LOC) scenarios related to the production, transport, distribution and utilization of hydrogen (Reproduced from Wen et al. [1]).

4.1. 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 or leakage rates**: 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 leak flow rate. However, the transient approach will be no longer conservative and needs additional justification to be used in the risk assessment, e.g. demonstration of efficiency of the appropriate safety barriers.
   c. **Leak sizes to calculate the leakage rates**: These are classified into three different categories:
      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.

      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.

      In the case of a presence of excess flow valves, the flow rate for the excess flow valve is characterized by the valve design (sufficient flow or force to overcome the power of the spring holding it open).
   d. **Leakage direction**: In most 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 passes the obstacle (for example obstacle is obstructing the jet flow). For example, jet releases into the ground or wall/ tank surface. Then, jet impingement should be considered. In this case, a CFD-based approach could be used to estimate the length of the plume. In case where it is not credible to release horizontal direction, then another direction should be considered.
   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 diameter at 1000 bar at ambient temperature (T=20°C) will give a mass flow rate of ~7 kg/s for largest leakage (full bore rupture).
2. *Liquid releases*:
   a. **Leak shape**: To simplify the approach for consequence assessment like gaseous hydrogen, it is recommended to consider the shape of the crack to be round instead of another shape, e.g., slits.
   b. **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 released 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 and only liquid phase release is considered. In most of the cases, the temperature of the release is considered at saturated conditions (T=-241.8°C).

c. **Leak flow rate and Inventory**: It is assumed that the flow is continuous at its maximum flow rate for jet release. In case of leak detection and isolation, transient release is considered. For pool release, liquid hydrogen 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 (which is the summation of detection and shut-off valve closure time).
d. **Leakage direction**: In most cases for jets horizontal releases give the largest flammable clouds. In case of the presence of obstacles or potential orientation of the jet downwards, jet impingement should be considered as well, which can potentially lead to pool formation.
e. **Release Height**: The release height corresponds to the lowest (from ground) leakage point in the hydrogen system installation.

4.2. 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 rate. The effects of the presence of a retention pit and bund must be included as this limits 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 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 liquid temperature (T=-253 ^{0}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 corresponding to the released mass of 1.75kg could result in the pool formation. It is assumed that the release is downward towards the ground, promoting the formation of the pool.

4.3. Atmospheric dispersion of hydrogen in case of outdoor release (either jet or pool)

1. The atmospheric conditions (or wind profile) usually are taken into account for 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 or for low velocity releases even from an elevated source.
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) [2-3].
   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, it is assumed to be 1/20 or 1/30 of the average height of these obstacles. The general guideline for the roughness is:

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[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.

i. 3 m for city center with high- and low-rise buildings
ii. 1m for regular large obstacles (suburban, forest)
iii. 0.5m for bushes and numerous obstacles, parking etc
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 several years) is available for the site under consideration.

4.4. 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 and mass. If for some reason a transient approach (in case of leak detection and isolation) is used, it should be justified, since the results are no longer conservative.
2. It is suggested to consider the concentration within the enclosure homogeneous applying the most conservative approach for the concentration and the flammable mass. Other approaches shall be justified.
3. If the estimated concentration is higher than 30 % H2 in air, then the worst case (stoichiometric concentration of 30 %) should be considered.
4. In case the enclosure is ventilated, then natural and forced ventilation should be considered for the estimation of the concentration: for this purpose, only effective ventilation areas should be considered (effect of the grid, obstacles, vent protections etc. reduces the effective ventilation area). A CFD approach is more appropriate/accurate for modelling of effects of ventilation on hydrogen-air flammable mixture.

Example: A small vertical release from a pipe containing gaseous hydrogen of 0.5 inches at 1000 bar at ambient and H_2 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 ~0.7 g/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.

4.5. Concentration ranges for explosion and flash fire scenarios

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, however a potential combustion/ignition of hydrogen/air mixture between 4%-8% does not create a significant overpressure, therefore it is recommended to consider other limits.
2. Other explosive limits in air can be considered:
    a) 8%-75%, according to NFPA 2 2020, Annex I.7, there is no sustainable ignition at hydrogen at concentrations lower than 8%, [4].
    b) hydrogen mass contributing to fast deflagration with a generation of a pressure wave is within 10%-75% concentration range [5-7].
3. For flash fire, the 8%-75% hydrogen envelopes should be considered according to NFPA 2 2020.

4.6. Unconfined Vapour Cloud Explosion

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

1. The centre of the explosion or ignition point is needed to calculate the source overpressure and decay of the overpressure at a certain distance. The location of ignition of flammable mixture needs to be considered in such a way that the calculations produce worst case explosion source overpressure.
2. The initial turbulence generated by the jet should be considered for the overpressure calculation. This is important for high-pressure (pressure greater than 1.9 bar) release, not for low pressure gaseous hydrogen and liquid release.
3. The possibility of deflagration to detonation transition should be considered if appropriate, (for instance if the release is within the vicinity of repeated obstacles or high congested area and confinement).
4. An explosion can have a severe impact on people (e.g., injury or fatality) and structures (buildings, fire water tanks etc.) (see Appendix 1 for further details). The former effects can be based only 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 diameter at 1000 bara at ambient temperature (T=20°C) will give the mass flow rate of 70g/s, flammable (4%-75%) mass/volume of 44 grams 9.35m^3 and explosive mass (10%-75%) of 6.4 grams the ignition point at 60% corresponds to 0.8m, hence the horizontal distances corresponding to overpressure of 100 mbar and 40 mbar are 2m and 4.2m.

