MultHyFuel

Deliverables D3.7 and D3.8

Developing Good Practice Guidelines in Project MultHyFuel

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Some of the research in the MultHyFuel project was undertaken by the Health and Safety Executive (HSE) collaboratively and under contract to MultHyFuel consortium, EU Commission, Clean Hydrogen Partnership (FCH JU) and Hydrogen Europe. This document's contents, including any opinions and/or conclusions expressed, or recommendations made, do not supersede current HSE policy or guidance.

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Acronyms

ALARP	As Low As Reasonably Practicable
ATEX	*Atmosphères Explosibles ATEX Workplace Directive 1999/92/EC, ATEX Equipment Directive 2014/34/EU*
CFE	Central Feared Event
CNG	Compressed Natural Gas
COMAH	Control of Major Accident Hazards 2015
DDT	Deflagration to Detonation transition
DPh	Dangerous Phenomena
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations 2002 (GB only)
EFV	Excess flow valve
EI	Energy Institute
EPS	The Equipment & Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations 2016
ESD	Emergency Shutdown Device
EU	European Union
EIHP	European Integrated Hydrogen Project
FCH JU	Clean Hydrogen Partnership (p.k.a. Fuel Cells & Hydrogen Joint Undertaking)
GPG	Good Practice Guidelines
H_2	Hydrogen
HAZID	HAZard Identification
HP	High pressure
HRS	Hydrogen Refuelling Station
HX	Heat exchanger
LEL	Lower Explosibility Limit
LFL	Lower Flammability Limit
LH_2	Liquid Hydrogen
LP	Low pressure
LPG	Liquid Petroleum Gas
LUP	Land use Planning
MAHB	Major Accident Hazards Bureau
MHYF	MultHyFuel
MP	Medium pressure
PED	Pressure Equipment Directive PED 2014/68/EU
PFD	Process Flow Diagram
P&ID	Piping & Instrumentation Diagram
./PSHH	Pressure sensor High-High
SEI	Thresholds of irreversible effects (in French "*Seuil des effets irréversibles*")
SEL	Lethal effects thresholds (in French "*Seuil des effets léthaux*" SEL)
SELS	Thresholds of significant lethal effects (in French "*Seuil des effets léthaux*")
SIF	Safety Integrity Function
SMS	Safety Management System
TPRD	Thermal Pressure Relief Device
TSHH	Temperature sensor High-Hhigh
UVCE	Unconfined Vapour Cloud Explosion
VCE	Vapour Cloud Explosion
RCS	Regulations, Codes and Standards
WP	Workpackage

1 About MultHyFuel

1.1 Project background

Clean hydrogen and fuel cell electric vehicles have developed significantly in recent years in order to rise up to the challenges associated with the transition to a Net-Zero carbon economy.

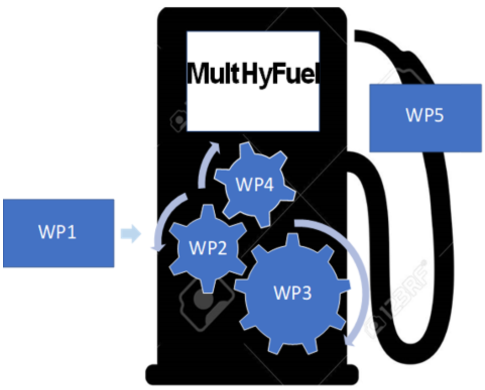
Associated infrastructure, in particular, hydrogen refuelling stations (HRS) have also been developing to respond to the increasing needs for hydrogen in the mobility sector. To facilitate the adoption of hydrogen as a mainstream energy source in the mobility sector requires higher levels of accessibility of HRS in the public environment.

In response to these challenges, the MultHyFuel project has studied how HRS could be relevantly and safely integrated in close proximity, alongside other conventional and alternative fuels for the advancement of hydrogen mobility.

The overall objective of the MultHyFuel project is to support the development of a common strategy for implementing HRS in a multifuel context, i.e. in a station delivering several "fuels". This strategy was based on a convergent and mutually reinforcing approach tailored to the specific objectives of the project. Key experimental data on hydrogen leaks was generated and shared with relevant stakeholders, including for model validation. Risk assessment techniques were tested on several case studies to study the impact of risk management measures/ safety barriers.

1.2 Project goals

The goal of MultHyFuel (MultHyFuel Project, 2021), indicated in Figure 1, is to contribute to the effective deployment of hydrogen as an alternative fuel by developing a common strategy for implementing HRS in multifuel contexts, contributing to the harmonisation of existing laws and standards, based on practical, theoretical and experimental data as well as on the active and continuous engagement of key stakeholders.



Goal: to contribute to the effective deployment of hydrogen by:

- **Helping develop a common regulatory framework for implementing HRS in multifunctional contexts, contributing to the harmonisation of existing laws and standards**
  - **Based on practical, theoretical and experimental data**
  - **As well as on the active and continuous engagement of key stakeholders.**

Figure 1 - Goals of MultHyFuel

1.3 Project workpackages

The strategy of MultHyFuel is to actively engage a community of stakeholders in the overall process, from gap identification to review and validation of the solutions proposed, to facilitate evidence-based policy-making, as well as standards' development/ update/ implementation, with the final aim of facilitating hydrogen fuel cell vehicle deployment and market uptake. Broadly speaking, the approach taken was to:

- Investigate HRS permitting requirements, zoning, potential major hazard scenarios, leak sizes and public guidance on risk assessment methodologies;

- Generate the knowledge base underpinning safety rules on hydrogen dispensing by providing experimental data from engineering research on hydrogen leaks and the impact of mitigation measures; and

- Generate preliminary good practice guidelines for implementation of evidence-based policies including zoning thresholds and safety requirements (i.e. separation distances, forecourt and dispenser design, safety barriers) based on the results of the experimental programme.

The key elements characterising the main workstreams are as follows:

WP1: A 'state-of-the-art-review' phase, conducted with the support of the Network of National Experts, to generate a preliminary diagnosis of the existing rules, standards and best practices in the domain.

WP2: Practical research and experimental laboratory work to address gaps in current understanding.

WP3: Development of preliminary good practice guidelines based on project results in terms of data and evidence derived from practical experimentation and subsequent analysis, and to transform the analysis and experimentation results into actionable information.

WP4: Engagement of key target stakeholders (namely policy makers, public authorities, standardisation bodies, *etc*.). This phase will guarantee the actual involvement of target stakeholders from the very initial analysis phases, up to the validation of the final results; this phase will be of primary importance to create actual commitment and shared consensus around the project results, and consequently guarantee their sustainability in the long run.

WP5: A specific workstream is dedicated to the dissemination and exploitation of project results.

1.3.1 Workpackage leaders and project strategy

Hydrogen Europe is the overall coordinator of the project (WP6), joining an international consortium which includes: INERIS (FR), ENGIE (FR), ITM Power (UK), HSE (GB), Shell (NL), SNAM (IT), KIWA (NL) and ZSW (DE).

Figure 2 shows a simplified organisational chart of the MultHyFuel project together with the relevant Workpackage Leaders and Figure 3 shows the project strategy and the interplay of the workpackages.

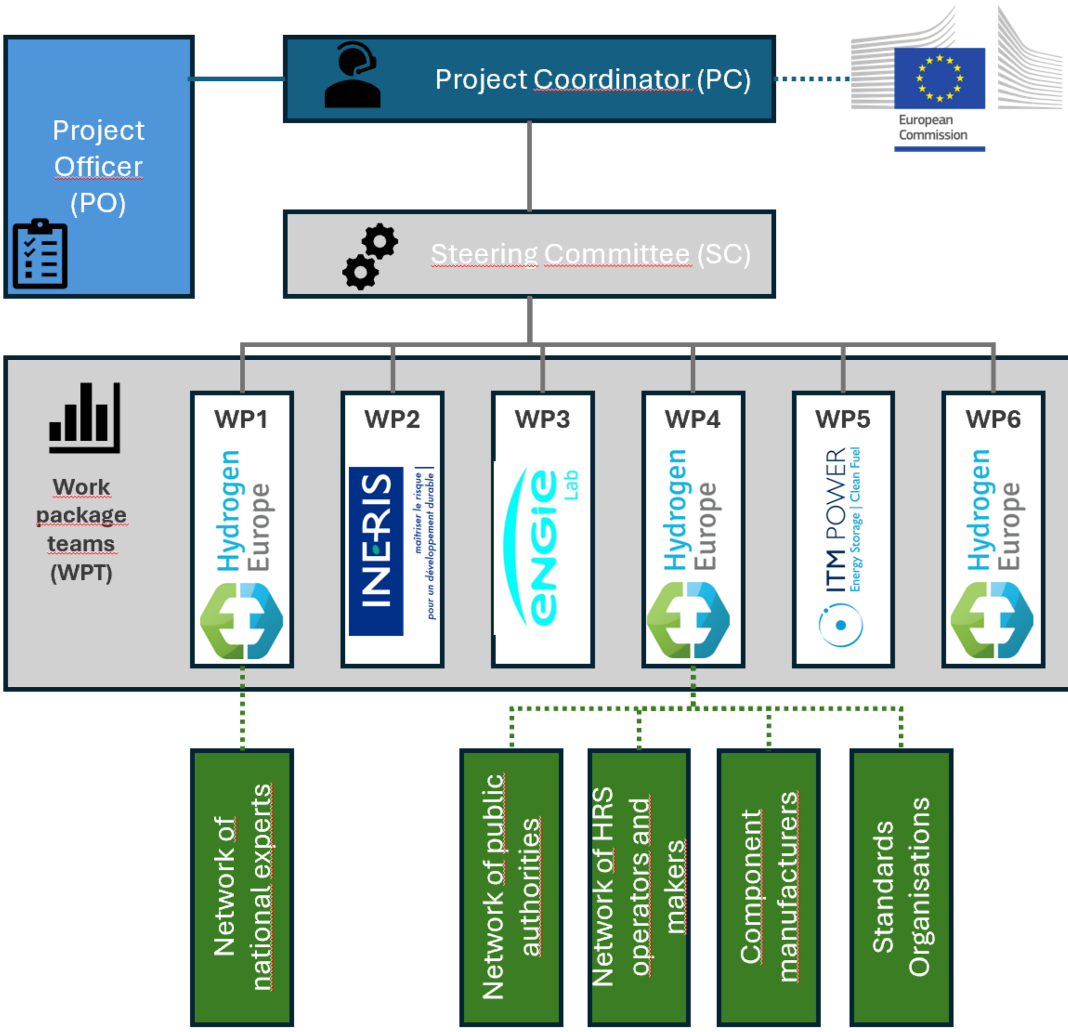


Figure 2 - Workpackage Leaders

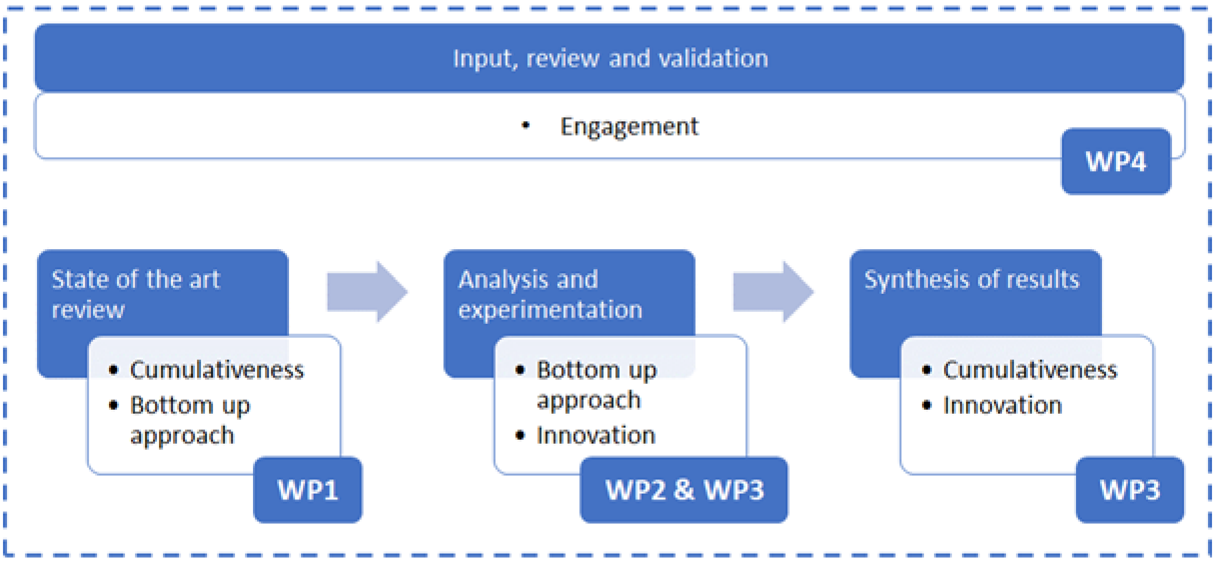


Figure 3 - MultHyFuel Strategy

1.4 Task 3.7

Task 3.7 of the MultHyFuel project involves the production of the preliminary good practice guidelines, based on the results of Task 3.6 and the safety barriers identified in Tasks 3.3 and 3.5. The preliminary good practice guidelines are based on research of a finite / limited scope (as described in Section 2), and they should be developed further in the future, however this document will be useful to:

- Provide examples of an approach to risk assessments and impact on any permitting requirements for multifuel hydrogen refuelling stations;
- Provide examples of safe designs for hydrogen refuelling stations in a multifuel context (safety barriers/ risk measures);
- Determine layout recommendations between the dispenser and the other components of the refuelling station on the forecourt;
- Understand how hazardous area zones around H_2 dispensers can be defined to allow adequate consideration of risk reduction measures;
- Provide references to new knowledge that has been generated by the project in the context of how it can be used for risk management and safe design and operation of multifuel refuelling stations; and
- Provide evidence-based technical recommendations for the development of future standards as well as further research.

1.5 Report structure

This document, which is made up of deliverables D3.7 and D3.8, summarises the work within MultHyFuel project to help provide the evidence base to formulate the further research work necessary to inform the development or updates to European regulations, codes and standards for the safe implementation of hydrogen refuelling stations in multifuel configurations.

Section 1 of this document provides some background information on the MultHyFuel project.

Section 2 lays out the Terms of Reference of the document and the caveats behind it.

Section 3 makes reference to the existing permitting requirements for hydrogen refuelling stations within Europe.

Section 4 summarises the risk assessment methodology adopted by the consortium that enabled the project to develop a view on the risk picture and some of the factors that feed into this. This includes the findings of the project experimental programmes as well as the potential consequence modelling approaches and techniques, and where there may be gaps in knowledge. This section aims to provide the reader with an idea of a possible approach to risk assessment, and separation distances that have been estimated using consequence models and verified via experimental results.

Section 5 looks at some example technical recommendations of risk management measures that could be adopted in multifuel HRS, in terms of the dispenser, forecourt layout and operation/ maintenance.

The document ends with Section 6 which gives some recommendations including some suggestions for further research to inform the potential development and/or update of Codes and Standards.

2 Good Practice Guidelines scope and Terms of Reference

2.1 Scope of Good Practice Guidelines Document

The preliminary good practice guidelines in this document have been borne out of the MultHyFuel project and developed based on research of a finite / limited scope within the available resource, funding and project duration, hence there are many elements which have not been considered; or indeed some which will need to be developed further in any future research work. This document will therefore need to be used with care, bearing in mind the boundaries, context and limitations of the research.

Some of the research in the MultHyFuel project were undertaken by the Health and Safety Executive (HSE) and the French National Institute for Industrial Environment and Risks (INERIS) collaboratively as project partners; and under contract to MultHyFuel consortium, EU Commission, Clean Hydrogen Partnership (FCH JU) and Hydrogen Europe. The contents of this document, including any opinions and/or conclusions expressed, or recommendations made, do not supersede current HSE or INERIS policy or guidance.

2.2 Caveats

- Where reference is made to EU Directives, this should be read as the relevant national legislation which transposes the directive.
- The research and therefore the good practice guidelines in this document do not take into account Regulatory Consents and Land-use Planning (LUP) implications, i.e. location and siting considerations of HRSs, and how potential major hazard scenarios from the bulk storage of hydrogen might impact surrounding human populations in residential or industrial and commercial areas. These will need to be considered as part of the assessment, subject to the regulatory control in the country within which the Operator's HRS is located;
- The focus of the project's detailed research phase has been on the study of the risks from the hydrogen dispenser, but not the bulk storage, H_2 onsite production and processing. Bulk storage, H_2 onsite production and processing were considered during the preliminary risk assessment phase (Task 3.3) but are not detailed in the current deliverable; however will need to be considered in the siting and design of HRSs: this includes risks from H_2 trailer(s) parked for unloading at the refuelling station, and pipeline transit. Associated risks will also need to be considered and managed, subject to the country's regulatory and permissioning control. For example, HRS are likely to be in scope of the Seveso Directive, so conformance to its requirements would be required in Europe; unless inventory is managed to be below the lower tier thresholds at all times;
- The experimental programme did not study liquid hydrogen (LH_2) releases;
- The results of the research reported in this document may only be specific to the assumptions made in the risk assessment, consequence modelling and conditions of the experiments conducted, e.g.
    - release of H_2 was not sustained at constant flowrate, there was a decay with time, as a buffer tank was not used. Consequence models typically assume constant release rates.
    - Weather conditions may have a significant influence on the dispersion results.
- The technical recommendations based on the results of this project could be applicable to similar HRS configurations and dedicated equipment as those studied within the project; and the assumptions behind these. The application to a larger scope will require dedicated risk assessments and additional validation;

- The experimental programme, consequence modelling and risk assessment generally did not wholly include hydrogen bulk storage, canopy configuration and design;
- Whilst likelihood and severity determine the level of risk, techniques to determine severity (i.e. methods to estimate populations exposed to the harm) is not part of this work; instead the focus is on the consequence assessment techniques that form part of the risk assessment process; and
- Research has been conducted at a high level and the findings and hence preliminary recommendations made in this document are at a snapshot in time. However, some of the research findings have helped identify knowledge gaps, which themselves would need addressing to properly inform Regulations, Codes and Standards (RCS); therefore it is expected that further research work would be required.

3 Permitting requirements in Europe

MultHyFuel Deliverable 1.4 (MultHyFuel D1.4, 2024) provides an assessment of the current EU legislation and Directives that would be expected to apply to HRS deployed in countries in the European Union, both from a general perspective, and also HRS specific legislation. There exists also specific GB regulations on HRS.

These include requirements for:

- protection from explosions (i.e. *ATmosphères EXplosibles* ATEX Workplace Directive 1999/92/EC), ATEX Equipment Directive 2014/34/EU) and pressure hazards (Pressure Equipment Directive PED 2014/68/EU);
- the operation of machinery (EUR-Lex Directive 2006/42/EC, 2006);
- interoperability requirements where the refuelling station dispenser and vehicle being fuelled are connected for the refuelling process; and
- other more specific considerations for operation of hydrogen refuelling stations.

Additional standards, and other industry documents, providing guidance that is applicable to hydrogen refuelling stations are also identified. Note that further information on some of these standards is provided as Section 5.2 of this document.