4.7. Flash fire

A flash fire has impact only on people (operators inside/outside of the occupied building). The following 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).

4.8. Jet fire

The 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 medium release from a pipe of 0.5 inches at 1000 bara at ambient temperature (T=20°C) in the horizontal direction will give the flame length of 4.5 m and 1 m width, the thermal radiation distances at corresponding to heat flux values of 10 and 5 kW/m^2 are 4.7m and 5.4 m correspondingly.

4.9. Burst

1. The effects to be considered (the corresponding overpressure threshold depends on local regulations and should be considered; accordingly, it is to be effects of blast on structure will depend on overpressure and impulse):
    a. indirect effects.
    b. irreversible effects.
    c. first lethal effects.
    d. significant lethal effects.
2. The 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 external mechanical aggression.
    b. For fire:
        i. Rupture coefficient is 1.9 for cylinders of type 1 and 2.
        ii. Rupture coefficient is 1.7 for cylinders of type 3.
        iii. 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 bara: the rupture pressure is considered to be 770 bara, the burst energy is ~6x10^7 J , than for instance Brode model [8] can be used for the calculations of the corresponding distances to the overpressure threshold of 200mbar and 50mbar of 13m and 43m correspondingly.

4.10. BLEVE

1. The Effects to be considered: blast and thermal effects (the corresponding thresholds depend on local regulations and should be adapted accordingly):
    a. indirect effects.
    b. irreversible effects.
    c. first lethal effects.
    d. significant lethal effects.
2. The 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 external mechanical aggression.
    b. For external fire aggression, loss of thermal insulation, (under the condition that the pressure relief valve is blocked):
        i. Rupture coefficient can be taken as 5 for liquid hydrogen tanks designed up to 14 bars.

4.11. 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 and volume based on 10-75% hydrogen concentration.
2. The possibility of deflagration to detonation transition should also be considered if appropriate (for instance if the release is within the vicinity of repeated obstacles or high congested area and confinement).
3. The effects of Initial turbulence generated by the release should be considered for the source overpressure, overpressure decay and impulse calculation. This is important for high-pressure (pressure greater than 1.9 bar) release, not for low pressure and liquid release.
4. Overpressure relief reduces the source overpressure; therefore, it is important to consider its effect:
    a. the presence of overpressure panels (if they are not blocked) depending on its effective size and opening pressure.
    b. ventilation inlet and outlet are considered as a 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 enclosure should be designed in such a way that it withstands effects of overpressure and rate of pressure as a function of time. In case the enclosure cannot withstand the overpressure, then the impact on surroundings must be estimated.
6. Acoustic waves generated within the enclosure can be calculated using CFD based approach, in addition it can be used to calculate external explosion overpressure and its impact on the surroundings.

4.12. Venting

Consequence assessment is needed in case of release of hydrogen from vents. For vents, vertical release direction is the most appropriate in most cases, except for 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 considered by the consequence of assessment. Typical weather conditions to be considered are F1.5, F3, D5 and D9. It is suggested to use the worst-case dispersion results to estimate the flammable mass and volume
Jet fire: Immediate ignition of release hydrogen can lead to jet fire being established at the base of the vent exit; this should be modelled. The effects of flame impingement and heat flux on adjacent structures and people present within the vicinity should be modelled.
Explosion: It is recommended to estimate the flammable mass and volume of plume of hydrogen-air mixture between H_2 concentration 10-75 % boundary. The center of the explosion i.e. point of ignition can be placed at 60% of the concentration (giving the maximum overpressure).

Example: A horizontal release of hydrogen from a vent exit (25.4 mm diameter) at a temperature of 20°C at 40bara and mass flow rate of 1 kg/s can lead to horizontal distances of corresponding to 4 %, 10 % and 60% are 4***6***m and 19m and 3m correspondingly. The flammable mass/volume corresponds to ***~3***kg, explosive mass is 0.***43***kg. The flame length and width of flame is ***21*** m and 3.***5 m*** respectively. The horizontal distance corresponding to a heat flux value of ***10*** and 5 kW/m^2 are 25m and ***29***m. The horizontal distances corresponding to overpressure values of 100 mbar and 40 mbar are ***23+3=26***m and ***51+3=54***m correspondingly.

Note this chapter does not cover source terms and assumptions for pressure peaking phenomena [9] 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 to model mitigation effects.

4.13. Summary

This chapter summarizes some preliminary approaches to estimate the source terms and consider hypotheses when conducting risk assessment of installations/facilities. These approaches and hypotheses should be refined following international harmonization in the next several years, which is being addressed in the frame of the International Energy Agency (IEA) TCP H2 Task 43.

4.14. References

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5. AVAILABLE ENGINEERING MODELS AND TOOLS

This chapter summarizes 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 and 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 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 e.g. loss of containment or overpressure. 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 database. A state of the art is only a snapshot at a given time, and the continuous development and improvement of these models with new data and application 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.

5.1 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 developers or users in various programming environments, but not available online will be listed in the next chapter.