It also identifies national legislation or standards / codes of practice applicable to HRS for 14 countries across Europe. Some European countries have legislation specific to hydrogen refuelling stations. Others do not have HRS specific legislation, but refuelling stations are able to be deployed based on a mixture of adherence with general legislation, and HRS specific standards and codes of practice.

MultHyFuel Deliverable 3.6 provides a more in-depth description of how approaches typically used (for instance, those documented in current standards) for HRS support compliance with the legislation, and other guidance, that is applicable.

This deliverable, D3.7/ D3.8, includes suggestions and technical recommendations for further research and considerations that may benefit the development or update of codes, standards and other guidance, and if applicable, legislation, in the future.

4 Risk assessment methodology

4.1 Risk assessment and management process

Risk assessment is the process of estimating the likelihood of occurrence of specific undesirable events and the severity of harm caused, together with a value judgement concerning the significance of the results. Risk assessment is a tool to aid decision making relating to risk management, i.e. the implementation of appropriate risk reduction measures.

Hazard and risk are two terms central to risk assessment. A hazard is any physical situation/ object that has the potential to cause harm to people, whilst risk is the likelihood of a specific undesired event occurring within a specified period. Risk is hence a function of both the likelihood and consequence and therefore severity of a specific hazard being realised. The more likely it is that a certain harm will happen and the more severe that harm is, the higher the risk.

Whilst likelihood and severity determine the level of risk, techniques to determine severity (i.e. methods to estimate populations exposed to the harm) is not part of this work; instead the focus is on the consequence assessment techniques that form part of the risk assessment process.

There are different techniques that can be used to identify the potential hazards at a multifuel refuelling station incorporating hydrogen. Hazard identification studies need to be comprehensive and should be undertaken by competent personnel, ideally comprising a team of specialists from different disciplines and using a systematic, defined methodology. Hazard identification is arguably the most important part of the risk assessment process.

For all the identified hazards, a suitable and sufficient risk assessment should be completed.

The risk assessment and its outcomes should be recorded in line with national regulatory requirements. The record should indicate the actions that are required to adequately control the risks, by means of risk reduction measures/ safeguards/ safety barriers.

There are sources that can provide relevant information on hazards and precautions when using hydrogen e.g., Safety Data Sheets, standards and codes, *etc*.

Where a generic/template risk assessment for the operations on HRSs is taken as a starting point, it would be recommended to review the information included in that document and evaluate if it reflects all safety aspects that could be relevant for the specific operation and circumstances. When any differences from the 'template' are noticed, additional safety precautions may be required (this would have to be determined and addressed before starting the specific activity). For example, during maintenance work, not all component replacement operations would be identical and, consequently, a single risk assessment would not be applicable to all of these operations.

The operator should review the risk assessment and risk management / controls put in place to make sure they are working, in case:

- The measures/ safeguards are no longer (as) effective; and
- there are changes in the refuelling station and its surroundings that could lead to new or heightened risks.

Also, a review should be considered if any problems are spotted or in the event of any accidents or near-misses.

4.1.1 Hazardous events and harm criteria

As illustrated by Figure 4, the risks associated with HRS are mainly related to the flammable properties of hydrogen and the high-pressure storage and dispensing equipment present at a refuelling station.

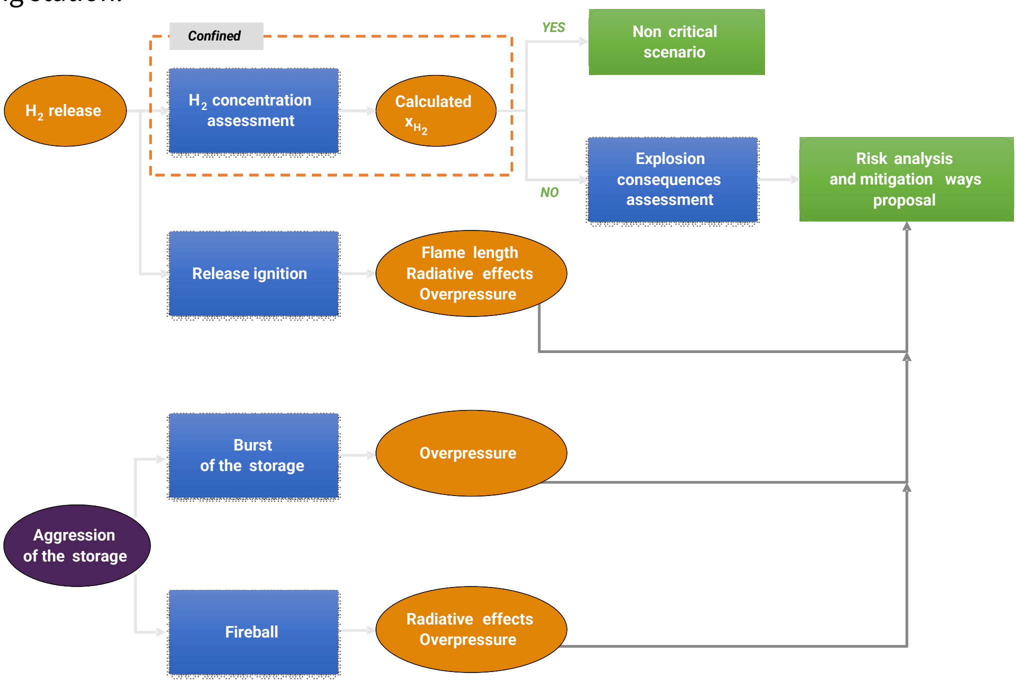


Figure 4 - Accidental events and associated consequences for hydrogen applications from MultHyFuel Deliverable D3.1 (MultHyFuel D3.1, 2021)

Should a leak from the H_2 equipment occur, hydrogen would be released and could generate:

- a jet fire, in case of immediate ignition, leading to radiative effects;
- a flash fire[1], in case of late ignition of a hydrogen cloud, leading to radiative effects;
- an unconfined vapour cloud explosion (UVCE), in case of late ignition of a hydrogen cloud, leading to overpressure effects; and
- a confined vapour cloud explosion (VCE), in case of late ignition in a closed space (e.g. container, dispenser) leading to overpressure effects. Detonation is probably unlikely, as typical dispensers will not have enough confinement due to their open bottom panel and ventilation holes, *etc*. and will probably not have large enough L/D (length/diameter) for run up to DDT; nor sufficiently large ignition sources to overdrive it to detonation. It is worth noting, however, that the overpressure generated would be a function of internal congestion within a dispenser, venting (or pressure relief through a weak structure), flammable gas concentration, strength of ignition source, time to ignition, *etc*.

Following the benchmarking exercise carried out within the project, the harm criteria chosen for use in the detailed risk assessment within the MultHyFuel project are as described in Table 1:

[1] The degree of congestion and/or confinement will influence whether a flashfire or VCE occurs

Table 1 - Harm criteria for H_2 scenario severity assessment in MultHyFuel

	Radiative heat fluxes	Overpressures	Whipping
Significant Lethal Effects (5%)	8 kW.m^{-2}	200 mbar	-
First Lethal Effects (1%)	5 kW.m^{-2} or 100% LFL	140 mbar	100% hose length
Irreversible Effects	3 kW.m^{-2} or 110% LFL	50 mbar	110% hose length
Indirect Effects (glass break)	-	20 mbar	-

LFL: Lower Flammability Limit

There is, however, information available from hydrogen applications/ other industries that could be used to identify harm criteria. In Great Britain, the regulations are not prescriptive; therefore, there is no 'mandatory' harm criteria to use in the risk assessment of major accident hazards. The Health and Safety Executive (HSE) document 'Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment' provides a summary of the hazards effects to offshore personnel in the event of an incident; this document is intended for use by UK offshore industry in the preparation and evaluation of their risk assessments. The EU's Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHy) project report D6.2 'Novel guidelines for safe design and operation of LH_2 systems and infrastructure' also provides information on harm criteria in Annex I (PRESLHy, 2021).

4.2 Hydrogen Refuelling Station configurations studied in MultHyFuel

4.2.1 Description of the configurations

After a benchmarking exercise on existing technology and equipment related to refuelling stations, as reported in Deliverable 3.1 (MultHyFuel D3.1, 2021), three configurations were established as case studies for the MultHyFuel project:

- **Configuration #1 Ready-to-deploy multifuel station**: Gaseous hydrogen for light and heavy-duty vehicles with high-pressure storage (trailers or bundles) located in a suburban/ urban location (see Figure 5 and Figure 6;

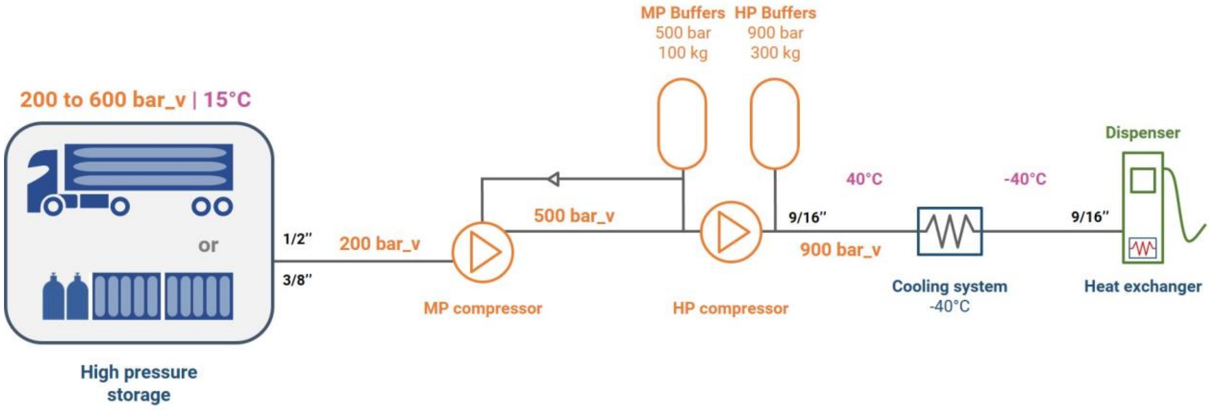


Figure 5 - Simplified PFD of "Ready-to-deploy"-station. v represents hydrogen in the gaseous phase

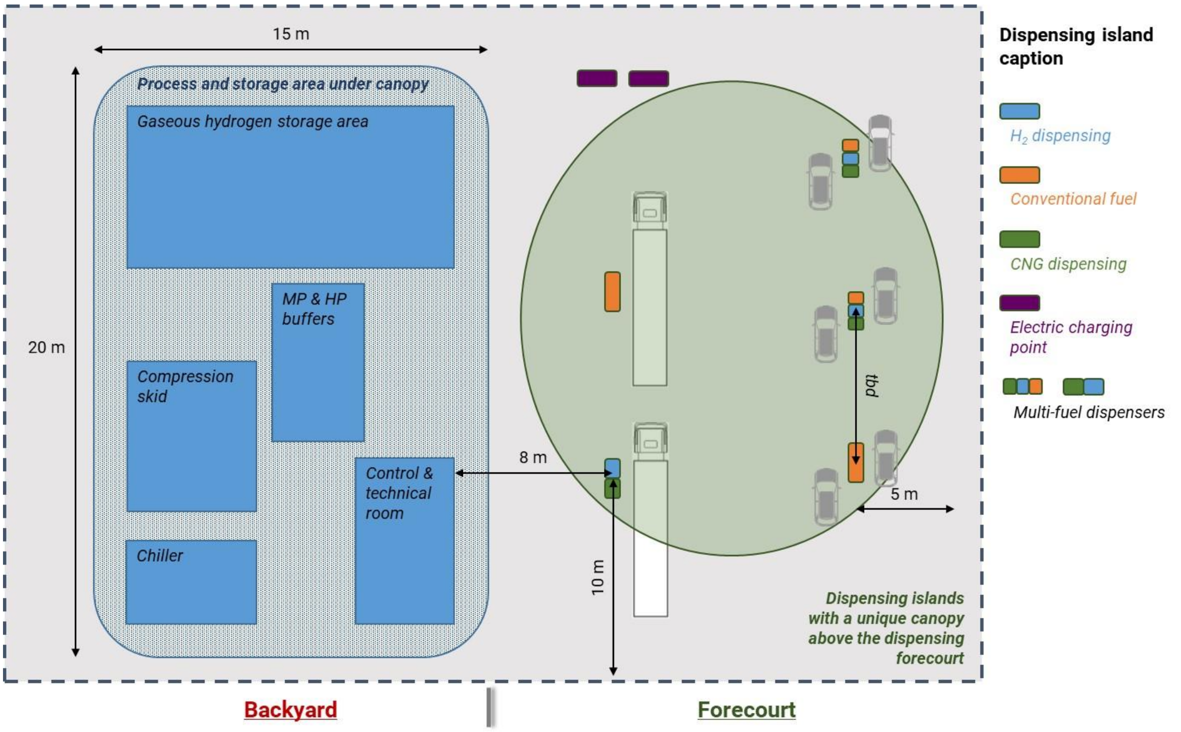


Figure 6 - Simplified and preliminary layout of "Ready-to-deploy" station

- **Configuration #2 – Onsite H_2 production multifuel station**: Gaseous hydrogen for light and heavy-duty vehicles with an onsite green hydrogen production by electrolysis, in a suburban location (a tube trailer can be used as spare supply or for expedition of H_2) (see Figure 7 and Figure 8); and

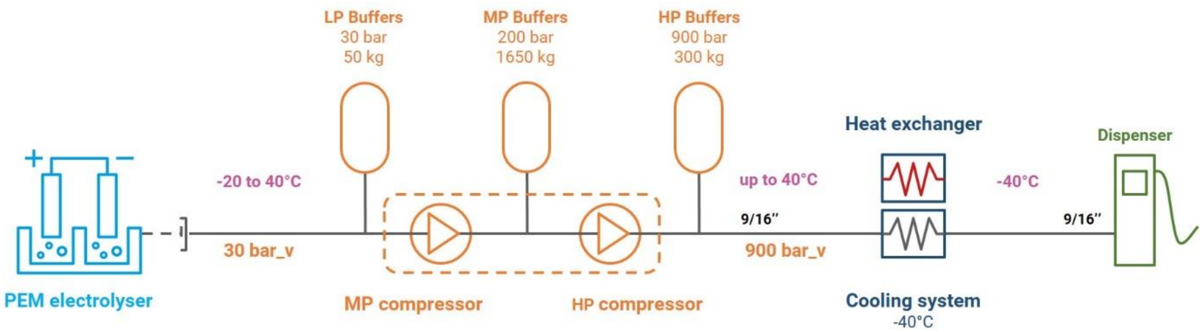


Figure 7 - Simplified PFD of "Onsite H2" station. v represents hydrogen in gaseous form

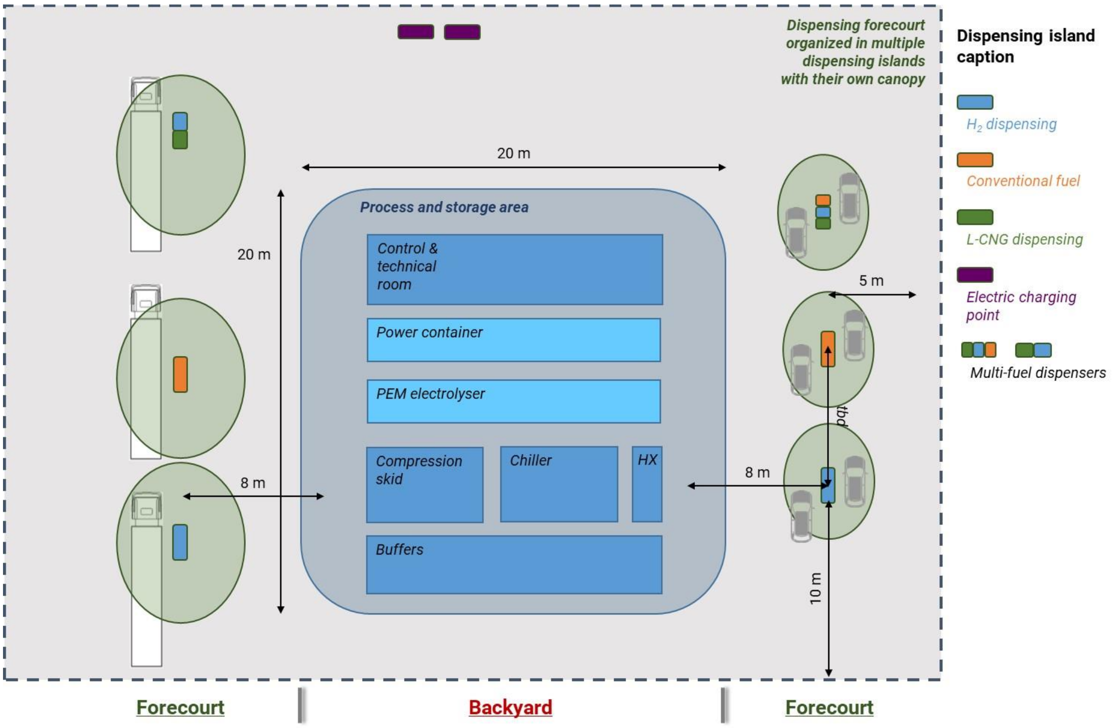


Figure 8 - Simplified and preliminary layout of "Onsite H_2" station

- **Configuration #3 – High capacity & High filling multifuel station**: Based on future large needs of hydrogen for mobility, situated in an industrial location to provide gaseous hydrogen for heavy-duty vehicles, with liquid hydrogen stationary storage, located in an industrial zone. See Figure 9 and Figure 10.