5.1.1 Open access tools

Regarding open tools, the e-Laboratory of Hydrogen Safety was conceived within the CHP NET-Tools project (https://www.h2fc-net.eu/net-tools https://www.clean-hydrogen.europa.eu/projects-dashboard/projects-repository/net-tools_en) and supported within the HyResponder (https://hyresponder.eu) project coordinated by Ulster University. The e-Laboratory is a free to access the state-of-the-art online tools for hydrogen hazards and consequence assessment. It includes many 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 horizontal and vertical downward release [2].
  - Adiabatic and isothermal 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). calculates the air flow rate to reach a given hydrogen concentration in air.
- Fire
  - Flame length correlation and three hazard distances for jet fire [3].
  - Pressure peaking phenomenon in enclosures for ignited releases [8,9].
  - Calculation of fireball diameter from high-pressure hydrogen tank rupture in a fire and LH2 spill [4,5,52].
- Explosion
  - Blast wave after hydrogen tank rupture without and with hydrogen combustion [6].
  - Mitigation of uniform and non-uniform hydrogen-air deflagrations by venting technique [10].
- Miscellaneous
  - The Abel-Noble Equation-of-State (EoS) calculates CGH2 mass in a volume by pressure and temperature [14].
  - Physical model of fuelling of Type IV hydrogen storage tank [53].

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/green-skills/hydrogen-safetyhttps://www.ulster.ac.uk/skillup/energy/hydrogen-safety
- Part-time Postgraduate Short Courses and CPD:
  - Principles of Hydrogen Safety: https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering/studyhttps://www.ulster.ac.uk/principles-hydrogen-safety
  - Hydrogen Safety Technologies: https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering/studyhttps://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] - used in QRA.
- Fire:
  - Flame properties (jet fires [26–28]).
- Explosion:
  - Deflagration within enclosures [26, 29].
- Miscellaneous:
  - Component leak frequencies [18] - used in QRA.
  - 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.

5.1.2 Commercial tools

Commercial tools are available for quantitative risk assessment and consequences analysis to be used for hydrogen safety using engineering models:

- FRED package from SHELL (https://www.gexcon.com/software/shell-fred/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-softwarehttps://www.gexcon.com/software/effects/).
- PERSEE+ from NATRAN-R&I (https://ri.natrangroupe.com/our-software-offers/).

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

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

5.2 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 which the users can directly use. These include those developed in previous CHP funded projects as well as elsewhere.

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

- Release:
  - Atmospheric dispersion of hydrogen (VentJet) [30];
  - Natural and forced ventilation models in enclosures [42]–[45];

  - Non-adiabatic blowdown model accounting for heat transfer through the tank wall [50] [51]; [62]-[67];
  - Steady-state single / two-phase choked/expanded flow through a discharge line with a variable cross-section with account of friction and extra resistances (DISCHA model from NCSRD) [52]–[54];
  - Extent of cryogenic pools [49];
  - Method for calculating the final state when mixing liquid hydrogen and moist air [49];
  - Condensation blocking in LH2 transferring process [60];

- 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];

- Vapour Cloud Explosion:

  - A vented explosion model developed by Warwick University during the HySEA project based on the paper [41];
  - Ventdef: A model for vented gas deflagration based on NFPA 68 (2018) [61];
  - A model implemented in FRED package for vented hydrogen deflagration [62];
  - Deflagration pressure from delayed ignition of under-expanded hydrogen jet [49], [68];
  - 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: https://shepherd.caltech.edu/EDL/PublicResources/sdt/ https://shepherd.caltech.edu/EDL/PublicResources/detdata/det_props.xls
  - Chemical Equilibrium models:
    http://www.gaseq.co.uk
    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;
- Physical and Chemical Properties:
  https://www.nist.gov/srd/refprop
  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.

5.3 Summary

This chapter gives a non-comprehensive list 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 1 summarizes the present capabilities of the different open-science tools concerning the main physical phenomena involved in a hydrogen accident. It also includes related references.

Table 1: 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], [52]	[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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6. GUIDANCE ON USING CFD TECHNIQUES FOR HYDROGEN SAFETY APPLICATIONS

Although the similarity law or integral models can be used to provide screening analysis to identify critical locations for detailed consequence modelling and QRA, their accuracy is constrained by the underlying assumptions in their derivations as well as the range and extent of experimental data used in their validations; and their similarity to the considered scenarios in terms of fuel, operating parameters and configurations. 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 and 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 might lead to different predictions for the same scenario.

To support consistent interpretation and use of CFD results in hydrogen safety assessments (including QRA and safety cases), CFD studies should, as a minimum, document scenario definition, numerical setup, model selection and validation evidence. Minimum reporting items for CFD studies used in QRA should include: scenario definition and source-term specification; geometry simplifications and rationale; domain size and boundary conditions; mesh statistics and grid-independence evidence; time-step choice and temporal convergence; turbulence, combustion, and radiation models and parameter values; thermophysical property models (including real-gas/cryogenic assumptions where relevant); validation evidence against relevant experiments; sensitivity/uncertainty assessment for key parameters.

While experienced users may try to use CFD models based on in-house codes (if available) or open-source software, those who are less familiar with CFD techniques are recommended to start with commercially available software for which there are user guidance as well as tutorial problems to assist learning. It is important to be aware that even if you use the same code as a published paper, you do not necessarily have access to the additional sub-models/add-ons which the authors introduced.

This chapter provides some guidance for simulating the following scenarios related to the accidental releases of gaseous hydrogen. Guidance on CFD simulations of cryogenic compressed or liquid hydrogen will be added in a future update of this document.

- Release
- Ignition
- Jet fire
- Explosion
- Miscellaneous

Appendix 5 provides a list of most available CFD codes which have been developed/applied to each of these scenarios here as well as some references where contact details and additional information can be found.

Since the quality of CFD predictions is influenced not only by the code itself, but also by the selected physical models, numerical implementation, boundary conditions, and user expertise, the credibility of a CFD study must be assessed on a broader basis than software selection alone. This Chapter, hence, also includes a section about Hydrogen Model Evaluation Protocol (HyMEP), which support the systematic assessment of CFD model credibility and user competence in hydrogen safety applications.

6.1. Release and subsequent atmospheric dispersion

CFD simulations have been widely used to model atmospheric dispersions of both gaseous and liquid H2 releases, especially for the release scenarios of large-scale LH2 spill, inside enclosures with or without confinement/congestions, close to the ground. These scenarios involve three dimensions and interaction between the releases and with the surroundings.

CFD simulations of the atmospheric dispersion or dispersion hydrogen in an enclosed space of released hydrogen should generally start with defining/quantifying the source terms, for which readers should consult Chapter 4 of this guidance.

Turbulence plays a crucial role in the dispersions by enhancing the entrainment of ambient air. Although large eddy simulations (LES) have been used for small scale releases, classical Reynolds-averaged Navier-Stokes (RANS and URANS) turbulence models, such as standard k-ε, RNG- k-ε or others are generally used to model the turbulent effects. There are many books about CFD techniques, in which readers can find description about these terms [e.g. 1,2]. For dispersion simulations, an ideal gas assumption in most cases is sufficient to describe gas behavior.

The atmospheric dispersion is closely related to the atmospheric boundary layer conditions, which are specified through the wind inlet profiles for velocity and turbulent conditions. These profiles are parameterized as the atmospheric stability according to the Pasquill-Gifford stability classes [3], which rates from class A (unstable) through D (neutral) to F (stable), see Chapter 3 for guidance. The atmospheric boundary layer can be modelled by imposing profiles for velocity, temperature and turbulence on flow inlet boundaries. These profiles can be specified as a function of the atmospheric stability and the surface roughness length according to van den Bosch's approach [4]. The velocity profile can be calculated following Van den Bosch [5]. To determine the heating from the ground a one-dimensional unsteady heat conduction equation can be solved inside the ground down to an assumed depth where the temperature is unaffected by the dispersion. To avoid resolving the temperature profile of the boundary layer [6] wall functions are recommended to be used for the gas phase solver:

$$T^* = \begin{cases} Pry^* & y^* < y_T^* \\ Pr_t(k^{-1}\log(\mathrm{E}y^*) + P) & y^* > y_T^* \end{cases} \tag{1}$$

where T^* is the dimensionless friction temperature, y^* is the non-dimensional distance from the wall, y_T^* is the non-dimensional thermal sublayer thickness, E (E = 9.793) is an empirical constant. *Pr*, Pr_t, and P are molecular Prandtl number, turbulent Prandtl number, and additional functions respectively. The function *P* is defined by the following expression:

$$P = 9.24\left[\left(\frac{Pr}{Pr_t}\right)^{\frac{3}{4}} - 1\right]\left[1 + 0.28e^{-0.007\frac{Pr}{Pr_t}}\right] \tag{2}$$

6.2. Ignition

CFD simulations of ignition can generally be divided into two categories: (1) the ignition mechanism; and (2) treatment of ignition in CFD simulations of fires/explosions. This section only addressed the 1st category, while for 2nd category, readers are referred to Section 6.3. Jet fire and Section 6.4. Explosion for the treatment of ignition in simulating these scenarios.

While simulating ignition mechanism, i.e., Category 1, using CFD techniques generally does not form part of a QRA process, some brief guidance is provided in this section while a list of available models is provided in Appendix 5.

Astbury and Hawksworth [7] analyzed the previously proposed mechanisms for hydrogen spontaneous ignition, which include the reverse Joule–Thomson effect, electrostatic charge generation, diffusion ignition, sudden adiabatic compression, and hot surface ignition. The possibility of spontaneous ignition due to Joule–Thomson expansion was ruled out, and the lack of experimental evidence about the other ignition mechanisms was also highlighted. It was suggested that two or more of the postulated mechanisms were present together in some spontaneous ignition events, e.g., certain forms of electrostatic charging might have contributed to spontaneous ignition of leaks in pressurized hydrogen releases. The main bodies of the literature on CFD simulations of hydrogen spontaneous ignition have focused on diffusion ignition while few addressed hot surface ignitions.

Because of the relatively fine grid resolutions required to capture the ignition process, it is generally not recommended to combine such simulations with the subsequent simulations of fire or explosion.

6.3. Jet fire

Accidental releases of hydrogen are generally related to small, medium or large leaks. Early ignition of these leaks generally results in jet fires. Knowledge of the flame length and thermal radiation heat flux distribution is important to inform QRA and the definition of the safety distances.

CFD simulation is an effective approach to predict the flame length and radiative heat flux by using advanced physical models. The critical pressure ratio across the leak/nozzle, p_1/p_{atm}, determines whether the flow is subsonic or sonic/supersonic. Here, p_1 is the pressure in the reservoir and p_{atm} is atmospheric pressure. The critical pressure ratio for the transition to sonic flow for hydrogen is 1.9 [8]. If $p1/patm$ < 1.9 the flow is sub- sonic and expanded. For $p1/patm$ > 1.9 the exit velocity remains locally sonic and the jet is under-expanded, meaning the exit pressure rises above ambient, with the result that expansion takes place outside of the real nozzle at a location down- stream of the Mach disc (referred to as the effective nozzle diameter) [9-11] , at which location the jet pressure has equilibrated with the ambient conditions. For jet fires at the scale of metres, it is generally computationally too expensive to use fine grid resolutions to capture the shock-laden near-nozzle region. Most CFD based numerical studies bypassed the shock-laden region and assumed subsonic inlet boundary conditions defined by the notional nozzle model proposed by Birch et al. [9,10] described above. It is also viable to represent the release blowdown characteristics using the volumetric source as an expanded implementation of the notional nozzle concept [11].