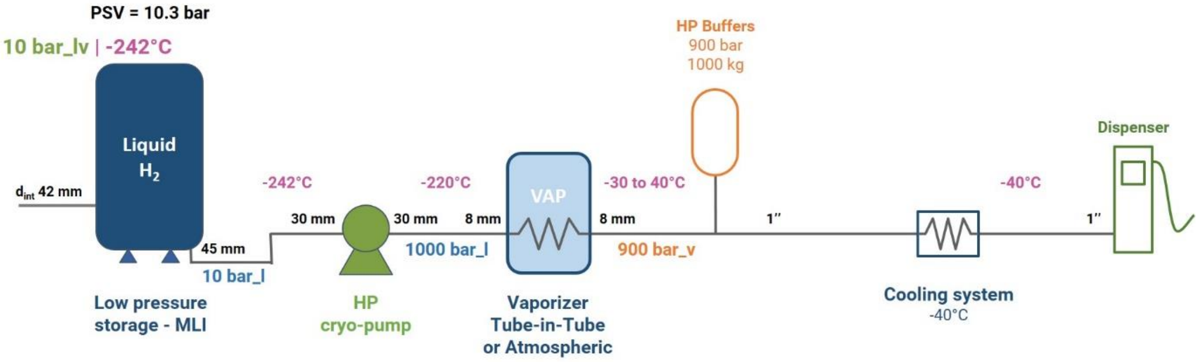


Figure 9 - Simplified PFD of "High capacity" station. v: for gaseous, l: for liquid

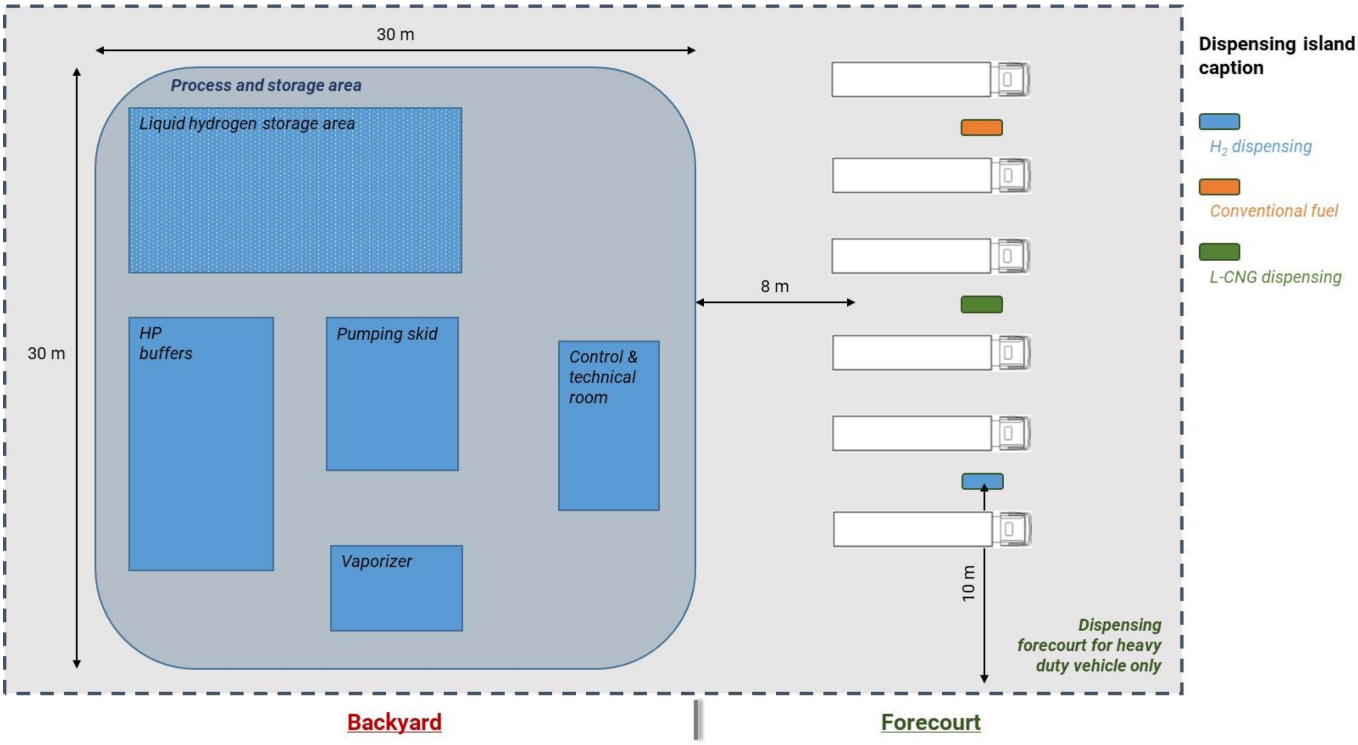


Figure 10 - Simplified and preliminary layout of "High capacity" station

4.2.2 Summary of HAZID

INERIS led a **Haz**ard **Id**entification (HAZID) exercise on Configuration #1, ENGIE led the HAZID on Configuration #2 and Air Liquide led the HAZID on Configuration #3. The aim of the HAZID study was to use structured brainstorming to systematically identify potential hazards associated with a particular concept/design, configuration/layout, operation/activity, including the likely initiating causes and possible consequences. Examples of safety barriers/ risk reduction measures were also brainstormed, these are as presented in Section 5, Table 15.

Guidewords are an important element of a HAZID and should be sufficiently comprehensive to stimulate identification of hazards and discussion, while avoiding the possibility of being too onerous for the stage of development. Occupational hazards (e.g. working at height, slips, trips and falls) were not considered because these hazards are not solely specific to HRS - these will need to be considered separately by the refuelling station operator.

There are two main, but contrasting, types of HAZID approaches, top-down and bottom-up. The triangle in Figure 11 represents a fault tree. At the top is a single hazard, and at the bottom are a large number of potential causes. Top-down studies use keywords or prompts for different types of hazards then the team works out if and how that hazard could be realised in the system being studied. Bottom-up studies are more detailed and comprehensive and use keywords about what could cause the system to lose control, or deviate from design intent, brainstorming what hazards could potentially be realised.

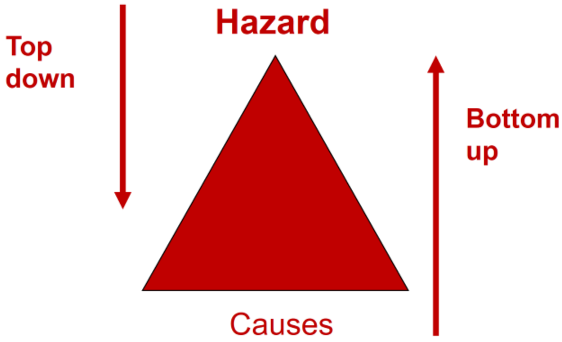


Figure 11 - Top-down vs Bottom-up HAZID techniques

The MultHyFuel project used a top-down HAZID approach, i.e. starting with the potential hazardous scenario and working out the possible causes and safety measures. The following hazardous scenarios / Dangerous Phenomena (DPh) were identified:

Table 2 – Summary list of dangerous phenomena identified during HAZID

Dangerous phenomena/ hazardous scenarios	Configuration #1	Configuration #2	Configuration #3
Jet fire	√	√	√
Flash fire	√	√	√
Vapour Cloud Explosion (VCE)	√	√	√
Unconfined Vapour Cloud Explosion (UVCE)	√	√	√
Catastrophic rupture (e.g. mix of H_2/Air or overpressure)	√	√*	√
Asphyxiation (no ignition)	√	√	√
Fireball	√	√	√
Hazards due to cryogenics			√
Liquid H_2 pool fire			√
Whipping of hose	√	√	√
Unexpected fire due to oxygen enrichment		√	

**additional scenario for a mix of H_2/O_2*

4.2.3 Risk screening process used

Risk is the combination of the likelihood of a specific undesired event occurring within a specified period and the severity of the injury or damage caused. The risk of a hazardous event is hence the combination of the severity of this event and of its likelihood. The more likely it is that a certain harm will happen and the more severe that harm is, the higher the risk. Consequences of the event is the extent over which a specified 'level of harm' would be experienced, i.e. "how far could the extent of the hazard reach?". In the context of harm to humans, severity is "how many people could potentially be 'harmed' from the event happening".

A screening risk matrix was needed to achieve quick risk ranking/ screening at the end of the HAZID sessions, in order to determine the representative set of scenarios to be taken forward to detailed risk assessment. The following research on hydrogen safety were used as a basis:

- (FCHJU project IDEALHY, 2013); and
- EIHP2 hydrogen applications – risk criteria and risk assessment methodology (FCHJU project FCHJU project EIHP2, 2003).

Through discussion with different project partners, the scaling and categories for the severity / likelihood and screening risk matrix were agreed, these are as described in Table 3 and Table 4. The screening scaling was largely based on the severity/likelihood matrices from the IDEALHY (FCHJU project IDEALHY, 2013) and EIHP2 projects (FCHJU project EIHP2, 2003).

Table 3 - Severity scale for the screening matrix

SCREENING RISK MATRIX SEVERITY SCALE		
Level	***Description***	***Definition***
1	Minor	No or minor effects
2	Moderate	Injured people
3	Major	One fatality
4	Catastrophic	More than one fatality

Table 4 - Likelihood scale for the screening matrix

SCREENING MATRIX LIKELIHOOD SCALE		
Level	***Description***	***Definition***
1	Rare	Might happen (unlikely to happen – no similar event known)
2	Forseeable	Could happen on a refuelling station (has occurred at least one time in industry)
3	Expectable	Can happen on a refuelling station (has occurred several times in industry)

The screening risk matrix is as shown in Table 5. The higher limit for the red zone was defined considering that a rare major or catastrophic scenario is not acceptable even if its likelihood is at the lowest level. Please note that a different, more detailed matrix with different scaling was used in the MultHyFuel risk ranking, as this screening matrix was solely used for screening/rapid risk ranking during the HAZID only.

Table 5 - Screening Risk matrix

Screening Risk Matrix	*Likelihood*			
	Level	***1***	***2***	***3***
Severity	***4***	5	6	7
	3	4	5	6
	2	3	4	5
	1	2	3	4

The red zone indicates the scenarios/ dangerous phenomena (DPh) that were studied in greater detail in MultHyFuel. The green zone indicates the scenarios that were not studied further.

The exercise led to a shortlist of 258 DPh (representative set of scenarios) studied in detail in Workpackage 3.4 of MultHyFuel:

- **26** scenarios common to all configurations;
- **33** scenarios common to configurations #1 and #2;
- **2** scenarios common to configurations #1 and #3;
- **38** scenarios specific to configuration #1;
- **66** scenarios specific to configuration #2; and
- **93** critical scenarios specific to configuration #3

In short, the representative set of scenarios that were studied were selected based on their qualitative risk ranking determined during the post-HAZID screening exercise (generically speaking, high severity and high likelihood scenarios). **However, due to constraints in project resource and duration, it was collectively decided by the Consortium that the MultHyFuel project would focus on the scenarios on the forecourt (and therefore dispenser)** and the potential interactions with the handling and use of several kinds of fuels. This means that the risks from the refuelling station backyard (non-public compound containing H_2 bulk storage (gaseous or liquefied), buffer tank, electrolyser, vaporisers, compressors, *etc*.) were not fully assessed.

Focusing on the hydrogen dispenser, the critical scenarios are given in Table 6.

Table 6 - List of critical scenarios on H2 dispenser identified during the HAZID

Considered equipment	Configurations #1-3
Dispenser	- Internal release not reaching flammable limits in terms of accumulation inside the entire volume of the dispenser, but H_2 jetfire hazards considered: * without immediate ignition * with immediate ignition (flame) - Internal release reaching flammable limits (i.e. maximum concentration inside the dispenser exceeds 4% H_2) followed by ignition (VCE)
Hose	- Release with immediate (flame) or delayed ignition (UVCE) – 700 bar - Release with whipping of hose
Nozzle	- Release with immediate (flame) or delayed ignition (UVCE) – 700 bar

Following the detailed risk assessment on the selected scenarios (likelihood vs. severity) in terms of harm to humans, events were plotted on a full risk matrix (that is different from the screening risk matrix). The matrix is subdivided into 25 cells (5×5 matrix) corresponding to pairs of "likelihoods" / "severity of consequences". The risk categorisation shown in Table 9 are those dictated in French legislation Légifrance Arrêté, 2005) – these were adopted for the MultHyFuel project. The likelihood ranges are those presented in

Table 8 - Human harm severity scale to humans external to the facilities

Severity level of consequence	Area defined by the thresholds of significant lethal effects (in French “Seuil des effets léthaux significatifs” SELS)	Area bounded by lethal effects thresholds (in French “Seuil des effets léthaux” SEL)	Area defined by the thresholds of irreversible effects (in French “Seuil des effets irréversibles” SEI)

V. Disastrous	More than 10 people exposed	More than 100 people exposed	More than 1000 people exposed
IV. Catastrophic	Less than 10 people exposed	Between 10 and 100 people exposed	Between 100 and 1000 people exposed
III. Major	At most 1 person exposed	Between 1 and 10 people exposed	Between 10 and 100 people exposed
II. Serious	No person exposed	At most 1 person exposed	Less than 10 people exposed
I. Moderate	No lethality zone outside the establishment	No lethality zone outside the establishment	

Table 7 and reported in Section 4.3.1 whilst the Severity ranges are presented in Table 8.

Table 7 - Accident Likelihood Scale (Légifrance Arrêté, 2005)

Likelihood interval	E	D	C	B	A
Frequency (per year)	$E > 10^{-5}$	$10^{-5}<D<10^{-4}$	$10^{-4}<C<10^{-3}$	$10^{-3}<B<10^{-2}$	$10^{-2}<A$

Table 8 - Human harm severity scale to humans external to the facilities (Légifrance Arrêté, 2005)

Severity level of consequence	Area defined by the thresholds of significant lethal effects (in French “Seuil des effets léthaux significatifs” SELS)	Area bounded by lethal effects thresholds (in French “Seuil des effets léthaux” SEL)	Area defined by the thresholds of irreversible effects (in French “Seuil des effets irréversibles” SEI)
V. Disastrous	More than 10 people exposed	More than 100 people exposed	More than 1000 people exposed
IV. Catastrophic	Less than 10 people exposed	Between 10 and 100 people exposed	Between 100 and 1000 people exposed
III. Major	At most 1 person exposed	Between 1 and 10 people exposed	Between 10 and 100 people exposed
II. Serious	No person exposed	At most 1 person exposed	Less than 10 people exposed
I. Moderate	No lethality zone outside the establishment	No lethality zone outside the establishment	

Table 9 - Risk Matrix representing the probability-severity risk pairs in terms of harm to humans (Légifrance Arrêté, 2005)

Severity in terms of harm to people exposed to the risk	Likelihood (increases from E to A)				
	E	D	C	B	A
V. Disastrous	NO (new site) / MRR (existing site)	NO	NO	NO	NO
IV. Catastrophic	MRR	MRR	NO	NO	NO
III. Important	MRR	MRR	MRR	NO	NO
II. Serious			MRR	MRR	NO
I. Moderate					MRR

The risk matrix in Table 9 defines three scenario risk zones, differentiated here by text and colour:

- a high-risk zone (red), represented by the word "NO". Identified risk reduction measures must be implemented to reduce the risk irrespective of cost;
- an intermediate risk zone (amber), represented by the acronym "MRR" (***M**esures de **R**éduction des **R**isques* or risk reduction measures) rank 1 or rank 2, within which risks need to be continually reduced to as low as reasonably practicable, proportionate to the level of risks whilst also considering economic viability; and
- a lower-risk zone (salmon), where compliance to regulations, codes and standards (RCS) and established good practice is still expected.

4.3 Likelihoods

The estimation of likelihoods is a key component of risk assessment. There are a number of different approaches that can include, but are not limited to:

- Frequency statistics derived from past incidents, commonly held in generic failure databases;
- Bayesian statistics which combine both objective and subjective data, based on expert judgment or lessons learned from past incidents; and
- The reliability of structures approach (AFS- *Approche de Fiabilité des Structures*), which combines the system physical characteristics and probability of human error, independent of past incidents.

The MultHyFuel project looked at the first and third methods from the bulleted list above, and the results of these are presented in Sections 4.3.1 and 4.3.2, and summarised in Section 4.3.3.

Numerous probability data sources exist, e.g. formulae from expert judgment, generic data from databases and past accidents, *etc*., the latter were analysed in the MultHyFuel project, as described in Section 4.3.1.

Due to limitations in the classical methods used to derive leakage frequencies from incident databases for new technologies such as high-pressure H_2, the second approach studied in MultHyFuel was an *ab initio* method involving the detailed analysis of potential initiating events was proposed in MultHyFuel, based on the characteristics of each item and its condition of use. For each specific component, a leakage frequency and a leakage flowrate (% of the full cross section) were obtained using a combination of fault tree analysis and physical models. Experiments were performed to attempt corroboration of both the leakage frequency and the flowrate. Only limited data has been available so far, but the results seem to give some support to the modelling approach. The key findings from this work are summarised in Section 4.3.2, and are also described in (Proust, Pique, Tarisse, & Jamois, 2023). The method seems applicable to many components but should be validated via further data and tests before adoption on a wider scale.

4.3.1 Likelihoods from generic failure databases

During the risk analysis exercise in MultHyFuel, it was found that there were large discrepancies in probability estimates between different generic failure databases (e.g. (BEVI, 2020), (SANDIA BD Ehrhart & ES Hecht, 2022), (Offshore Norway/ Norske olje og gass PLOFAM2, 2018)). Sandia developed hydrogen-specific leak frequencies as a function of the area/size of the leak using a Bayesian statistical analysis to produce hydrogen specific data from the generic databases: offshore petroleum, chemical processes, compressed gas and nuclear industries (LaChance, 2008). It was expected that there would be some difference between databases, such as that between

Sandia and Norskeolje&gass PLOFAM, however those from BEVI are several orders of magnitude different from the other two databases. This is as shown in

Table 10, where the frequency intervals are:

- A : greater than 10^{-2} per year;
- B : between 10^{-2} and 10^{-3} per year;
- C : between 10^{-3} and 10^{-4} per year;
- D : between 10^{-4} and 10^{-5} per year; and
- E : lower than 10^{-5} per year.

Table 10 - Likelihood assessment for loss of containment from the hydrogen dispenser hose

Config.	Central Feared Event (CFE)/ Top Event	Pressure	Time maximum filling (h/day)	DATABASE			DPh/ major accident event
				BEVI	**Sandia**	**Norskeolje &gass PLOFAM**	
1	Loss of H_2 containment (medium leak 10%) on hose	350 bar	3.33	A	D	E	(U)VCE Flashfire Jet fire
2			5	A	D	E	
3			21.7	A	C	D	
1		700 bar	3.33	A	D	E	
2			5	A	D	D	
3			21.7	A	C	D	
1		1000 bar	3.33	A	D	D	
2			5	A	D	D	
3			21.7	A	C	D	
1	Full bore rupture (1'' = 25.4 mm) on hose	350 bar	3.33	B	D	E	
2			5	B	D	E	
3			21.7	A	C	D	
1		700 bar	3.33	B	D	E	
2			5	A	D	D	
3			21.7	B	C	D	
1		1000 bar	3.33	B	D	D	
2			5	B	D	D	
3			21.7	A	C	D	

MultHyFuel's analysis of likelihood data from these generic databases revealed some strengths and weaknesses in the approach:

Strengths

- Relatively simple to implement;
- Relatively generalisable; and
- Considers failure modes specific to mechanical components.

Weaknesses

- The estimation of the likelihoods does not consider the initial event, the barriers and the ignition likelihood in great detail; and
- The models may not be 100% representative of reality (technology implemented in a refuelling station) and may not be adaptable to the configurations being studied.

4.3.2 Likelihoods from the Reliability of Structures approach (*AFS- Approche de Fiabilité des Structures)*

As aforementioned, a further method (AFS) was developed within MultHyFuel to calculate the frequencies of component (e.g. valves, fittings, *etc.*) leakage and potential flowrates, based on contact mechanics, i.e. the physical analysis of the component characteristics and the potential failure mechanisms arising from its operation, i.e. pressure cycling, mounting/ dismounting, *etc*.

An average number of operations/ cycles to failure is estimated (3rd column of Table 11) and the probability of failure is typically the inverse following the Reliability of Structures Theory (AFS). The frequency of failure for each considered component (in the last column) is derived by multiplying by the number of that specific component present in the dispenser (5th column) and the number of cycles per year (6th column). When the failure is due to a human action, a series of manual operations like refuelling a vehicle at the dispenser and the sequence of operation can be described by a fault tree and the probability of failure is calculated using Boolean algebra. The probability of missing a simple/ routine operation is set to 1/1000 (based on information available from literature). The frequency is then derived as explained, based on the assumed average number of operations or rather, its inverse. The full details on the method can be found in (Proust, Pique, Tarisse, & Jamois, 2023). The application of the AFS approach to our study is presented in Table 11.