Buoyancy plays an important role in modelling jet fires. Hence, a compressible solver with consideration of the buoyancy effect is needed for CFD simulations of jet fires. For small- and medium-scale jet fires, the large eddy simulation (LES) approach can be used to model the turbulence effect [12], while for large scale jet fires Reynolds Averaged Navier Stokes (RANS) approach is the only choice to avoid extremely long computing time.

In jet fire simulations, the ignition is normally treated by defining an ignition patch with high temperatures. Although any turbulent combustion models for non-premixed flames can be used for modelling of jet fires, the eddy dissipation concept (EDC) for combustion [13] is widely used due to its simplicity and accuracy. Thermal radiation can be modelled according to a finite volume method by solving discrete transport equations [14]. In hydrogen -air flames, the only significant source of radiative emission is excited-state $H2O^*$ molecules. The absorption coefficient for water vapour can be modelled according to Leckner [15]. Small-scale hydrogen jet fires can be assumed to be optically thin. While large-scale ones cannot be regarded as optically thin, these fires behave like self-absorbing medium, i.e., radiation absorption occurs within the fire [12]. While modelling transient jet fires resulting from a blowdown process, to avoid the requirement of the change of grid at the inflow boundary due to the time-varying notional nozzle diameter, the release of hydrogen can be implemented as a volumetric source [14]. The volumetric source is treated as source terms for mass, momentum, energy, turbulent kinetic energy and turbulent dissipation rate depending on the dynamics of properties at the notional nozzle.

In semi-confined or confined environments, jet fires would result in thermal loads and pressure impacts on walls, ceiling or equipment and devices. In general, QRA typically includes consideration only for the thermal loads [16].

6.4. Explosion

One of the hazards from the delayed ignition of hydrogen is the pressure generated during combustion, commonly termed explosion. Overpressure can be generated from the combustion of a mixture confined in an enclosure or in an unconfined space. Most hydrogen explosions fall into the deflagration mode, in which the combustion wave propagates at a velocity lower than the speed of sound (sub-sonic) into the fresh, unburned mixture. In extreme cases, especially in the presence of confinement and obstacles, the enhanced flame acceleration can lead to deflagration to detonation transition (DDT), depending on mixture size, equivalence ratio and the degree of confinement. The resulting blast waves create significant overpressure and impulse posing significant hazards.

Considerable efforts have been devoted to CFD modelling of hydrogen explosions at realistic scales with success in capturing the global behaviour and evolutions of the overpressure. For modelling slow deflagrations, the compressible equations with low Mach number approximation can be solved to reduce computing time, the fully compressible reactive Navier-Stokes equations may describe fast deflagrations while detonation is usually modelled using the compressible Euler equations. Ignition can be initiated by a spark [19] or hot patch set to relatively high temperature. Combustion is often modelled with the EDC [13] or flame wrinkling model [20] in which the transport of the progress variable is governed by a laminar burning velocity and a flame surface wrinkling factor. When the flame wrinkling model is used with OpenFOAM code, there is an ad-hoc spark ignition model for regress variable which can be used to trigger ignition [19]. These relatively simple combustion models can be coupled with some ad-hoc refinement to incorporate the variation of laminar flame speed with mixture composition and non-unity Lewis number effects. Such combination is sufficient to capture the global features of turbulent deflagrations in hydrogen explosions [20] for QRA, but their ability to resolve fine flame features is limited due to the lack of essential physics to address the underlying fine chemical and physical processes, and fine grid resolution. To simulate the consequences of an accidental hydrogen release, a viable approach is to simulate the dispersion and mixing of hydrogen first and use that as initial cloud conditions to conduct CFD simulations of explosions [20].

For large-scale explosions, it is not possible to define sufficient grid resolutions to capture the underlying physics. Therefore, the potential improvement of predictions by more advanced models is limited. For the case of explosion modelling in congested region where geometries cannot be fully resolved by grids, the porosity distributed resistance (PDR) approach [21] should be used to model the effect of small-scale obstacles, e.g., pipes and vessels on flame propagation and on explosion overpressure. The PDR approach uses a porosity modified standard k-ε turbulence model, and the transport equations for the flame wrinkling parameter are solved. The location and strength of ignition sources also significantly affect the consequences of an explosion, which should be carefully chosen. It is recommended that the ignition point is placed in the central region of the flammable cloud where the stoichiometric condition is met of higher (up to the upper flammability limit), and the ignition energy is sufficient to start flame propagation.

6.5. HyMEP as a rationale for minimum reporting requirements

The need for transparent, traceable and fit-for-purpose CFD studies in hydrogen safety is aligned with the outcomes of the EU funded SUSANA project, which developed the Hydrogen Model Evaluation Protocol (HyMEP) [22] as a structured framework for assessing both the capability of CFD users to apply modelling strategies correctly and the accuracy/credibility of the CFD models themselves. HyMEP formalizes the evaluation of CFD analyses through staged activities that include: scientific assessment (qualitative appraisal of the physical model and numerical schemes against the state of the art, including limits of applicability); verification (ensuring equations are correctly implemented and solved); validation (comparison with experimental data across the intended range of applicability); sensitivity studies (to identify dominant variables and the influence of modelling/numerical choices such as mesh, time step, numerical scheme, boundary conditions and domain size in open and semi-confined configurations); and statistical analysis using Statistical Performance Measures (SPM) to quantify error and bias and to support quantitative acceptance criteria. The protocol culminates in an assessment report documenting evidence from each stage, thereby enabling regulators/certifying bodies and project stakeholders to judge whether a CFD study supporting a safety case is scientifically robust.

HyMEP is further supported by dedicated verification and validation databases and by project documentation intended to harmonize good practice and reporting. The validation database assembled within SUSANA includes a broad set of experiments (on the order of several tens), grouped by key hydrogen safety phenomena—release and dispersion, ignition, fires, deflagrations, detonations, and deflagration-to-detonation transition (DDT)—and is complemented by benchmarking exercises where multiple partners simulate selected scenarios following best-practice guidance and validation procedures. In this context, the minimum reporting checklist introduced above directly reflects the type of information required to apply a HyMEP-like evaluation approach, and it supports reproducibility, comparison across tools, and consistent decision-making in hydrogen safety engineering.

6.6. Summary

This Chapter provides some guidance for simulating each of the following scenarios:

- Release
- Ignition
- Jet fire
- Explosion
- Miscellaneous

It also briefly introduces HyMEP as a structured framework for assessing both the capability of CFD users to apply modelling strategies correctly and the accuracy/credibility of the CFD models themselves.

Readers should also consult Appendix 5, which provides a list of most available CFD codes which have been developed/applied to each scenario described here as well as some references where contact details and additional information can be found.

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7. GUIDANCE ON USING PREVENTION AND MITIGATION BARRIERS

This chapter provides an overview of guidance for prevention and mitigation against LOC and overpressure. The procedural barriers, for example regular audits and maintenance, are additional barriers which could be put in place to make sure hydrogen leaks are minimized. e hydrogen risk.

7.1. Summary of prevention and mitigation strategies

A prevention measure or barrier is defined as a safeguard that stops the causes or reduces its frequency 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 of loss of containment, e.g., release, spill, cryogenic exposure, fire, and vapour cloud explosion, etc.

It should be noted that the scope of this chapter covers unintentional releases resulting in leakage. Furthermore, any measures used to minimize and control potential ignition sources (e.g., HAC, ATEX equipment, bonding, grounding and lightning protection) are covered in Appendix 6.

7.1.1. Gaseous and Liquid Release

Table 2 suggests prevention and mitigation measures which can be used for the release of liquid and/or gaseous hydrogen.

Table 2: Prevention and mitigation measures – liquid and gaseous release.

Prevention and Mitigation Strategies	**Purpose**	**Description**	**References**
Cryogenic spill protection (CSP)	To prevent structural damage.	CSP is used when there is a risk of cryogenic exposure to the structures leading to damage in case of cryogenic fluid leakage. It is well known to be used in the LNG shipping industry.	[1]
Bunds or impounding basin or spill containment system	To contain the spilled liquid.	Bunds or impounding basins can be used to collect leaked liquid hydrogen. 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. **Note:** there is no strong consensus about usage of bunds for LH_2 applications. It is advised to the project to do a proper risk assessment before using it for their own application.	*[2] and [3]*

Gravels	To make sure that LH2 is evaporated quickly resulting in quick dispersion	Alternate mitigation measures which can be used for liquid hydrogen release are 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. **Note:** there is no strong consensus about usage of gravel for LH_2 applications. It is advised to the project to do a proper risk assessment before using it for their own application.	[4]
Automatic shut-off valve	To stop the leakage of hydrogen	A valve to shut off the flow of hydrogen. An automatic shut-off valve shuts down the flow when it is de-energized.	*[5] and [6]*
Excess Flow Valves	To restrict/limit the flow of hydrogen	An excess flow valve is a mechanical safety device designed to automatically restrict or shut off the flow of liquids or gases when a downstream pipe, hose, or system ruptures.	
Restriction Orifice	To restrict/limit the flow of hydrogen	In the event of a flexible hose rupture, a restriction orifice, often paired with automatic shut-off valves or excess flow valves, prevents catastrophic and rapid release. It can be installed at the trailer side or in the flexible hose.	

It is recommended that wherever possible hydrogen connections are welded instead of flange or threaded connection. Furthermore, redundant components, for example, the use of two safety valves or of a safety valve and a bursting disk and check valves to prevent the backflow. It is recommended that refuel trailers have anti-tow-away devices and physical protection such as bollards to prevent damage to the system. Furthermore, break-away devices are provided in the hoses to reduce anti-whip protection to hoses.

7.1.2. Formation of a flammable hydrogen-air mixture

Following liquid/gaseous hydrogen release, leaked hydrogen can disperse with air, resulting in formation of a flammable hydrogen-air mixture. The delayed ignition of such a mixture could lead to the possibility of vapour cloud explosion regardless of whether the hydrogen is released in a confined, semi-confined, or non-confined environment.

In case of release of hydrogen in a confined environment, e.g., hydrogen release inside a fuel cell compartment, underground car park, car and 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 3. These measures could also be considered with caution for releases in semi-confined, but highly congested geometries.

Table 3. Prevention and mitigation measures to limit flammable cloud for indoor release.

Prevention and Mitigation Strategies	Purpose	Description	References
Forced and natural ventilation	Reducing the flammability by enhancing the dispersion	Forced ventilation increases the airflow in areas where there is a possibility of hydrogen leaks/release and substantial accumulation.	[7-10]
Inerting	Reducing the flammability of the mixture by inerting it.	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.	[11-16]
Igniters	Reducing the overall concentration by controlled burning of the mixture locally.	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.	[17-22]
Partial Autocatalytic Recombination Systems (PARs)	Controlled reaction of hydrogen-air mixture resulting in reduction of overall concentration	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 nuclear Containment.	[23-27]
Catalytic Recombination	Controlled reaction of hydrogen-air mixture	Catalytic recombination is used in Automotive industries.	[28-29]
Reducing the confinement		Modification of geometry such that it reduces confinement is reduced in order to prevent stagnant zones of the hydrogen-air mixture. It will also aid in increasing the mixing of the hydrogen-air mixture due to buoyancy.	Not applicable
Hydrogen mixing dampers	Reduction in flammability of the mixture	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	[32]

		avoided preventing fast combustion, which could be critical to the integrity of the containment.	