Table 11 - Failure frequency and leak size for hydrogen dispenser components outputs from MultHyFuel WP2 experimental programme based on this method

Component	Solicitation	$N_{cycle\text{-}op\text{-}failure}$	% fullbore	$N_{component}$	$F_{cycle\text{-}operation}$	$F_{failure\text{-}component}$
Pipe 9/16 (ID=7.9 mm)	Fatigue due to P and T cycling	10000000000	100	10	10000	1E-05
Pipe 9/16 (ID=7.9 mm)	Corrosion	1000	100	1	1	1E-03
Pipe 3/8 (ID=5.1 mm)	Fatigue due to P and T cycling	20000000000	100	10	10000	5E-06
Pipe 3/8 (ID=5.1 mm)	Corrosion	1000	100	1	1	1E-03
Pipe 1/4 (ID=2.7 mm)	Fatigue due to P and T cycling	2E+11	100	2	10000	1E-07
Pipe 1/4 (ID=2.7 mm)	Corrosion	1000	100	1	1	1E-03
Hose 3/8 (ID=4 mm)	Fatigue due to P and T cycling	10000	100	1	10000	1E-00
Hose 3/8 (ID=4 mm)	Misuse (driving on, tearing off)	200000000	100	1	10000	5E-05
Nozzle 3/8 (ID=4 mm)	Deficient maintenance (nozzle, receptacle)	50	9	1	1	2E-02
Nozzle 3/8 (ID=4 mm)	Deficient refuelling operation	100	9	1	10000	1E+02
Nozzle 3/8 (ID=4 mm)	Wear (seals)	140000	9	1	10000	7.14E-02
Nozzle 3/8 (ID=4 mm)	Misuse (driving on, tearing off)	200000000	100	1	10000	5E-05
Breakaway 3/8 (ID=5.1 mm)	Fatigue due to P and T cycling	10000000	9	1	10000	1E-03
Breakaway 3/8 (ID=5.1 mm)	Deficient mounting (plugging, maintenance)	100	9	1	1	1E-02
Flow valves 9/16 (ID=7.9 mm)	Deficient mounting (maintenance)	100	3	5	1	5E-02
Flow valves 9/16 (ID=7.9 mm)	Wear (seals)	300000	1	5	10000	1.67E-01
Flow valves 1/4 (ID=2.7 mm)	Deficient mounting (maintenance)	100	16	1	1	1E-02
Flow valves 1/4 (ID=2.7 mm)	Wear (seals)	20000000	8	1	10000	5E-04

Component	Solicitation	$N_{cycle\text{-}op\text{-}failure}$	% fullbore	$N_{component}$	$F_{cycle\text{-}operation}$	$F_{failure\text{-}component}$
Pressure control valve 9/16 (ID=7.9 mm)	Deficient mounting (maintenance)	100	1	1	1	1E-02
Pressure control valve 9/16 (ID=7.9 mm)	Fatigue due to P and T cycling	10000000	4	1	10000	1E-03
Pressure control valve 9/16 (ID=7.9 mm)	Wear (seals)	1000000000	1	1	10000	1E-05
Pressure safety valve 3/8 (ID=1.1 mm)	Deficient mounting (maintenance)	100	1	1	1	1E-02
9/16 Union Couplings (ID=7.9 mm)	Deficient mounting (maintenance)	100	5	20	1	2E-01
9/16 Union Couplings (ID=7.9 mm)	Untightening due to P cycling	3000000	5	20	10000	6.67E-02
3/8 Union Couplings (ID=5.1 mm)	Deficient mounting (maintenance)	100	8	20	1	2E-01
3/8 Union Couplings (ID=5.1 mm)	Untightening due to P cycling	2000000	8	20	10000	1E-01
¼ Union Couplings (ID=2.7 mm)	Deficient mounting (maintenance)	100	19	20	1	2E-01
1/4 Union Couplings (ID=2.7 mm)	Untightening due to P cycling	2500000	19	20	10000	8E-02

In Table 11, the figures in navy blue are the default (conservative) values, where information was lacking to accurately model the scenario. In red, are the scenarios exhibiting a very high failure frequency, i.e. scenarios which would require reliable and efficient risk mitigation measures. The scenarios range from full bore leakage to 1% full bore. Such leakages may be ranked from "medium" to "large", but not "minor" nor "very small". It is believed that this stems from the nature of the technology chosen, i.e., very 'rigid components' with high tightness requirements but with little deformability, where a small mechanical deviation has the potential to trigger a leakage.

MultHyFuel's exploration of the AFS approach revealed some strengths and weaknesses:

Strengths

- Takes into account failure modes specific to each mechanical component;
- Possibility of carrying out sensitivity analyses and optimisation of certain parameters;
- Quantification of specific degradation modes for each component; and
- Gives an accurate picture of the impact of each cause and mode of degradation on overall equipment failure

Weaknesses

- Requires a good level of knowledge of mechanical and probabilistic models (both skills in statistics and probability, as well as in materials and mechanical engineering);
- There can be significant uncertainty in the numerous input data and mathematical models;
- Models may be difficult to generalise and apply to other configurations (Requires a lot of data on equipment, processes, system environment); and
- The deterministic approach and the result correspond to a lifetime – does not allow you to benefit from the advantages of the probabilistic approach.

4.3.3 Advantages and limitations of using likelihoods from historical data/generic database information vs. Reliability of Structures approach

The different approaches to estimating the probability examined in MultHyFuel have their own strengths and weaknesses. The approach using data from generic historical databases will rely heavily on operational experience, which is still lacking for hydrogen.

The mechanical-probabilistic 'Reliability of Structures' AFS approach summarised in Section 4.3.2 and Likelihoods from the Reliability of Structures approach (*AFS- Approche de Fiabilité des Structures* described in (Proust, Pique, Tarisse, & Jamois, 2023) develops a detailed analysis of the degradation modes depending on the components present in the system. This is the reason why this approach could be considered by some as more representative of the estimation of the likelihood for HRS accident scenarios. However, this approach is very rough and needs to be improved before it can be deployed at large scale. Only limited data is available so far. Whilst the method seems applicable to many components, it should be validated via further tests and data from operational experience. For instance, estimation of data uncertainty (e.g. estimate of the head loss through the leak path when determining the leakage cross section, *etc*.). All potential initiating events need to be considered in hazard analysis, and these should be validated through testing or lessons learned from past incidents. The method is also sensitive to the technical and operational details of the process and one difficulty is to obtain sufficient information. Hence, it is strongly advised to examine the procured components carefully and the written schemes in the technical documentation as part of the assessment. It is also advisable to apply only the order of magnitude in the final figures as input into the risk assessment, even though more accurate figures are generated.

In a similar manner, for real-life applications, careful consideration and due diligence would need to be exercised when using data from generic databases to ensure applicability to the systems being risk-assessed.

In conclusion, existing generic databases give a wide range of likelihoods which are dependent on the data source, but are preferable to the Reliability of Structures industry-focused (AFS) approach. This is because the latter does not yet have sufficient data to support its immediate application. Due diligence is essential when either of the approaches are being used.

4.4 Consequences

The risk of a hazardous event is the combination of the severity of this event and of its likelihood. Likelihood aspects have been presented in the previous section. Consequences of the event is the extent over which a specified 'level of harm' would be experienced, i.e. "how far could the extent of the hazard reach?". In the context of harm to humans, severity is "how many people could potentially be 'harmed' from the realisation of that event?" Severity is evaluated from superimposing consequence/ hazard footprints over maps/grids of location-dependent estimates of population.

This section is dedicated to looking at the consequences or how far a hazardous event could reach. A selection of available engineering methods to assess the consequence and severity are presented. Comparisons have been carried out between calculations and experiments performed within the MultHyFuel project to evaluate relevance, accuracy and limitations of some analytical models.

In the MultHyFuel project, the focus has been on dispenser and forecourt scenarios. In real life applications, the risks from the siting/location of the HRS and bulk storage and processing of hydrogen will need to be assessed to get a complete risk picture.

In general, whatever the station configurations, the scenarios are very similar for the forecourt area.

4.4.1 Key conclusions from WP2 experimental results

The main aim of the experimental work performed in the MultHyFuel project was to produce the missing data needed for risk analysis and to implement usable risk mitigation for HRS in a multifuel context; i.e. on sites where pressurised gaseous hydrogen is dispensed alongside other conventional fuels.

The four main objectives were as follows:

- Determine flow rates, extents of hazardous zones and ignition probabilities for potential major hazard events on HRS plant;
- Investigate experimentally, key fire and explosion scenarios, which cannot be analysed sufficiently using consequence modelling tools;
- Test the performance and reliability of key safety barriers identified in the project, under real-life conditions; and
- Conduct experiments to estimate the effect of hazardous occurrences on hydrogen dispensers affecting other dispenser types on a multifuel forecourt, and vice versa.

A mock-up hydrogen dispenser and simplified forecourt, including a parked vehicle was setup (MultHyFuel D2.4, 2024) as shown in Figure 12. Hydrogen was supplied to the dispenser at test pressures of 350 and 700 barg.

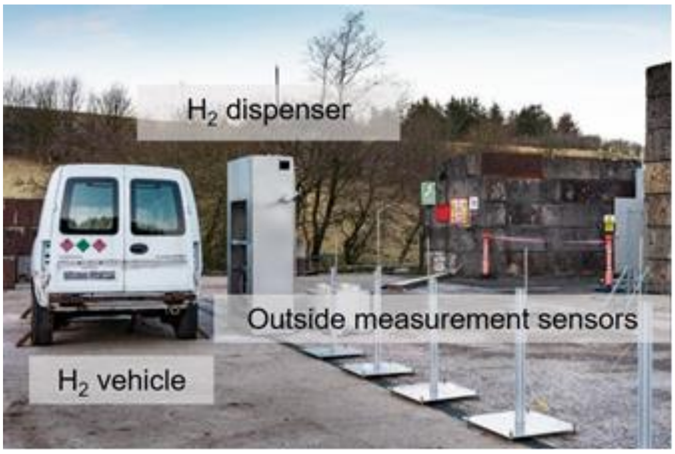


Figure 12 - MultHyFuel experimental forecourt with the dispensing area

Considering only the forecourt events of the refuelling station, for the key major hazard scenarios identified in Section 4.1.1, two main categories were identified:

- Hazardous events outside the dispenser; and
- Hazardous events inside the dispenser.

Outside the dispenser, i.e. H_2 release coming from the dispensing hose, two top events were considered and simulated, mainly linked to the H_2 jet:

- A jet fire considering an instantaneous ignition of the release; and
- The whipping of the dispenser hose without H_2 jet ignition.

In the event of an ignited hose release, it might whip even faster and the flame would move around. This scenario was not taken forward to the experimental programme as it is a combination of the other two scenarios.

These events in the free field are illustrated in Figure 13.

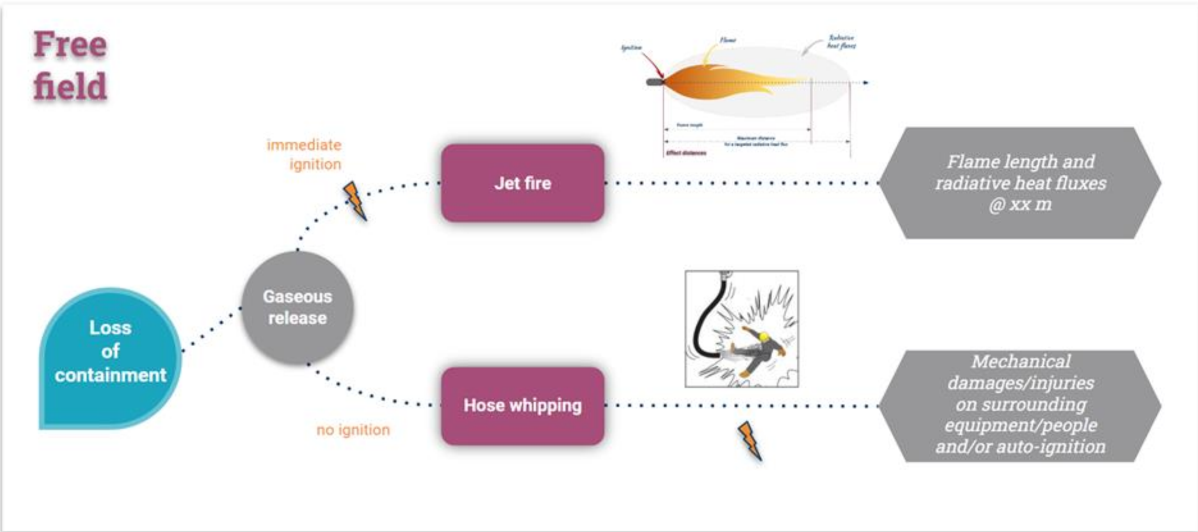


Figure 13 - Potential hazardous events in case of H_2 release in "free" field

Inside the dispenser, in the case of an internal H_2 release, the following events have to be assessed:

- The accumulation of H_2, taking into account ventilation characteristics;
- If flammable limits are reached, explosion inside the dispenser in case of delayed ignition of the accumulated H_2, considering explosion venting if it exists; and
- Propagation of the overpressure and/or thermal fluxes outside the dispenser through the structure apertures or if the structure is destroyed.

The chain of events of loss of containment in confined spaces up to the resulting potential scenario is showed in Figure 14.

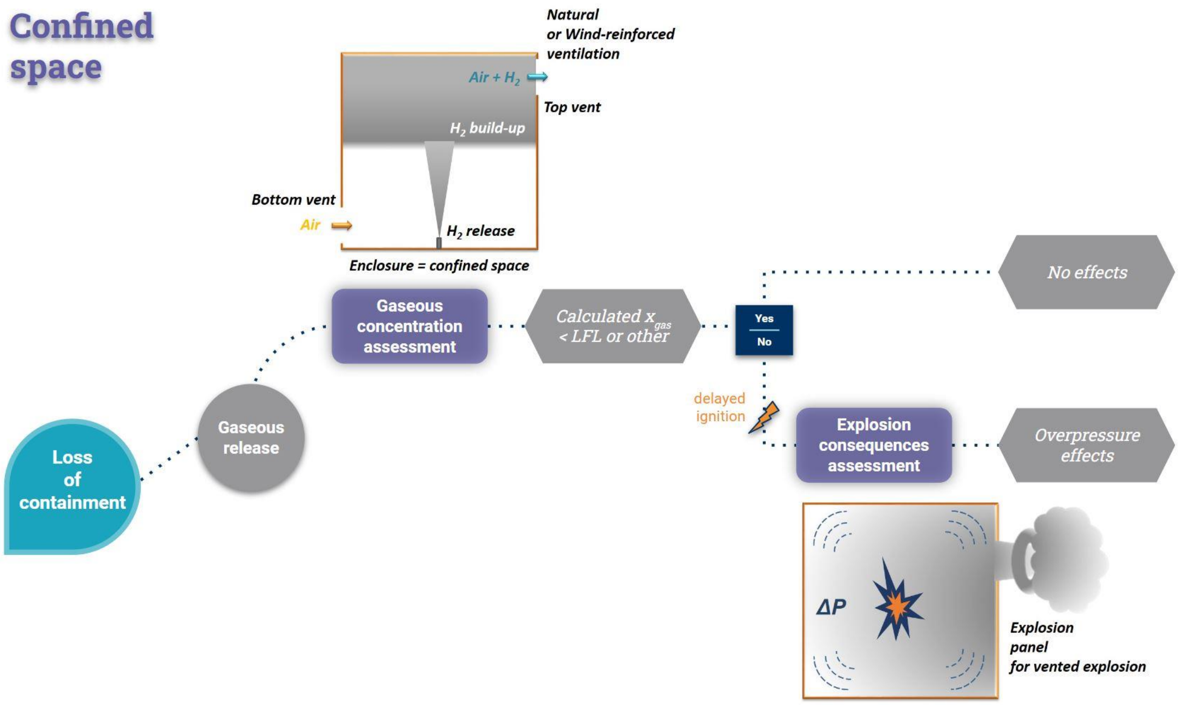


Figure 14 - Potential events in case of H_2 release in "confined" space with ventilation

Accidental events outside the dispenser

Potential consequences resulting due to a failure in the dispenser hose resulting in a release of hydrogen were experimentally assessed using a mock-up of the dispenser. A jet fire ensued, the length of which is heavily determined by the flow characteristics and pressure of the hydrogen gas.

A typical jet flame is shown on Figure 15, the hydrogen flame is hardly visible to the naked eye. The infra-red (IR) flame was more than 5 m long for an ignited release outside horizontal leak via a 3/8" pipe (70 g/s) at 700 bar; and about 4 m long for 35 g/s at 300 bar. The maximum temperature measured in the flame jet is about 1200°C. In (MultHyFuel D2.4, 2024), these results are compared to that of (Proust & Studer, High Pressure Hydrogen Fires, 2011), who observed similar flame lengths of 5 m for a 80 g/s through a 2 mm hole at 900 barg. Further work will be required to determine if longer flame lengths can be achieved or if the flames are limited to around 5 m; this should be compared to models such as (Molkov & Saffers, Hydrogen Jet Flames, 2013).

Figure 15 - Standard (left) and IR image of a jet flame (right)

The flame and temperature effects of the ignited releases were found to be significant and extended up to 5 m at 700 bar. It should be noted that there were reduced and diminishing flow rates in these experiments compared with what is achieved in real life dispensers, so this distance could increase.

The conducted experiments showed that the whipping of the hose itself is not sufficient to ignite the hydrogen contained/released from within it. The hose, when whipping, does pose a significant mechanical impact risk that could affect nearby people, vehicles or equipment.

Accidental events inside the dispenser

MultHyFuel WP2 experiments showed that there was not enough confinement in the dispenser configuration tested (open bottom, ventilation holes, *etc*.), for detonation to occur. The dispenser did not have a large enough length vs. diameter ratio (L/D) for run up to deflagration-to-detonation (DDT) and it also did not have a large enough ignition source to overdrive it to detonation.

A loss of hydrogen containment within a pipe with a release hole size of 0.2 mm and 0.5 mm diameter was shown to pose a significant hazard to the mock-up dispenser. The risk of escalation to surrounding equipment and people on a multifuel forecourt in this case is non-zero.

Unignited releases from a 0.2 mm diameter hole at 700 bar with standard ventilation posed the highest hazard with a peak hydrogen accumulation within the mock-up dispenser housing of 26 vol% (which is close to stoichiometric). Increasing the passive ventilation area in the mock-up dispenser housing reduced the concentration of hydrogen that could accumulate.

An internal hydrogen leak in the dispenser can cause a flammable concentration to form outside of dispenser. It was shown in the experiments, which used a pyrotechnic ignition source 1.5 m away, that external ignition of the gas could occur, which then burnt back to the leak source location and formed a stable jet fire. This jet fire caused significant equipment damage within the dispenser housing, but the pressures experienced within the dispenser were reduced (compared to internal ignition) and the housing survived.