HAC, ATEX equipment, bounding and grounding, lightning protection etc.

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 3 are less likely to be effective. The following strategies, summarized in Table 4, should be considered.

Table 4. Prevention and mitigation measures to limit flammable clouds in an open environment.

Prevention and Mitigation Strategies	Purpose	Description	References
Vapour barrier	Control dispersion of the gases	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 can reduce the spread of LNG, thus reducing the overall size of the flammable cloud footprint.	[33-35]
Water sprinklers	Reduce the flammability	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. **Note:** there is no strong consensus about usage of water sprinklers / mists for LH_2 applications. IT is advised to the project to do a proper risk assessment before using it for their own application	[36-38]

7.1.3. Jet and Pool Fire

In case of immediate ignition of hydrogen, there is a possibility of formation of a jet or pool fire. The direct fire impingement or engulfment and the thermal heat flux can have an impact on people and surrounding structures. For example, leaks 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 Cloud Explosion* (BLEVE) of the liquid hydrogen storage tank. Potential prevention and mitigation measures are summarised in Table 5.

Table 5. Prevention and mitigation measures related to hydrogen fires.

Prevention and Mitigation Strategies	Purpose	Description	References
Firewall and Fire blankets and barriers	Fire Shielding	A firewall is a passive structure often used in gaseous hydrogen refuelling stations to prevent personnel/objects from fire hazards and thermal radiation. The use of firewall/fire barriers and blankets 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 and facility is recommended.	[39-42]
Water mist (active fire protection systems)	Flame quenching	Water mist is used in partial suppression of the fire against 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.	[42-49]
Sprinkler system (active fire protection systems[3])	Flame quenching	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 gaseous hydrogen storage tanks. Sprinkler systems are used in buildings containing gaseous hydrogen storage tanks. Sprinkler systems or water spray can also be used externally on the surfaces of hydrogen tanks to cool tanks. They shall nether be used on the LH2 pressure relief devices.	[50-51]
Passive Fire coatings (passive fire protection systems[4])	Stop the spreading of fire	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.	[52-53]

[3] 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.

[4] 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.

Design of structure against heat load	Heat containment	The exposed structure is designed to make sure that it withstands the impact of fire.	[54]
Inert gas injection	Cooling the flame	Inert gas systems or fine water mist are injected into the fire to dilute oxygen and reduce heat generation.	[55-56]

7.1.4. Overpressure and Vapour Cloud 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 6.

Table 6. Prevention and mitigation measures used for hydrogen explosions.

Prevention and Mitigation Strategies	**Purpose**	**Description**	**References**
Pressure relief vents or pressure relief devices e.eg., Rupture disks	Overpressure Relieve	Pressure relief allows overpressure to be vented. Typically used in liquid/gaseous hydrogen storage tanks to vent overpressure.	[57-58]
Thermal Pressure Relief	Overpressure Relieve	They are designed to prevent damage from excessive pressure in case of thermal expansion. Typically used in gaseous hydrogen storage cylinders of type IV etc.	[59]
Vents	Overpressure Relieve	Explosion vent is a safety device used to protect against excessive internal overpressure generated in case of internal explosion. These contain membranes 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.	[60-62]

Water mist and deluge	Flame quenching	Water deluge or water mist generated ahead of flames cools the flame thereby generating lower flame speeds and lower overpressure. They are typically used explosion mitigation in offshore platforms. Note: Droplets generation ahead of the flames can increase the turbulence in the unburnt gases resulting in turbulent flame acceleration. It is recommended that this aspect is taken into account when using this mitigation.	[63-69]
Proper design of the occupied buildings against pressure loads	Explosion Containment	Designing the building to account for pressure loads (overpressure and impulse) generated in case of a credible explosion scenario.	[70-71]
Chemical inhibition	Flame quenching	Chemical inhibition systems contain chemicals (NaHCO3 , HBr and NaCl etc) when injected quickly suppresses the combustion and stopping the flame propagation.	[72-75]
Separation distances	Separate the hazard.	Separation distance is used to avoid incidents to escalate to other parts of plant or to protect neighbours.	[76-77]
Flame arrestors or flame flash back arrestors or detonation arrestors	Flame quenching	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. **Note:** There is no strong consensus about usage of flame arrestors or flame flash back arrestors or detonation arrestors for H_2 applications. It is advised to the project to do a proper risk assessment before using it for their own application	[78-79]

Soft barriers		Soft barriers could be used to limit combustion near ceiling (in flame accelerating beams) or other places with significant congestion. The use of large balloons to prevent flammable mixtures in certain regions but still gives volume for gas expansion during explosion.	[80]
Modification of geometry		Layout/geometry optimization (e.g., limiting the obstacles and the confinement) to limit turbulence generation and thereby reducing the maximum flame speed and maximum overpressure produced in case of ignition of hydrogen-air mixtures.	Not applicable
Blast dampers	Blast shielding	Blast dampers are designed to provide protection to persons and equipment during blast events, mitigating the passage of blast pressure along a ventilation system.	[81-82]
Blast walls	Blast shielding	A blast wall is simply a barrier used to protect the vulnerable structure and its occupants from explosion overpressure, fire and debris.	[83-85]
Blast Resistant Building	Blast containment	Blast resistant buildings are modular buildings that are designed to withstand significant explosions overpressure. Therefore, they are suitable to keep personnel occupying them safe, and/or protect valuable or safety critical equipment.	[86-88]

It is not recommended that mitigation measures or barriers mentioned above be used blindly. It must be considered part of the design by a competent person/team after discussion. Since it is always possible that mitigation measures used for certain consequences might have opposite effects, i.e., enhance the consequences instead of limiting it. For example, the firewalls (see Section 7) present in the hydrogen refueling 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 two or three, 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 a liquid hydrogen pool can result in substantial evaporation of liquid hydrogen generating large quantities of flammable hydrogen-air mixture. Delayed ignition of hydrogen-air mixture can result in explosions. Therefore, instead of mitigating the 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 CFD-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 the design of the mitigations.