When a leak from a 0.2 mm diameter hole at 700 bar with standard ventilation was ignited internally within the mock-up dispenser housing, the inclusion of a weak panel into the mock-up dispenser housing provided mitigation of the overpressure generated during the explosion. The inclusion of the weak panel prevented the door of the dispenser from being ejected from the mock-up dispenser housing and thus the chance of serious injury from secondary blast effects. The orientation should be carefully considered as the weak panel directs pressure and flame/temperature effects in that particular direction.

Without mitigation, an internal release which was ignited internally in the mock-up dispenser housing caused damage to forecourt structures and nearby vehicles, which could also impact humans if they were within the hazard range. The door to the dispenser was released at a significant velocity and caused substantial damage to the vehicle. Had the vehicle not been in the way, it would have travelled a considerable distance. It could have caused significant harm or death to people impacted by it.

Conclusions drawn from the modelling results

Simulated accidental events assumed the absence of safety barriers and emergency protocols, i.e. risk reduction and mitigation measures have not been considered in the consequence modelling, leading to conservative estimates of consequence in general.

The only passive mitigation that has been studied, are natural ventilation openings/ apertures to limit H_2 accumulation inside the dispenser; as well as explosion panels to limit internal overpressure in case of an explosion, should an ignition source meet the flammable cloud.

If internal and external hazardous events are compared, the strongest effects and largest hazardous distances are obtained for the ignition of an internal leak. If this event is not mitigated (or the mitigation measures fail) a panel could be thrown a considerable distance (in the experiment, it hit the vehicle parked in front of it). This is a low probability event, and the consequences can be mitigated through enhanced ventilation by removing the dispenser top or fitting an adequately-sized explosion relief panel.

For an explosion (deflagration) inside the dispenser with a roof explosion venting panel fitted:
For a H_2 concentration that was modelled to be close to stoichiometry, and without other safety features
Internal overpressure: 170 mbarg
External overpressure calculated at 1 m: 10 mbarg
Temperature at 1 m: lower than 40°C
Hazard distances for overpressure of 10 mbarg (conservatively lower than the harm criteria defined in Table 1) for the dispenser, are in the 1 m range.

Table 12 - Measured internal overpressures and deflagration associated effects for a dispenser with and without roof explosion venting panel for a release flow rate of 1.2 g.s-1 (i.e. 784 NL.min-1)

Parameters for explosion severity assessment	[TT17] 700 bar / 0.2 mm	[TT18] 700 bar / 0.2 mm
Max measured %-H_2	25%	25%
Explosion vent panel	Roof	-
Explosion vent area	0.288 m^2 // 1/2 footprint	0.048 m^2 // 10% footprint
Measured internal ΔP	**168 mbarg**	**626 mbarg**
External ΔP at 1.24 m	26 mbarg	134 mbarg
Temperature at 1.24 m	37°C	28°C

ΔP = Overpressure

For the Ignition of a hose release forming a jet fire:

However, the more likely scenario to occur, and one that is harder to mitigate, is the ignition of an accidental release from the dispensing hose on the forecourt, and this can be used to define the separation distances. Note that the experiments for MultHyFuel had reduced flow rates for the jet releases (70 g/s at 700 bar and 35 g/s at 300 bar), however other experiments with releases at 80 g/s at 900 bar cited in (MultHyFuel D2.4, 2024) had similar jet lengths of around 5 m.

Release from dispenser hose on the forecourt:

In some countries, the installation of flow restrictors before the dispenser hose are mandatory.
Typical flow rate from a dispenser is 60 $g.s^{-1}$ for cars (700 bar) and 120 $g.s^{-1}$ for buses (350 bar). However, there are international working groups looking at the future use of e.g. 180 $g.s^{-1}$ for heavy duty vehicles.

In MultHyFuel project, jet fire is the identified worst case, when considering the hazards from the forecourt alone, compared to an explosion in the dispenser due to the fast attenuation of the overpressure with the distance compared to thermal effects from a sustained flame if the release is not stopped. It is acknowledged, however, that not all potential configurations could be fully explored within the project's scope, and certain accidental scenarios — especially those involving confinement or directional release — might lead to more severe consequences under specific conditions.

Table 13 - Calculated and measured flame lengths

Flow rate	Pressure	Equivalent diameter	Flame length
Calculated values from HRS process data			
60 $g.s^{-1}$	700 bar	1.43 mm	4.3 m
120 $g.s^{-1}$	700 bar	6.1 mm	6.1 m
180 $g.s^{-1}$	700 bar	2.5 mm	7.6 m
300 $g.s^{-1}$	700 bar	3.2 mm	9.7 m
120 $g.s^{-1}$	350 bar	2.8 mm	6.4 m
Measured values from HSE experiments			
36 $g.s^{-1}$	30 bar	5.3 mm	3.8 m
63 $g.s^{-1}$	53 bar	5.3 mm	5 m

Considering the aforementioned flow rates, HSE's and other MultHyFuel experiments are consistent with the calculated leak flow rates for modelling consequences, see Table 13, reproduced from Table 51 of (MultHyFuel D3.6, 2024). It was found that flame length distances are in the 6 m range for a theoretical 120 $g.s^{-1}$ flow rate. *(NB: the current French regulation* (Légifrance Arrêté 1416, 2018) *requires a separation distance 14 m for 120* $g.s^{-1}$ *and of 10m for 60* $g.s^{-1}$ *,these required distances may be reduced to 10 meters (for 120* $g{\cdot}s^{-1}$*) and 8 meters (for 60* $g{\cdot}s^{-1}$*) under specific conditions—namely, if automatic safety measures stop the gas flow within less than 2 seconds at the point of rupture.).* Separation distances for other countries can be found in (MultHyFuel D1.4, 2024). It is worth noting that flame length is not necessarily adopted as the separation distance. LFL (with or without a safety factor applied) could also be adopted as the relevant separation distance. (BCGA GN41, 2020) provides some context as to the meaning of separation distance.

Note also that in the MultHyFuel project, it was assumed that the H_2 dispenser unit is separate from those of other conventional fuel types. The feasibility of a single dispenser that houses all fuel types including H_2 (multifuel dispenser) was not part of the research. Future work should examine the impact of accident scenarios with multifuel dispensers on separation distances.

Additionally, an analytical comparison has been carried out between H_2 FCEV and CNG-V infrastructure. Using numerical simulations using the Schefer Model (Schefer, Houf, Bourne, & Colton, 2006) and (Schefer, Houf, Williams, Bourne, & Colton, 2007); and assuming maximum delivery pressure, specific nozzle diameter for each fuel type and a jet fire due to hose full bore rupture with immediate ignition, flame lengths and associated effects were found by the MultHyFuel project to be higher for CNG compared to H_2. The required separation distance is thus less for H_2 than it is for CNG, taking account of the current (and different) operating conditions and flow rates for both fuels. This is as detailed in Appendix A – Comparative analysis between hydrogen and compressed natural gas and Table 17, with further details in MultHyFuel deliverables (MultHyFuel D3.6, 2024) and (MultHyFuel D1.2, 2021) as well as (MultHyFuel D1.4, 2024).

4.4.2 Example models for severity assessment

There can be a large degree of variation in the design and layout of H_2 infrastructure, and for time, economic and resource reasons, it would be unfeasible to exhaustively experiment on all configurations and associated potential hazardous events. Modelling tools are thus essential in order to perform risk assessments on such installations, at the different stages of design, optimisation and deployment.

In this section, examples of engineering models that can be used to assess consequence of the potential key H_2 hazardous events are presented.

For each potential event to be assessed in terms of consequence, there exists:

- several scientific approaches;
- several methodologies to analyse the scenario, to extract the input data for the calculation, to use the relevant parameters when required;
- several safety strategies including the choice of harm criteria to define hazardous or safety distances; and
- several calculation tools.

This section presents the main modelling tools and software used for consequence assessment of the potential SCEs (Safety Critical Events), and the associated models used for severity assessment.

4.4.3 Integral type modelling tools (non-exhaustive)

A brief description of the software tools currently available for consequence modelling of H_2 accidents is presented in this section.

HyRAM (Sandia National Laboratories): A toolkit that integrates deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterising the impact of hydrogen hazards on people and structures. HyRAM incorporates generic probabilities for equipment failure and probabilistic models for heat-flux impact on humans and structures, with computationally and experimentally validated models of hydrogen release and flame physics.

PHAST/PHAST Risk: A process hazard analysis software tool, available from Det Norske Veritas GL (DNV GL), for all stages of design and operation, which examines the progress of a potential incident from the initial release to far-field dispersion analysis, including modelling of pool spreading and evaporation, and flammable and toxic effects (DNV, 2024).

Moreover, PHAST is also used in combination with DNV GL's proprietary Unified Dispersion Model (UDM). This combination allowed the creation of a software tool named **SAFETI-NL** used for quantitative risk assessment calculations in the Netherlands. It has been developed by DNV GL and it is used to carry out quantitative risk analysis (QRA) of onshore process, chemical and petrochemical facilities as well as analysis of chemical transport risk.

4.4.4 CFD tools (non-exhaustive)

FLACS (GEXCON)**:** A suite of 3-D computational fluid dynamics (CFD) tools with a series of standard modules and additional bolt-ons designed to meet specific requirements. This software is used for ventilation, gas dispersion and explosion simulations in safety analyses, including a fire module.

ADREA-HF (NCSRD): The CFD tool was enriched to perform CFD modelling for cryogenic dispersion, BLEVE, explosions and jet fires including radiation.

KFX-Exsim: A CFD tool developed by DNV GL. It is a 3-D explosion simulation software technology used for offshore and onshore facilities. It allows the optimisation of offshore platform layout to reduce explosion consequences; as well as the quantification of blast wave load acting on safety critical objects such as the temporary refuge (TR), lifeboats and living quarters. Moreover, this software has the ability to give probabilistic explosion analysis, has cost-benefit analysis capabilities to feed into ALARP decisions ; and can also be used for incident investigations.

ANSYS Fluent is a commercial CFD software developed by ANSYS Inc. It is widely used in industry and has a broad range of capabilities, including turbulence modelling, multiphase flows, heat transfer, and combustion. Fluent has a user-friendly interface and provides many pre-defined solvers, making it easy for users to get started with their simulations. Fluent also has strong post-processing capabilities and integrates with other ANSYS simulation tools.

OpenFOAM is an open-source CFD software - developed by OpenCFD Ltd and OpenFOAM Foundation - with a wide range of capabilities for fluid dynamics simulations, including turbulence modelling, multiphase flows, and reacting flows. It has a large user community and a vast library of user-generated solvers and tools. The software is flexible, allowing users to develop custom solvers and work with complex geometries. This CFD code is well known in the academic and industrial sectors.

4.4.5 "Engineering tools" (non-exhaustive)

Additional tools – public or specifically developed by Industry or research institutes – can be used as well. (EHSP, 2023) Guidance on Hydrogen Safety Engineering provides information about available tools. Depending on the tools, they are currently more suited to the assessment of the consequence of hazardous events involving pressurised hydrogen at ambient temperature.

In some cases, it has been highlighted in the PRESLHY European funded project that some modules of these tools can be used to calculate the consequence of events related to liquid hydrogen hazardous events.

Additionally, some of these tools are in continuous adaptation and improvement, based on ongoing research and operational experience.

e-Laboratory: Initially developed in the Horizon 2020 NET-Tools European funded project, it is a medley of tools dedicated to gaseous hydrogen. This suite of tools is hosted online and is freely available to the public.
As highlighted and validated in the PRESLHY project:

- The Similarity Law can be used with LH_2 to estimate the distance from the nozzle where a concentration of interest is reached (Cirrone, 2019);
- A non-adiabatic blowdown model for a hydrogen storage tank could accurately predict the pressure and temperature dynamics during blowdown for transient mode; and
- The release model can be used to predict the mass flow rate generated by a full bore or partial rupture of a pipe for cryogenic and ambient temperature.

ALDEA by Air Liquide: Air Liquide Dispersion and Explosion Assessment tool with modules developed for gaseous and liquid hydrogen hazardous events, from the release to the explosion, considering scenarios in free field and confined spaces. Consequences of the burst of pressurised gaseous and liquid hydrogen tanks can be assessed as well.

FRED by Shell: Shell-developed suite of tools that allow calculating consequences of burst, jet fire, UVCE, VCE, dispersion of GH_2, VCE and pool fire for LH_2.

EPHEDRA tools by INERIS: a platform for EFFEX (for VCE), PROJEX (for physical burst), EXOJET (for UVCE) tools, and HyPond tool which is a single algebraic formula to estimate the maximum extent of the liquid pool likely to spread on the ground following a low-pressure spillage of liquid hydrogen.

DISCHA tool by NCSRD: to calculate accurate physical properties of pure substances and perform discharge calculations either in transient (blowdown) or steady state mode, taking into account discharge line effects. The tool can also perform tank-to-tank transfer calculations under single or two-phase conditions.

GASP (Gas Accumulation over Spreading Pools) modelling tool is used for LH_2 pool scenarios. This calculation tool is a pool spread and vapourisation model that has been developed in association with the Health and Safety Executive (HSE). GASP has been extensively tested and validated for LNG and liquid hydrogen releases.

4.4.6 Modelling approaches adopted in the MultHyFuel project

Two series of calculations have been performed during MultHyFuel project:

- Assessment of severities of the identified critical scenarios during the HAZID
- Calculation of the simulated accidental scenarios for the forecourt areas

Table 14 gives references of approaches used and corresponding models.

Table 14 - References of the theoretical approaches used in MultHyFuel project

Scenarios to be assessed	Theoretical approaches / References
Gaseous hydrogen	
Burst / catastrophic rupture of pressurised vessel	(Brode, 1959)
Flow rate and flammable cloud characteristics	(Birch, Hughes, & Swaffield, 1987), (W, 1978), (Epstein & Fauske, 2003)
Jet fire	(Schefer, Houf, Bourne, & Colton, 2006) and (Schefer, Houf, Williams, Bourne, & Colton, 2007)| Flame, radiative heat fluxes]
Unconfined Vapour Cloud Explosion*	(Yellow Book - CPR, 1995), (Bauwens, Chaffee, & Dorofeev, 2011) | TNO Multi-Energy model and its 5-level system, to represent different levels of severity based on the degree of congestion (obstacles and obstructions)
Dispersion in confined space	(Linden P. F., 1999) | Natural ventilation
Vapour Cloud Explosion	FM Global Approach (Bauwens, Chaffee, & Dorofeev, 2011) | Molkov Approach (Molkov, Dobashi, Suzuki, & Hirano, 1999) | Vented deflagrations
Liquid hydrogen	
Storage burst	(Betteridge & Phillips, 2015.)| Fireball, (Brode, 1959) | Overpressure
Flow rate and flammable cloud characteristics	(Leachman, Jacobsen, Penoncello, & Lemmon, 2009), (Venetsanos, 2018), (Epstein & Fauske, 2003)
Jet fire	(Schefer, Houf, Bourne, & Colton, 2006) and (Schefer, Houf, Williams, Bourne, & Colton, 2007)| Flame, radiative heat fluxes + PRESLHY validation
LH_2 pool	(Dienhart & Verfondern, 1997), (Batt, 2014)

Unconfined Vapour Cloud Explosion*	Helmholtz free energy based EoS + (Birch, Hughes, & Swaffield, 1987) + TNO ME 6

**Note that for the severity assessment of explosions, taking into account release flow rates for gaseous and liquid scenarios, low levels of congestion for the considered structures and their environment, and corresponding existing accidentology… detonation appeared not relevant. Thus, only consequences of deflagrations have been evaluated, but aggravating conditions have been considered through the choice of the appropriate Multi-Energy level.*

4.4.7 Comparison of experimental results against consequence modelling

4.4.7.1 Key conclusions

Analysis of the experimental results has been performed in order to formulate recommendations on design, modelling and mitigation, through comparison of experimental measurements with analytical calculations. Reverse calculations were performed in order to better understand discrepancies.

Designing scenarios for safety:

- High pressure release from the distributing hose in the forecourt is potentially the worst-case scenario, if bulk storage (permanent or transient) and processing of H_2 are not considered; and
- In case of release inside the dispenser, with sufficient openings for natural ventilation and dedicated explosion venting panels, if ignited, the effects will be contained inside the dispenser with no or limited effects of propagation outside the dispenser.

Consequence Modelling:

- Consequence models tend to be inherently conservative and care needs to be taken not to reinforce conservatism via double-counting; and
- There is a need to carefully define source terms by a relevant and critical analysis of the system and associated equipment.

Dispenser design:

- Dispenser design should incorporate openings/ apertures for natural ventilation and wind-reinforced ventilation;
- Horizontal ventilation apertures are more efficient to benefit from wind, whatever the wind orientation;
- Dedicated explosion venting panels
    - These should be built to one of the recognised standards such as (BS EN 14994, 2007) or NFPA 68. For a 1 m^3 dispenser housing as used in the experiment, these give vent areas of 0.9 and 1.2 m^2 respectively.
    - In the MultHyFuel experimental setup, there was a tall (2 m height), relatively thin (0.5 m width) dispenser with a weak panel of 0.5 m^2 located on the top (equal to the entire footprint) of the dispenser. This is below that specified in the relevant standards, but extra venting was available through the ventilation apertures and the open bottom of the dispenser. The dispenser also experienced some plastic deformation, but the standards specify a vent area such that no plastic deformations occur.
    - If explosion vent panels are not sized to one of these standards or the MultHyFuel test configuration, there should be reliable modelling or experimental testing to demonstrate their suitability.

- The design of dispenser housings and their explosion venting panels should be a topic of future of research, but a general principal is that dispensers should be shorter, however they should be taller than the average height of a person, so at least 1.8m in height), rather than tall and thin, to allow for a suitably-sized explosion panel. The aspect ratio H/L/W for the studied mock-up dispenser, which was approximately 2 m/1 m/0.5 m, required the size of the explosion panel to be equal to the whole footprint of the dispenser (1 m × 0.5 m). This vent size was considered, according to the experimental results, sufficient to mitigate the consequences of the potential explosion inside the dispenser for the current aspect ratio.

- Strategically safe location of apertures, specifically for huge openings and openings dedicated to explosion venting, to direct the hazard and limit damage and potential for human injuries. In practice, this is likely to be openings located in the upper segment of the dispenser and pointing vertically upwards away from the customer refuelling the vehicle. Orientating the vent panels to a closely located wall or canopy would restrict the venting, and as such would require even larger vent panels; and
- Early detection of releases from distributing hose and efficient associated emergency protocol (requirement: maximum detection and reaction time can vary between 2 s and 5 s depending on local regulations).

Recommended methodology for consequence assessment

For the dispenser:

- Assess accumulation for the most critical and probable release(s);
- Assess consequences of the deflagration; and
- Limit the internal overpressure to as low as reasonably practical, and at most 200 mbar (this is the pressure considered to avoid global destruction of the dispenser housing)
  - By decreasing H_2 build-up
    e.g. with more ventilation, by limiting the flow rate
  - And/or with explosion venting panels

For the forecourt:

- Assess immediate ignition of the jet (i.e. flame) due to hose release;
- Limit the release:
  - By early detection of the release or the flame;
  - Have an efficient emergency protocol to stop the release.