7.2. 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.

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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.

Appendices

Appendix 1 References for Risk Assessment Methods

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.

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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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Failure mode and effects analysis

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Hazard Identification (HAZID)

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Hazard and operability Analysis (HAZOP)

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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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Appendix 2 References for Risk Assessment Tools

HYRAM

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HYRAM

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Appendix 3 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. [1,2] and UK HSE [3]. There are numerous references (e.g., Baker et al. [1], Merx [4] and CCPS [5]) 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.

1. W.E. Baker, P.A. Cox, P.S. Westine, J.J. Kulesz, R.A. Strehlow, Explosion hazards and evaluation, 0444 42094 0, Elsevier, New York (1983)
2. W.E. Baker, J.J. Kulesz, R.E. Ricker, R.L. Bessey, P.S. Westine, V.B. Parr, et al. Workbook for predicting pressure wave and fragment effects of exploding propellant tanks and gas storage vessels (1975), Technical Report NASA-CR-134906

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5. CCPS Guidelines for evaluating the characteristics of vapour clouds explosions, flash fires and BLEVEs 0-8169-0474-X, Center for Chemical Process Safety (1994).

Appendix 4 Heat Flux Effects on Structure and People

The heat flux can have an impact on people and storage tanks. For example, PGS-35 [1] recommends that 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 [2] provides guidance on vulnerability of fire and plant/structure. Table 2.1 [2] gives typical times 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 from [3].

NFPA 25 [3] summarized 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 to 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.

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2. Risk assessment data directory – Vulnerability of plant/structure, IOGP Report 434-15 https://www.iogp.org/bookstore/product/risk-assessment-data-directory-vulnerability-of-plantstructure/
3. NFPA 2, Hydrogen Technologies Code, National Fire Protection Association (2020).

Appendix 5 List of CFD models and tools for hydrogen safety applications

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.

This Appendix provides a list of most available CFD codes which have been developed/applied to each scenario described in Chapter 6 and some references where contact details and additional information can be found. In addition to list the organizations which developed the original codes, the organizations which have modified or adapted the codes to establish models for different LOC scenarios are listed with references reporting on the simulations/validation. The lists were compiled from the information submitted by the relevant stakeholders, which mainly consists of those organizations whose codes/models are listed and provided references for their application or validation studies. The inclusion of the models and references, by no means, represents view of the EHSP on the quality of any specific model or its validation. Some CFD tools will appear more than once under the same name for different scenarios or applied by different authors to simulate these scenarios.

Readers who are interested in any specific code/model should follow the contact information in the references provided to contact the relevant organization. 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.

A5.1 Release

This section covers models for both gaseous and liquid hydrogen releases. The relevant LOC scenarios include pressurized 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.

CFD models for hydrogen release

Name of the code/original developer	Key publications
ADREA-HF	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 Commercial code *www.ansys.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.
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Appendix 6 Hazardous area classification (HAC)

Hazardous area classification is a technique for evaluating the probability of formation of a flammable atmosphere and its likely duration. It is widely used in the chemical industry to decide whether electrical and other equipment needs special protective features to prevent it from causing a fire or explosion. It is a legal requirement in Europe (and the UK) for facilities to store, handle or process flammable or combustible material. This is a fundamental requirement of EU Directive ATEX 1999/92/EC which is covered by DSEAR in the UK.

The correct selection of mechanical and electrical equipment (both inside and outside process equipment and is closely related to release and dispersion phenomena for hazardous areas requires the following information:

- Classification of the hazardous area (as in zones);
- Temperature class or ignition temperature of the gas or vapour involved:

The Regulations define 3 zones that can exist within a hazardous area:

- Zone 0 - A place in which an explosive atmosphere is present continuously or for long periods.
- Zone 1 - A place in which an explosive atmosphere is likely to occur in normal operation occasionally.
- Zone 2 - A place in which an explosive atmosphere is not likely to occur in normal operation, but if it does occur, will persist for a short period only.

Ventilation plays an important role in preventing flammable atmospheres and therefore the classification process. Typically, recommended protection types for equipment are Intrinsically safe used in Zone 0, flameproof, increased safety and intrinsically safe are used in Zone 1, while non-sparking, pressurized, and simplified protection are used in Zone 2.

The hole size represents the effective leak area through which flammable gases or vapors may leak and disperse within the vicinity of the equipment. It is a critical parameter used for calculating the volume of flammable gas clouds and the distance to the lower flammable limit (LFL), which is used to define the boundaries of hazardous zones. The selection of hole size affects the predicted size of Zone 1 or Zone 2 areas and the required safety measures. **IEC 60079-10-1:2020**: Provides reference hole sizes in Table B.1 for hazardous area classification, which are used in conjunction with ventilation and release modeling to determine zone extents. Note that leak sizes specified for the consequence modelling is different from leak sizes.