Modelling of accidental events with gaseous hydrogen
H2 accumulation in confined space:

(Linden P. F., 1999) is a relevant approach, but will overestimate the concentration in most cases because:

- Release is considered constant, continuous and infinite
- Concentration is the maximum reached at steady state
- Wind reinforced ventilation is not considered

Deflagration in confined space:

FM Global approach (Bauwens, Chaffee, & Dorofeev, 2011) or Molkov approach (Molkov, Dobashi, Suzuki, & Hirano, 1999) can be used, but can overestimate overpressure because:

- Concentration is considered homogeneous in the entire volume.

- Stratification is not considered although it exists, inducing an overestimation of the amount of H_2 to be considered in the explosion.

Flame:

Schefer Approach (Schefer, Houf, Bourne, & Colton, 2006) and (Schefer, Houf, Williams, Bourne, & Colton, 2007) can be used:

- Not easy to compare to experimental data since some biases are induced by the test facility (i.e. the method assumes constant release flowrate, whereas constant flowrate may not be realistic specifically where the hydrogen source is finite); and
- Nevertheless, consistency is observed with reverse calculations from corrected data (Corrected data here implies Flow rate, Q, that was not calculated from the initial release pressure and hole diameter, but the experimentally measured Q, where it was found Q decreased with release time).

UVCE:

No data is available from the project to provide recommendations. Thus, if necessary, the recognised TNO method in the Yellow Book (Committee for Prevention of Disaster, 1995) could be used with the Multi-Energy Method, with Blast Strength Level appropriate to the assessed phenomena and conditions. According to published studies, in most cases where there is sufficient vent area, the Multi-Energy Model using Strength Level 5 is appropriate (E Vyazmina, S Jallais, D Miller, 2016). Nevertheless, in case of high congestion levels and/ or high flow rate (> 1kg/s) the Multi-Energy Model with Blast Strength Level 6 or 7 would be more appropriate. To use the Multi-Energy Method, it is also necessary to determine the combustion energy contributing to the UVCE. This energy is obtained by multiplying the combustion energy (expressed in J/kg) by the flammable mass participating in the explosion. The combustion energy is an intrinsic property of the combustible gas (around 120 MJ/kg for hydrogen). The flammable mass involved in the explosion depends on how the flammable cloud forms and how it interacts with any obstruction in its path.

Modelling of accidental event with liquid hydrogen:

No data is available from MultHyFuel project to provide technical recommendations. Nevertheless, other projects such as PRESLHY, SH2IFT or ELVHYS could be consulted to more specifically address liquid hydrogen scenarios, which are not in the scope of the MultHyFuel project.

4.4.7.2 Caveats – Critical analysis

Some limitations are stated in this section regarding calculations and experiments performed in MultHyFuel to evaluate the potential hazards of H_2 dispensers in a multifuel station configuration:

- Consequence modelling tends to overestimate the consequences of potential hazardous events for all scenarios, whatever the considered phenomenon. Hence, calculated values tend to be conservative.

Main impacting parameters for experiments / Simulation representativity:

- Weather conditions and wind may influence the dissipation/attenuation of the effects;
- Numerical modelling assumed a constant release → whereas this may not be the case for real life and/or experimental conditions for a given duration;
- Layouts of multifuel stations can vary, and may be different from the one studied in MultHyFuel;

- Findings may be different if safety barriers are taken into account, for e.g. gas/ flame detection, actuation of safety features and emergency protocols, *etc*.; and
- The impact of conventional fuels on the H_2 dispensing system has not been fully assessed in the project; and will need further investigation.

Nevertheless, the studies carried out experimentally and analytically in MultHyFuel to help inform technical recommendations on consequence assessment of the Safety Critical Events identified in the project are most probably conservative through the chosen assumptions, hypotheses and the analyses performed at each step where there were uncertainties.

4.4.8 Safety critical scenarios & HRS risk profile

The results of the detailed risk assessment that was carried out within MultHyFuel on the three selected case studies, are described in (MultHyFuel D3.6, 2024). Some key findings include:

The equipment that registers the highest number of critical hazardous events is the dispenser, however, the storage, compression, and liquid equipment in the refuelling station backyard (processing and bulk storage of hydrogen were not part of MultHyFuel detailed analysis), also present a significant number of scenarios. The distribution of dangerous phenomena by equipment is illustrated in Figure 16. However, it was collectively decided by the MultHyFuel consortium to focus on the dispenser, due to project resource and time constraints. For the risk assessment and management to be complete, the hazards and risks from H_2 bulk storage and processing will need careful assessment, in addition to the careful siting selection of the refuelling station.

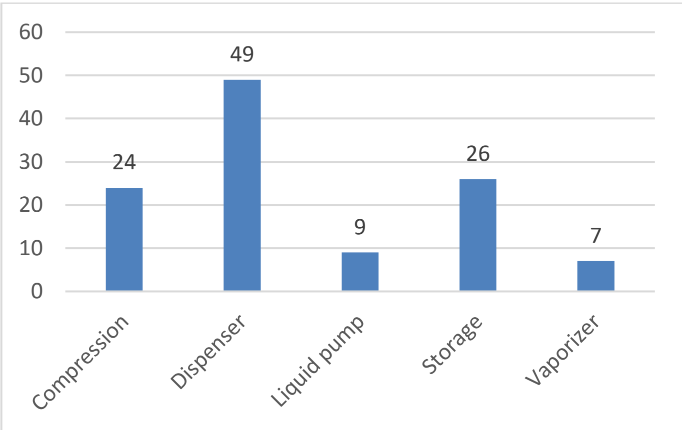


Figure 16 - Distribution of dangerous phenomena by equipment

The main hazardous scenarios on a HRS identified during the detailed risk assessment process in Workpackage 3.5 of MultHyFuel are as illustrated in Figure 17.

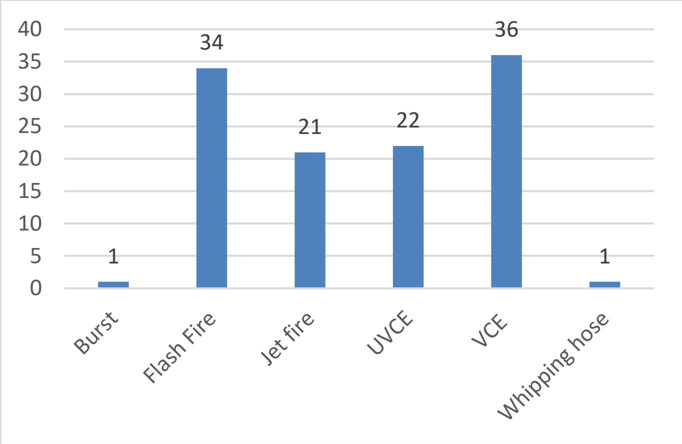


Figure 17 - Main safety critical major hazard events

The Safety Critical Scenarios identified on the hydrogen dispenser for all configurations are detailed below:

- Loss of H_2 containment (medium leak 10% Diameter of pipe) on valve/piping - Flash Fire;
- Loss of H_2 containment (full bore rupture) on valve/piping - Flash Fire;
- Loss of H_2 containment (full bore rupture) on valve/piping - Jet fire;
- Loss of H_2 containment (medium leak 10% Diameter of pipe) on hose - Flash Fire;
- Loss of H_2 containment (full bore rupture) on hose - Flash Fire;
- Loss of H_2 containment (full bore rupture) on hose - Jet fire;
- Loss of H_2 containment (full bore rupture) on hose - Whipping hose; and
- Hydrogen release at vent line exit - Flash Fire.

The additional Safety Critical Scenarios identified specific to Configuration #3 (but LH_2 scenarios were not analysed in detail experimentally) are:

- Loss of H_2 containment (small leak) on valve/piping - VCE considering Natural ventilation;
- Loss of H_2 containment (medium leak 10% Diameter of pipe) on valve/piping - jet Fire;
- Loss of H_2 containment (medium leak 10% Diameter of pipe) on hose - jet Fire;
- Loss of H_2 containment (small leak) on hose - jet Fire; and
- Loss of H_2 containment (small leak) on hose - UVCE.

Detailed risk assessments carried out in the MultHyFuel project (Figure 16) showed that the dispenser is a critical piece of equipment in a service station. The top event or CFE is the loss of containment of hydrogen, which can lead to explosions in the open air (UVCE) or in a confined environment (VCE inside the dispenser) or to jet fires or flashfires. This high risk of leaks is related to the high numbers of fittings in the different dispensers, equipment failure (e.g. due to hydrogen embrittlement, human error during maintenance, bad connections to the hose or nozzle, impact risks like vehicle crash, or domino effects due to the range of fuels in the multifuel station. The risk of ignition of these leaks can be controlled through zoning the internals of the dispenser and using appropriate ATEX-rated equipment.

The effects on people would potentially be immediate, given the proximity of the people on the fueling station dispensing area. The MultHyFuel project demonstrated the impact of having vehicle passengers (e.g. on a bus, *etc.*) on the number of critical scenarios (differences between Option 1: One driver inside each truck and 50 passengers inside each bus; and Option 2: Two drivers for each of the trucks and buses present on the HRS site. A key critical measure is to minimise the number of people in the vicinity of the dispensers during refuelling.

4.4.9 Domino effects

The definition of "domino effect" in the field of safety, is an escalation incident in which a primary undesired event sequentially or simultaneously triggers a secondary undesired event(s), called the domino event. Whilst domino events generally tend to be low frequency, they do need consideration in risk management because they could potentially give rise to high consequence events that may have higher severity than the primary event.

Experimental work performed in MultHyFuel WP2 demonstrated that the consequences arising from a domino event inside or outside the H_2 dispenser are limited.

Based on the highest consequence event experimented on in the MultHyFuel project, i.e. dispenser internal explosion due to an accidental H_2 release, or a jet fire from a hose ignited release, the consequence distances were found to be not too severe (assuming the internal explosion is mitigated). Damage was observed in the case of an internal explosion (unmitigated) from a H_2 release for a car parked at less than one meter from the dispenser due to a dispenser mobile plate, (for the MultHyfuel mock-up dispenser, which may not be a universal design for dispensers). This type and level of damage could potentially be minimised with optimisation of the dispenser design, including but not limited to explosion panels.

Additionally, in order to attempt to simulate worst case conditions, the experimental work performed in MultHyFuel project did not include emergency procedures such as:

- H_2 sensors inside the dispenser to limit H_2 concentration using automatic shut-off valves to isolate the supply, and so limiting energy of the deflagration;
- Excess flow valve upstream of the dispenser limiting the flow rate in case of release followed by ignition;
- H_2 sensors and flame detectors outside the dispenser to stop and limit consequences of external releases; and
- Break-away coupling to isolate the piping in case the dispenser hose is torn-off.

Safety equipment and protocols can potentially limit the duration and severity of unexpected accidental events, and therefore reduce the risks of potential domino effects.

The scenario of a hydrocarbon fire close to the H_2 dispenser was studied experimentally in MultHyFuel. A 2 m^2-120 litre diesel pool fire was initiated 2.7 m from the pressurised mock-up of a hydrogen dispenser. It was found that for this set up, the pool fire did not pose a significant hazard to the dispenser. There was no significant temperature increase, and the pressure loss was small within the hydrogen dispenser mock-up, indicating little evidence of the potential for multifuel escalation.

5 Risk management/ safety barriers on an HRS forecourt

5.1 Hierarchy of Controls

It is good practice to apply good engineering principles as a hierarchy by aiming to eliminate a hazard in preference to controlling the hazard; and controlling the hazard in preference to providing personal protective equipment. In many cases, this hierarchy will automatically be realised if the duty-holder makes decisions which err on the side of safety and which take account of the integrity and effectiveness of various risk control measures. Other principles and hierarchies exist in specific regulations and guidance; these should be applied as appropriate.

A holistic approach is important to ensure that risk reduction measures that are adopted to address one hazard do not disproportionately increase risks due to other hazards; or compromise the associated risk control measures. Where appropriate, consideration should also be given to the balance of risk between workers and the public, and to the increased risk due to action taken during normal operation which is intended to reduce risks during an emergency condition.

As per many standards, the hierarchy of controls approach is taken by industry to select the safety barriers to implement, so that the most effective barriers are introduced first.

The (ISO/TR 15916, 2015) standard (Basic considerations for the safety of hydrogen systems) considers in Section 7.1.3 that hazards should be addressed in the following order:

1. Eliminate the hazard;
2. Prevent the hazard;
3. Avoid the hazard. For example, by limiting the exposure to the hazard either by limiting the time of exposure or by limiting the number of people being exposed;
4. Mitigate the hazard; and
5. Accept the hazard (only if the consequences of a hazard are insignificant, or they can be tolerated). Careful examination to justify the decision that it can be accepted should be necessary in this case.

The (ISO/TR 15916, 2015) standard also highlights the importance to seek design and operation that minimises the severity of the consequences of mishaps, and lists examples that could help to achieve that in Section 7.1.4.

The (ISO 19880-1, 2020) standard (Gaseous hydrogen – Fuelling Stations – Part 1: General Requirements) indicates, in Annex B (Further guidance on risk management) the three stages of safety assurance that should be considered:

1. Prevention of accidents. This includes, for example, application of state-of-the-art technology, following simple handling procedures, designing user-machine interfaces in a straightforward manner, or preventative maintenance;
2. Mitigation strategies. This includes, for example, application of state-of-the-art technology, barriers and layers of protection, safety measures and safety distances; and
3. Structured and effective emergency response.

In terms of hazard mitigation, the (ISO 19880-1, 2020) standard specifies different types of barriers in its Section 5.3 (Mitigation measures to improve system safety):

- Mitigations which reduce the potential for the formation of a flammable mixture;
- Mitigation for the formation of a flammable mixture in enclosures;
- Mitigation for the formation of a flammable mixture under a canopy;

- Mitigations which reduce the potential for ignition;
- Mitigation of the escalation and/or impact of a fire or explosion originating from the fuelling installation;
- Mitigation of the effect of an external fire /events on the fuelling station installation; and
- Mitigation of risk to the high-pressure hydrogen storage system of the vehicle being fuelled.

Annex B of the (ISO 19880-1, 2020) standard provides further guidance on risk management, where the general mitigation strategies considered are:

- Minimisation of the potential for the formation of a flammable mixture;
- Minimisation of the potential for ignition (from both piloted and spontaneous ignition sources);
- Mitigation of the effects of flammable gas releases originating from the fuelling station installation;
- Mitigation of the impact to the fuelling station installation from an external fire;
- Reduction of the physical effects of the explosion generated by potential leaks or releases.
- Minimisation of confinement of hydrogen systems;
- Maximisation of natural ventilation; and
- Safety distances.

There are other relevant strategic objectives that are not covered by any of the previous RCS mentioned but which also ought to be considered. DSEAR[2] (Legislation, 2002) which is Great Britain's implementation of the European Union-wide *ATmosphères EXplosibles* ATEX Workplace Directive 1999/92/EC) and EC Chemical Agents Directive 98/24/EC (CAD). HSE's Approved Code of Practice (ACOP) (2013) and guidance provides practical advice on how to comply with the regulations. DSEAR Reg 6(2) sets out that substitution of the dangerous substance is the preferred approach. Where this is not reasonably practicable, DSEAR Reg 6(3)(a) requires that the risks are controlled under the hierarchy of control set out in DSEAR Reg 6(4):

- Reduction of the quantity of dangerous substances to a minimum. {DSEAR Reg 6(4)(a)};
- Avoidance or minimising the release of a dangerous substance. {DSEAR Reg 6(4)(b) + ACOP para 200-208)}. Steps towards control under this regulation could be achieved by minimising leak points in the distribution system (consider the type of pipe fittings used) and minimising breaking of connections to those only essential during maintenance;
- Control releases of dangerous substances at source {DSEAR Reg 6(4)(c)}. The use of detection systems is required where hydrogen could leak or could accumulate, or close to hydrogen connections that are routinely coupled;
- Prevention of the formation of an explosive atmosphere, including the application of appropriate ventilation. {DSEAR Reg 6(4)(d)}. This would include installing suitable ventilation in the dispenser to reduce the concentration of hydrogen that could accumulate.
- Collect or contain release or remove to safe place {DSEAR Reg 6(4)(e)};
- Avoidance of - (i) ignition sources including electrostatic discharges; and (ii) adverse conditions which could cause dangerous substances to give rise to harmful physical effects. {DSEAR Reg 6(4)(f)}. Steps under this regulation include ensuring equipment used aligns with the requirements of ATEX certification.
- Segregation of incompatible dangerous substances. {DSEAR Reg 6(4)(g)}; and
- Mitigation of the detrimental effects of a fire or explosion is required under DSEAR Reg 6(3)(b) with measures set out under DSEAR Reg 6(5). Where a potentially explosive atmosphere

[2] UK enactment of The Explosive Atmospheres Directive (99/92/EC) and Chemical Agents Directive (98/24/EC)

remains it must be classified as hazardous or non-hazardous, and appropriately zoned if deemed hazardous {DSEAR Reg 7}.

BCGA GN 13 (BCGA GN13, 2021) is a bit more compact as it uses risk assessment, elimination/control, hazardous area, emergencies, information/instruction/training, identification, and coordination. It lists controls against each of the categories of controls, plus includes measures in its Section 7).

(Energy Institute Guidance EI 3312, 2025) 'Supplement to the Blue Book' provides guidance for companies that provide sites for the refuelling of hydrogen-powered motor vehicles, including HGVs, and for authorities responsible for granting permits and supervising these companies when co-location with petrol filling stations (PFS) is proposed. It gives a summary of regulations, requirements, criteria and conditions based on current industry good practice as reflected in British Compressed Gases Association, (BCGA CP41, 2018). This publication links this good practice with current industry guidance relating to petrol filling stations (PFSs) and as such should be used in conjunction with the (APEA/EI 'The Blue Book', 2024).

MultHyFuel project's preliminary risk assessment (HAZID sessions) brainstormed a list of non-exhaustive, technical recommendations, as shown in Table 15 (Pique, *et al*., 2022), the project has categorised these into three classes.

Table 15 - Examples of recommendations listed during the HAZID sessions (Pique, *et al*., 2022)

Topics	Examples of recommendations
Design of the refuelling station	- Design of canopy roof to limit degree of confinement - Prefer storage with open structure on the top, or placed underground
Management of refuelling station	- Avoid unloading during thunderstorms / inclement weather conditions
Detection systems to implement	- H_2 flame and gas detection with associated emergency protocols (e.g. alarms, shutdown…)
Importance of isolation device	- Shut-off valves to isolate equipment in case of burst or dysfunction
Choice of materials	- H_2 compatible materials (e.g. for fittings, pipings, seals…) - Asphalt is prohibited to avoid air (O_2) condensation increasing combustible reactivity in case of ignition of LH_2
Location of equipment to limit domino effect	- Safe location of outlet of vent lines - Location of venting of TPRD to avoid impact on other installations
Consideration of natural hazards specific to each site	- Consider the specificities of the natural hazards (i.e. snow, rain, wind/tornado, seismic area, seaside environment) of the site
Periodic control	- Commissioning and periodic control for the integrity of H_2 equipment on the whole HRS (i.e hoses, liquid tank or tube trailer, dispenser, piping, buffer storage)
Addition of prevention and/or mitigation barriers	- Flowrate restriction orifices, break-aways, quick couplings, pressure safety valves, bursting discs, explosion panels, concentration sensors, pressure and temperature sensors, flow meter
Key parameters to monitor and control	- Temperature and pressure of the type-III and IV cylinders should be considered in the transfer protocol from compressor/buffer to fuel cell vehicle - Vibration alarm on compressor with emergency shutdown
Management of ignition sources	- Comply with Hazardous Area Classification - Explosive Atmosphere (ATEX)-certified devices

As mentioned, (MultHyFuel D3.6, 2024) classified the safety barriers into three categories, as illustrated in Figure 18:

- technical barriers;
- human barriers; and

- barriers which involve technical and human barriers. These barriers are called manually operated safety barriers, so their effectiveness will be dependent on human factors, and hence the potential for human error.

In the category of technical safety barriers, these may be safety devices or Safety Instrumented System (SIS).

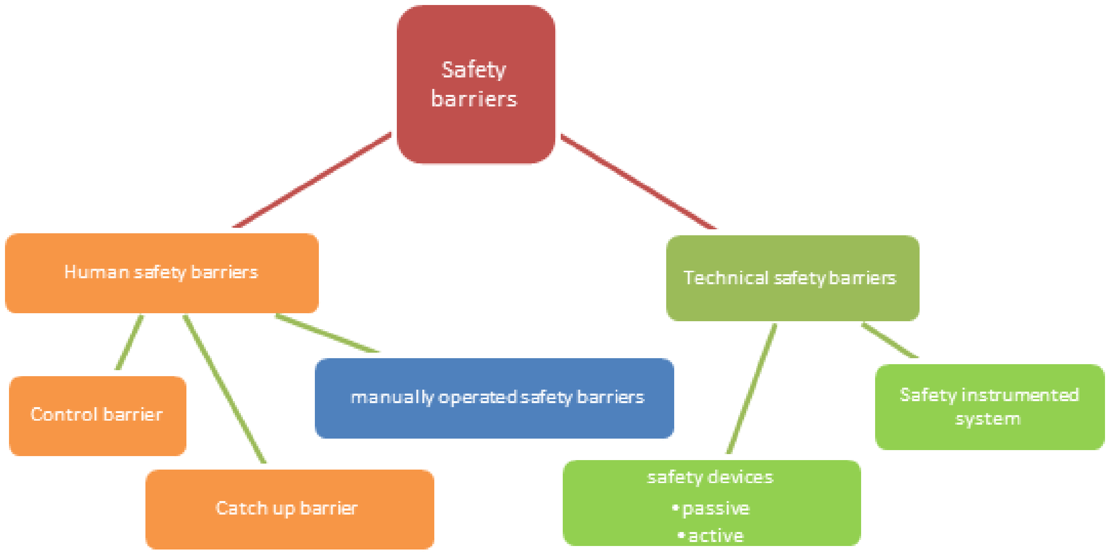


Figure 18 - Categories of safety barriers looked at in MultHyFuel

The following table lists the safety barriers identified in MultHyFuel WP3 for the hydrogen dispenser (non-exhaustive).

Table 16 - list of the safety barriers related to hydrogen dispenser identified in the WP3

Human safety barriers
Prevention barrier
Video surveillance to identify malicious acts and intervention
Control barriers
Prevention barrier
The human factors and organisational measures to implement in order to avoid having passengers near the dispenser during dispensing operations
Clear operating instructions for users to fill their cars
Leak detection systems (manual checking like foaming bubble test)
Leak tests (fuelling protocol/ program to follow)
Maintenance and inspection of dispenser and hose (including the hose shroud)
Permit to work systems
Procedure of controls on dispenser and hose (including the hose shroud)
Technical safety barriers
Active safety device
Prevention barrier
Check valve in vehicle tank to avoid backflow

Pressure safety valve(s) to avoid incoming overpressure
Protection barrier
Breakaway device
Hose arrestor to limit whipping
Passive safety device
Prevention barrier
Crash protection around the island
Natural Ventilation aperture(s) to avoid accumulation of hydrogen in the dispenser
Protection barrier
Explosion venting panel
Restriction orifice to limit the effects, in case of leak
Safety instrumented system
Prevention barrier
Isolation system (closed valve) in case of high pressure reached
Mechanical ventilation to avoid accumulation of hydrogen in the dispenser if natural ventilation is insufficient
Temperature sensors (before the breakaway) and stop refuelling if temperature is too high or too low (fuelling protocol)
Protection barrier
Fire protection system (fire detection and isolation system) outside the dispenser
Isolation system (closed valve) in case of low pressure/flow
Gas detection in the dispenser with installation shutdown capability
Technical/human safety barriers
Manually operated safety barriers
Protection barrier
Emergency button to stop fuelling

5.2 Example relevant standards

5.2.1 ISO 19880-1

The (ISO 19880-1, 2020) standard (Gaseous hydrogen – Fuelling Stations – Part 1: General Requirements) was prepared by the Technical Committee (ISO/TC 197, 1990) (Hydrogen technologies). This standard provides minimum requirements for fuelling stations dispensing gaseous hydrogen to light duty road vehicles, although requirements and guidance for refuelling medium and heavy-duty road vehicles are also covered. Operational safety requirements are not addressed in this standard to the same level of detail as design requirement, but a summary is provided in Chapter 5.5 of this document.

The systems in fuelling stations that are covered in (ISO 19880-1, 2020) are: hydrogen on-site production, hydrogen delivery, compressors, pumps and vaporizers, buffer storage, pre-cooling device and dispensers.

The (ISO 19880-1, 2020) standard contains a section on risk management where risk assessment is included as well as mitigation measures (see Section 5.1 of this report), safety distances and barriers against non-hydrogen hazards. Other sections refer to, in a non-exhaustive list:

- Safety and operation of hydrogen supply, which covers hydrogen onsite generation, hydrogen delivery and pipeline;
- Safety of equipment and components, which includes recommendations for e.g. piping, storage, and compressors, as well as hazardous area classification;
- Safety of dispensing systems, providing recommendations on several aspects e.g. dispensing systems safety devices and hydrogen components, hazardous areas around the dispenser, and operation, maintenance and inspection of gaseous hydrogen fuelling stations;
- Electrical;
- Instrumentation and control systems;
- Operation;
- Inspection and maintenance;
- The standard's Annex A on safety methodologies and risk assessment includes in A.2.2 example safety distances from different countries/regions (status in 2016) – these figures are not meant to be a recommendation for these applications; and
- Its Annex F provides information on potential countermeasures for unsuitable fuelling protocols.

There are other relevant documents that are part of the ISO 19880 standard series (Gaseous hydrogen – Fuelling Stations):

- The standards that have currently been published are:
  - ISO 19880-2. Gaseous hydrogen – Fuelling stations – Part 2: Dispensers and dispensing systems;
  - ISO 19880-3:2018. Gaseous hydrogen – Fuelling stations – Part 3: Valves;
  - ISO 19880-5:2019. Gaseous hydrogen – Fuelling stations – Part 5: Dispenser hoses and hose assemblies (review is under development);
  - ISO 19880-8:2019 (plus 2021 amendment). Gaseous hydrogen – Fuelling stations – Part 8: Fuel quality control (review is under development); and
  - ISO 19880-9:2024. Gaseous hydrogen – Fuelling stations – Part 9: Sampling for fuel quality analysis.
- The standards that are currently under development or in draft are:
  - ISO/DIS 19880-7. Gaseous hydrogen – Fuelling stations – Part 7: Rubber O-rings; and
  - ISO/AWI TS 19880-10. Gaseous hydrogen – Fuelling stations – Part 10: Mobile fuelling stations.

5.2.2 ISO 17268

The (ISO 17268, 2020) standard 'Gaseous Hydrogen Land Vehicle Refuelling Connection Devices', soon to be replaced by ISO/FDIS 17268-1 was prepared by (ISO/TC 197, 1990), in collaboration with the Technical Committee CEN/TC 268 (Cryogenic vessels and specific hydrogen technologies applications) responsible for the publication of the document under Vienna Agreement as an EN ISO standard.

This standard is applicable to refuelling connectors with nominal working pressures of up to 70 MPa. The components of a connector are the receptacle and protective cap which are mounted on the vehicle, the nozzle and the communication hardware. The (ISO 17268, 2020) standard does not apply to connectors used for dispensing of blends of hydrogen with natural gas.

This standard contains specific sections on design and construction requirements for nozzles and receptacles, and two annexes on receptacle/nozzle interface envelope and hydrogen receptacles. In addition, there are sections covering design verification test procedures, instructions and marking.

ISO 17268-1 is dedicated to flowrates up to 120 g/s, whereas ISO 17268-2 aims to address flowrates from 121g/s to 300 g/s dedicated mainly to heavy-duty applications.

5.2.3 ISO 19885-1

The (ISO 19885-1, 2021) standard (Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 1: Design and development process for fuelling protocols) was prepared by (ISO/TC 197, 1990). This document focuses on fuelling protocols for gaseous hydrogen dispensing to hydrogen powered vehicles; Annex A of the standard provides specific requirements for road vehicles at public fuelling stations and is based on (ISO 19880-1, 2020). This document does not cover dispensing to gaseous hydrogen vehicles with a hydride-based hydrogen storage system.

This standard includes a section on the general description of the process for the design and development of a fuelling protocol, as well as sections on the definition of fuel protocol requirements for dispensing including e.g. definition of the fuelling envelope, fuelling protocol design and definition including e.g. communications between vehicle and dispensing system, development and verification of the fuelling protocol, and validation of the fuelling protocol in the dispenser control systems.

There are other documents being drafted as part of the ISO 19885 standard series 'Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles':

- ISO/AWI 19885-2. Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 2: Definition of communications between the vehicle and dispenser control systems; and
- ISO/AWI 19885-3. Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles.

5.2.4 EN 17127

The (BS EN 17127, 2024) standard 'Outdoor Hydrogen Refuelling Points Dispensing Gaseous Hydrogen and Incorporating Filling Protocols' was prepared by Technical Committee CEN/TC 268, based on content within (ISO 19880-1, 2020). This document defines the minimum requirements for the interoperability of hydrogen refuelling points dispensing gaseous hydrogen to vehicles compliant with UN R134 (Regulation No. 134), and Regulation (EC) No 79/2009 (out of force since July 2022). (UNECE, 2015).

This standard includes sections on general requirements for hydrogen refuelling points, requirements for the fuelling protocol including process limits, vehicle to station communications, pressure and temperature control faults, overpressure protection, and inspection and validation of hydrogen refuelling points. This document also contains annexes such as Annex B which includes some examples of countermeasures for unsuitable fuelling protocols.

5.2.5 Other hydrogen standards

There are other hydrogen standards which, although they are not specific for gaseous hydrogen refuelling stations, may provide requirements that could also be relevant.

5.2.5.1 ISO/TR 15916

The (ISO/TR 15916, 2015) 'Basic Considerations for the Safety of Hydrogen Systems' is an informative technical report which was prepared by (ISO/TC 197, 1990). This technical report contains generic guidance for the use of gaseous and liquefied hydrogen, as well as for the storage of hydrogen in either of these or other forms (hydrides). This document provides information on properties of hydrogen (general, selected thermophysical and basic combustion properties), safety considerations for the use of hydrogen in its gaseous or liquid forms, and mitigation and control of hazards and risks.

The latter section covers a broad range of topics e.g. strategies to prevent the formation of unwanted hydrogen/oxidiser mixtures, detection considerations for hydrogen gas and for fire, considerations for facilities (e.g. location, exclusion zones, protecting barricades, safety control equipment, ventilation, alarms and warning devices, fire protection and firefighting), considerations for operations, and recommended practices for organisations. (ISO/TR 15916, 2015) is currently under development in (ISO/TC 197, 1990) with a view to a revision being published as a technical specification (ISO/TS 15916).

5.2.5.2 NFPA 2

The NFPA 2 standard: Hydrogen Technologies Code (NFPA 2, 2023) provides fundamental safeguards for the generation, installation, storage, piping, use and handling of GH_2 and LH_2, for stationary, portable and vehicular infrastructure applications.

The NFPA 2 standard does not apply to the design of components related to the transport of hydrogen or propulsion of hydrogen motor vehicles, mixtures of GH_2 and other gases with a hydrogen concentration of less than 95% by volume, or metal hydride materials outside metal hydride storage systems.

The standard contains specific sections on GH_2 and LH_2 where bulk systems are covered, as well as specific sections on GH_2 vehicle fuelling facilities and LH_2 fuelling facilities.

5.2.5.3 ANSI/AIAA G-095A-2017

The (ANSI/AIAA G-095A, 2017) Guide contains guidelines for safely storing, handling, and using hydrogen in gaseous (GH_2), liquefied (LH_2), slush (SLH_2), or solid (SH_2) forms, whether used as a propellant or nonpropellant. Topics covered include sections on hydrogen properties and hazards, materials compatibility, facility design, design of components, detection, and transportation. It also covers various operational issues and emergency procedures. Additional information regarding codes, standards, and regulations, as well as a sample safety data sheet, training examples, and other useful material are referenced and can be found in its annexes. The guide provides a minimum set of practical guidelines for safe hydrogen use. The guide is more comprehensive for liquid hydrogen than gaseous, as it is more focused on aerospace applications instead of HRS.

5.2.5.4 Other International Standards for hydrogen refuelling stations

Other standards related to gaseous and liquefied hydrogen fuelling stations which might be useful in the development of refuelling interfaces and equipment include, but are not limited to:

- BS ISO 15859-2:2004 Aerospace series. Space systems. Fluid characteristics, sampling and test methods. Hydrogen;
- (ISO 19880-1, 2020) Gaseous hydrogen. Fuelling stations. General requirements;

- (ISO 19880-2, 2025) Gaseous hydrogen. Fuelling stations. Dispensers and dispensing equipment;
- 12/3025963 DC BS ISO 15399. Gaseous hydrogen. Cylinders and tubes for stationary storage;
- PD ISO/TR 19811:2017 Gas cylinders. Service life testing for cylinders and tubes of composite construction;
- ASTM D7606 - 17 Standard Practice for Sampling of High Pressure Hydrogen and Related Fuel Cell Feed Gases;
- 18/30295505 DC BS EN ISO 19884. Gaseous hydrogen. Cylinders and tubes for stationary storage;
- BS ISO 19880-3:2018 Gaseous hydrogen. Fuelling stations. Valves;
- BS EN ISO 17268:2020 Gaseous hydrogen land vehicle refuelling connection devices;
- BS ISO 19880-5:2019 Gaseous hydrogen. Fuelling stations. Dispenser hoses and hose assemblies;
- BS ISO 19880-8:2019 Gaseous hydrogen. Fuelling stations. Fuel quality control;
- BS EN ISO 11114-1:2020 Gas cylinders. Compatibility of cylinder and valve materials with gas contents. Metallic materials;
- BS EN 17339:2020 Transportable gas cylinders. Fully wrapped carbon composite cylinders and tubes for hydrogen;
- BS EN 17533:2020 Gaseous hydrogen. Cylinders and tubes for stationary storage;
- BS EN 17127:2020 Outdoor hydrogen refuelling points dispensing gaseous hydrogen and
- incorporating filling protocols;
- BS EN ISO 20088-2:2020 Determination of the resistance to cryogenic spill of insulation materials. Vapour exposure;
- BS EN ISO 20088-3:2019 Determination of the resistance to cryogenic spillage of insulation materials. Jet release;
- BS EN ISO 20088-1:2016 Determination of the resistance to cryogenic spillage of insulation materials. Liquid phases;
- BS 6364:1984 Specification for valves for cryogenic service;
- BS 5429:1976 Code of practice for safe operation of small-scale storage facilities for cryogenic liquids;
- BCGA CP 33 The bulk storage of gaseous hydrogen. BCGA Revision 1: 2012 (BCGA CP33, 2012); and
- BCGA CP 36 Cryogenic liquid storage at users' premises. BCGA Revision 1: 2024 (BCGA CP36, 2024).

5.2.5.5 ISO 13984:1999

The (ISO 13984, 1999) standard 'Liquid hydrogen – Land vehicle fuelling system interface' [soon to be replaced by ISO DIS 13984], a key liquid hydrogen refuelling standard, was prepared by (ISO/TC 197, 1990). This international standard is applicable to the design and installation of liquid hydrogen (LH_2) fuelling and dispensing systems for land vehicles. This includes design parameters, testing guidance, and training and facility information on dispensing systems (i.e. systems between an LH_2 tank and a vehicle). In particular, its Section 4.2.6 "Vehicle refuelling connections" provides best practice for connections that are often connected and disconnected. (ISO/TC 197, 1990) is in the process of revising standards relating to the refuelling of vehicles with liquid hydrogen, including revision of ISO 13984.

5.2.5.6 TS 19889-1

The technical specification (TS 19889-1, 2025) 'Hydrogen technologies – Interoperability – Part 1: Interface Between Gaseous Hydrogen Trailer and Hydrogen Fuelling Station' is under development within (ISO/TC 197, 1990). This Technical Specification will address general safety requirements of the interface between a hydrogen gaseous trailer and the refuelling station to enhance their interoperability. This work is essential for the large-scale deployment of hydrogen applications. The work encompasses the equipment (e.g. specific hardware formats used to interface for various functions such as hydrogen transfer, instrument gas control, flexible hose, vent system, safety barriers and prevention measures, *etc*.), manual procedures, automated protocols, and safety aspects related to their interoperability.

5.2.6 Explosion venting standards

Loss of containment of hydrogen in enclosed spaces could result in an explosion if the formed explosive atmospheres finds an ignition source. If the prevention measures implemented are not sufficient to mitigate the risk to tolerable levels, explosion mitigation strategies should be considered as part of the design, for instance, explosion venting. International standards have been developed to define the requirements in area, installation and inspection of explosion venting devices. Such standards are based on empirical correlations from data of explosions for different substances, for which assumptions and limitations are specified (these assumptions and limitations must be validated for the application before application). The following are just some example standards, but exercising due diligence is advised as to the suitability of their application.

These standards give vent areas so that the structure is undamaged after the explosion venting, but in the case of dispensers allowing some plastic deformations may result in required vent areas that can be accommodated in dispensers. Further experimental testing would be required to verify explosion vents in cases where plastic deformations are tolerated.

5.2.6.1 NFPA 68

The (NFPA 68, 2023) standard 'Explosion Protection by Deflagration Venting' applies to the design, location, installation, maintenance, and use of devices and systems that vent the combustion gases and pressures resulting from a deflagration within an enclosure so that structural and mechanical damage is minimised.

Section 6 of the standard contains a section on fundamentals of venting of deflagrations which includes e.g. enclosure design and support, gas deflagration fireball dimensions and definition of independent vent. Other sections covered in this standard include, but are not limited to, venting deflagration of gas mixtures and mists, venting of deflagrations of gases and dusts in pipes and ducts operating at or near atmospheric pressure, and details of deflagration vents and vent closures. The latter covers, for example, requirements for normally open vents, normally closed vents and equipment vent closures. There is also a section on inspection and maintenance. Relevant information from annexes include Annex E which discusses a methodology for estimating fundamental burning velocity, Annex G which explains a methodology for calculating the correction factor due to increased vent panel mass, and Annex K provides an example vent sizing for hydrogen mixtures.

5.2.6.2 BS EN 14994

The standard (BS EN 14994, 2007) 'Gas Explosion Venting Protective Systems' was prepared by Technical Committee CEN/TC 305 (Potentially explosive atmospheres - Explosion prevention and protection), under a mandate given to CEN by the European Commission and the European Free

Trade Association, and supports essential requirements of EU Directive 94/9/EC. This EU Directive, on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres, was repealed by Directive 2014/34/EU.

This European standard specifies the basic design requirements for gas explosion venting protective systems. The (BS EN 14994, 2007) standard is one in a series of three standards on gas explosion venting to be used together; the other two standards in this series are:

- (BS EN 14797, 2006). Explosion venting devices; and
- (BS EN 14460, 2018). Explosion resistant equipment.

The (BS EN 15089, 2009) standard 'Explosion Isolation Systems' should also be considered.

The BS EN 14994 standard is applicable to:

- Vent sizing to protect against the internal pressure effects of a gas explosion;
- Flame and pressure effects outside the enclosure;
- Recoil forces;
- Influence of vent ducts; and
- Influence of initial temperature and pressure.

The BS EN 14994 standard is not applicable to:

- Fire risks arising either from materials processed, used or released by the equipment or from materials that make up equipment and buildings;
- Design, construction and testing of explosion venting devices, which are used to achieve explosion venting; and
- Protection against overpressures caused by events such as overfilling, overpressurisation, fire engulfment, overheating, *etc*.

The BS EN 14994 standard contains, amongst others, sections covering venting of enclosures, venting of isolated compact enclosures (with methods to size vent openings), supplementary design aspects (with methods to estimate flames ejecting from a vent opening and maximum external peak pressures for air/gas mixtures ignited in a compact enclosure and maximum recoil forces) and information for use. In addition, Annex A explains a method for the assessment of the level of congestion in rooms containing turbulence including elements.

5.2.6.3 EN 14797

The standard (BS EN 14797, 2006) 'Explosion Venting Devices' was prepared by Technical Committee CEN/TC 305 under a mandate given to CEN by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s).

This European standard provides the requirements for venting devices used to protect enclosures against the effects of internal explosions arising from the rapid burning of suspended dust, vapour or gas contained within. It includes requirements for the design, inspection, testing, marking, documentation and packaging. Flameless explosion venting devices are treated in a separate standard.

The EN 14797 standard contains, amongst others, sections covering design requirements, types of explosion venting devices (with additional information in Annex A), back pressure supports and testing of explosion venting devices.

5.2.6.4 EN 14460

The standard (BS EN 14460, 2018) 'Explosion Resistant Equipment' was prepared by Technical Committee CEN/TC 305 under a standardisation request given to CEN by the European Commission and the European Free Trade Association and supports essential requirements of EU Directive(s).

This European standard specifies requirements for explosion resistant equipment which will be able to withstand an internal explosion without rupturing and will not give rise to dangerous effects to the surroundings. It is applicable to equipment (vessels and systems) where explosions are considered to be an exceptional load case.

This standard is valid for atmospheres having absolute pressures ranging from 800 mbar to 1100 mbar and temperatures ranging from −20 °C to +60 °C. This standard may also be helpful for equipment intended for use in atmospheres outside the validity range stated above, as this subject is not covered by specific standards. This standard applies to equipment and combinations of equipment where deflagrations may occur. This standard is only applicable for equipment where metallic materials provide the explosion resistance.

The EN 14460 standard contains, amongst others, sections covering explosion pressure shock resistant equipment where information about e.g. design pressure, design temperature and additional loads is explained, and explosion pressure shock resistant design. Information in annexes include, for example, calculation of design pressure for single vessels and explosion in pipes and interconnected vessels.

5.2.6.5 BS EN 15089

The (BS EN 15089, 2009) standard 'Explosion Isolation Systems' was prepared by Technical Committee CEN/TC 305 under a mandate given to CEN by the European Commission and the European Free Trade Association and supports essential requirements of EC Directive(s).

This European standard describes the general requirements for explosion isolation systems and specifies methods for evaluating the efficacy of the various explosion isolation systems, and methods for evaluating design tools for such explosion isolation systems when applying these in practice. This European Standard also sets out the criteria for alternative test methods and interpretation means to validate the efficacy of explosion isolations.

This standard is applicable only to the use of explosion isolation systems that are intended for avoiding explosion propagation between interconnected enclosures.

The (BS EN 15089, 2009) standard contains, amongst others, sections covering types of explosion isolation systems, requirements of explosion isolation components e.g. detection devices, design (including information in an annex on verification of design methods) and testing.

5.2.7 Hazardous Area Classification Standard, Codes and Guidance

A number of different methodologies exist to establish hazardous area classification and their extents in an outdoor environment. These are generally based on calculations using the pressure of the system and the anticipated size of the release.

To comply with directive 99/92/EC (also known as ATEX 137 or the ATEX Workplace Directive) related to the health and safety protection of workers who are potentially at risk from explosive atmospheres, different standards can be used. A commonly used standard is the IEC 60079-10-

1:2020 (IEC 60079-10-1, 2020), which can be used for the classification of hazardous areas indoors and outdoors and establishing the extent of these hazardous areas.

Published UK based guidance can be obtained from Energy Institute EI 15 and British Compressed Gas Association (BCGA) recommended Codes of Practice. (BCGA CP4, 2020), (BCGA CP33, 2012) and GN13 (BCGA GN13, 2021) are especially pertinent for the hydrogen refuelling station.

Appendix A of (MultHyFuel D3.6, 2024) presents a detailed description of hazardous area classification definitions, of the standards/codes/guidance for the determination of hazardous zones and extents, and available dispersion methodologies accepted by the standards and codes.

5.2.8 Separation distances standards, hazard ranges obtained in MultHyFuel

(MultHyFuel D3.6, 2024) indicates a list of references which were reviewed for their approaches in determining minimum separation distances: ISO 19980-1:2020 (Section 5.2.1), (NFPA 2, 2023), (EIGA Doc 75/21, 2021), BCGA Guidance Note 41 (BCGA GN41, 2020) and (IEA Hydrogen TCP Task 43, 2024). The full benchmarking is provided in Appendix B of (MultHyFuel D3.6, 2024). Separation distances methodologies are not prescribed at the European level, and different approaches will therefore be taken by the different countries. This includes the consideration of different hazard scenarios.

5.2.8.1 EIGA document 75/21

EIGA document 75/21 'Methodology for determination of safety and separation distances' (EIGA Doc 75/21, 2021) describes the basic principles to calculate appropriate safety and separation distances for the industrial gases industry.

This methodology can be explained in four steps:

1. Identify the hazard sources and events, taking into account the likelihood;
2. Calculate the effects on neighbouring objects and population taking into account mitigating factors;
3. Determine the safe distance to each object or population to meet the minimum hazard criteria; and
4. Consider additional prevention or mitigating factors and re-calculate safe distance.

Section 3.3 of (MultHyFuel D3.6, 2024) provides more detail about the methodology described in (EIGA Doc 75/21, 2021).

5.2.8.2 BCGA GN 41

Section 3 of BCGA Guidance Note GN 41 'Separation distances in the gases industry' (BCGA GN41, 2020) focuses on providing some explanation of what separation distances are (and what they are not) and also defines some safety distance and hazardous area. Section 6 focuses on the measurement of separation distances. The appendices of this guidance note provide various separation distances that have been published in different BCGA documents, and provides guidelines on their implementation:

- Appendix 1 of (BCGA CP4, 2020): Gas supply and distribution systems (excluding acetylene);
- Appendix 8 of (BCGA CP33, 2012): The bulk storage of gaseous hydrogen at users' premises; and
- Appendix 10 of (BCGA CP41, 2018): The design, construction, maintenance and operation of filling stations dispensing gaseous fuels.

5.2.8.3 IEA Hydrogen TCP Task 43

The Hydrogen Technology Collaboration Programme (Hydrogen TCP) is organised by the International Energy Agency (IEA). The Hydrogen TCP is divided into tasks that address specific topics that aim to tackle issues related to the implementation of hydrogen technologies and applications (IEA Hydrogen, 2024).

Task 43 of the Hydrogen TCP focuses on safety and regulations, codes and standards of large-scale hydrogen energy applications, where subtask C and subtask D refer to safety distance methodologies and hazardous areas methodologies, respectively. (IEA Hydrogen TCP Task 43, 2024).

Section 3.5 of (MultHyFuel D3.6, 2024) provides, in Table 14, a harm criteria comparison that was undertaken as part of (IEA Hydrogen TCP Task 43, 2024).

5.3 Regulated mitigation measures

To limit the potential impact of hazards, mitigation measures should be considered and put in place. Mitigation measures to improve system safety are included in (ISO 19880-1, 2020) to be complied with by all Member States. All identified hazardous areas must be well ventilated. A common practice is also to add fire protection walls which allow the reduction of safety distances, and buildings enclosing and surrounding potentially explosive atmospheres must be reinforced and made of non-combustible materials.

As mentioned in Section 3, Project Deliverable D1.4 (MultHyFuel D1.4, 2024) sets out some examples of regulated mitigation measures that are enforced in a number of countries such as Austria, Germany, Finland, France and The Netherlands. Operators will need to check which mitigation measures are compulsory in their country of operation. The deliverable also provides some details on other obligations, with some generic ones being highlighted below.

5.3.1 Other obligations

As a general rule, refuelling stations should be built in a well-ventilated area, outdoors. If some of the equipment is located in closed spaces, the risk assessment should determine ventilation and gas detection requirements. In line with all country's respective legislations, a risk assessment is likely to conclude that an emergency shutdown system is required, this is also stated in (ISO 19880-1, 2020). If mechanical ventilation is required, it should be switched on automatically when the emergency shutdown is triggered.

Requirements and/or guidance on the set point of hydrogen gas sensors to trigger an alarm and shutdown are available from a number of guidance, codes and standards, e.g. (HSE GB, 2004), (Legifrance Circulaire n° 3 , 1985), (IEC 60079-29-2, 2015), (ISO 19880-1, 2020), (ISO 26142, 2010) *etc*. The requirements will vary from country to country and will also depend on a number of factors, namely the potential type and volume of release, ventilation conditions as well as sensor response time, and importantly also on the location where the equipment is deployed. In the absence of local requirements, the risk assessment and functional assessment must review the gas sensors as part of the safety instrumented system, including the selection of the set point of the detector to take into account, the response time required to avoid the hazardous scenario.

As a general rule, the type of fire extinguisher for hydrogen fires is not prescribed in European standards and that the choice of fire extinguisher would be based on a risk assessment by the operator/ dutyholder, or sometimes recommended by local fire authorities. In Great Britain for example, there is a British Standard on the selection and positioning of fire extinguishers: (BS 5306-

8, 2023), so this would be used to inform the risk assessment as to the choice of fire extinguisher. It is important to be aware that hydrogen fires are not considered to be extinguished until the supply of hydrogen has been shut off or exhausted since there is a danger of reignition and explosion. In summary, fire extinguishers are not used on hydrogen fires in practice, as H_2 can reaccumulate and relight around the person using the extinguisher. A CO_2 extinguisher will not help extinguish the hydrogen fire itself. The best advice would be to shut off the hydrogen supply and let it run out and follow advice from local fire authorities. Only when there is no hydrogen left, i.e. when H_2 containment is confirmed to be re-established, should any (remaining) fire then be extinguished in line with its origin class. It is however worth noting, that although fire extinguishers may not be appropriate for hydrogen fires, they may still be needed in the vicinity to tackle incipient fires (e.g. paper and other combustible debris, *etc*.).

5.4 Design

Once the hazardous area/ zone classifications of the multifuel station have been established, suitable control and mitigation measures need to be applied through appropriate installation design, use of compliant equipment, safe systems of work and competent personnel. For example, this is mandated by DSEAR[3] in GB, and the BCGA Guidance Note (BCGA GN13, 2021) provides guidance on the application of the GB DSEAR Regulations and related regulations for compressed gases. Section 7 of the GN13 (BCGA GN13, 2021) lists the following example generic measures:

- Separation: separation distances as per (BCGA CP41, 2018) for gases industry, physical barriers, safety signs and warning notices, etc. Walkaways for personnel, segregation of incompatible materials, control access, reduce number of people being exposed;
- Appropriate equipment, e.g. ATEX-rated;
- Manage refuelling flow rate;
- Material compatibility and selection;
- Electrical engineering controls. Electrical equipment in hazardous area. Earthing and bonding, lightning protection;
- Isolation;
- Portable and temporary-use equipment and tools;
- Safe systems of work;
- Competent personnel;
- Appropriate clothing; and
- Management of ancillary service providers, housekeeping, vegetation and vermin.

5.4.1 Dispenser risk reduction measures

The dispenser is a critical piece of equipment in a service station. The CFE is the loss of containment of hydrogen, which can lead to explosions in the open air or in a confined environment (VCE inside the dispenser) or to jet fires or flashfires. This high risk of leaks is related to the high numbers of fittings in the different dispensers, equipment failure, human error during maintenance, bad connections to the hose or nozzle, impact risks like vehicle crash, or domino effects. Besides that, for bulk H_2 storage and processing, the risk reduction measures for dispensers would be key to reducing risks on the HRS.

(ISO 19880-1, 2020) Sections 5 and 8 as well as Annex B define the minimum design requirements for dispensers, including assembly, dispensing system hydrogen components, location, hazardous area zoning, system process control, safety devices, *etc*.

[3] UK enactment of The Explosive Atmospheres Directive (99/92/EC) and Chemical Agents Directive (98/24/EC)

MultHyFuel Deliverable (MultHyFuel D3.1, 2021) Section 4.1.4 describes some measures for conventional refuelling stations. The dispenser is installed on a so-called under-dispenser containment (UDC) sump, providing containment of product leaks that may occur from dispenser hydraulics or pressurised mechanical connection under the dispenser and equipped with a number of additional safeguards against product loss as a result of mechanical impact, such as:

- Crash protection, e.g. by bollards around the dispenser;
- A shear valve in the UDC for closing off fuel supply from the storage tank upon vehicle impact; and
- A breakaway coupling at the dispenser hose for stopping the flow from the dispenser in case of hose rupture due to vehicle drive away.

MultHyFuel Deliverable (MultHyFuel D3.2, 2021) Tables 13 and 14 give a list of example safety barriers from the MultHyFuel benchmarking exercise, and those relevant to the H_2 dispenser are as listed here, in no particular order.

- Shutoff valve including a Safety Integrity Function (SIF) automatic sequence;
- Emergency shutdown system or device (e.g. push button leading to actions to shut down the hydrogen system);
- Pressure monitoring on piping/storage to detect a leak associated with safe automatic actions to shut down the hydrogen system;
- Pressure relief valve to avoid overpressure in equipment. Verification of best response time achievable;
- Pressure switch (e.g. PSHH leading to an automatic emergency venting);
- Flame detection associated with safe automatic actions to shut down the hydrogen system;
- Temperature switch (e.g. TSHH leading to an automatic emergency shutdown);
- Hydrogen detectors or sensors linked to ESD and shut off valves associated with safe automatic actions to shut down the hydrogen system and reduce release inventory. Hydrogen detection apparatus used in hydrogen sensing and monitoring systems should meet the accuracy requirements of (ISO 26142, 2010);
- Breakaway couplings at the dispenser hose for stopping the flow from the dispenser in case of hose rupture due to vehicle drive away;
- Excess flow valves in the pipework upstream of the dispenser;
- Non-return valves in the pipework upstream of the dispenser;
- Pressure relief valves in the pipework upstream of the dispenser;
- Rupture discs in the pipework upstream of the dispenser;
- Explosion vent (e.g. container);
- Separation distances;
- Crash-barrier around equipment as passive barrier to avoid external impact from vehicles;
- Shear valves in the under-dispenser containment sump (which shuts off the flow of fuel in case of crash on the dispenser);
- Firewalls to avoid escalation/domino effects;
- Gas detectors and emergency shutdown protocol to reduce release inventory; and
- Automatic emergency Shutdown Device (ESD) and shut-off valves as part of a SIF to reduce release inventory.

Pique *et al*. (2022) categorises some of the above safety barriers into classes:

- Detection systems
    - H_2 flame and gas detection with associated emergency protocols (e.g. alarms, shutdown, *etc*.)
- Importance of isolation device

- Shut-off valves to isolate equipment in case of burst or dysfunction.

- Choice of materials
    - H_2 compatible materials (e.g. for fittings, piping, seals, *etc.*)
- Location of equipment to limit potential domino effects
    - Safe location of outlet vent lines.
    - Location of venting of TPRD to avoid impact on other installations.
- Addition of prevention and/or mitigation barriers
    - Flowrate restriction orifices, breakaways, quick couplings, pressure safety valves, bursting discs, explosion panels, concentration sensors, pressure and temperature sensors, flow meter.
- Key parameters to monitor and control
    - Temperature and pressure of the type-III and IV cylinders should be considered in the transfer protocol from compressor/buffer to fuel cell vehicle.
- Management of ignition sources
    - Comply with Hazardous Area Classification zoning rules.
    - Explosive Atmosphere (ATEX)-certified devices.

(MultHyFuel D3.6, 2024) Section 1.6. makes reference to the following in terms of dispenser design good practice:

- Openings/ apertures for natural ventilation and wind-reinforced ventilation can reduce H_2 accumulation;
- Horizontal ventilation apertures allow dilution benefits offered by the wind, whatever the wind orientation;
- H_2 detection inside the dispenser with associated emergency protocol and actuation in case of detection and alarm at a preset threshold;
- (Automatic) excess flow valves and shut-off valves in the pipework upstream of the dispenser to stop flow in case of catastrophic release;
- Remotely operated shut off valves (ROSOVs);
- Dedicated explosion venting panels:
    - These should be built to one of the recognised standards such as (BS EN 14994, 2007) or (NFPA 68, 2023). For a 1 m^3 dispenser housing as used in the experiment, these give vent areas of 0.9 and 1.2 m^2 respectively.
    - In the experiment, there was a tall relatively thin dispenser with a weak panel of 0.5 m^2 located on the top (equal to the entire footprint). This is below that specified in the relevant standards, but extra venting was available through the ventilation apertures and the open bottom of the dispenser. The dispenser also experienced some plastic deformation, but the standards specify a vent area such that no plastic deformations occur.
    - If explosion vent panels are not sized to one of these standards or similar to the case considered experimentally within the MultHyfuel project, there should be modelling or experimental testing to demonstrate their suitability.
    - The design of dispenser housings and their explosion venting panels should be a topic of future research, but a general principle is that dispensers should be shorter, however it should be taller than the average height of a person (at least 1.8 m in height), rather than tall and thin, to allow for a suitably-sized explosion panel. (N/B: In the current project case study, the aspect ratio H/L/W was approximately 2 m/1 m/0.5 m, and incorporated an explosion panel equal to the whole footprint of the dispenser (1 m by 0.5 m). According to project experimental results, this vent

opening with the aforementioned aspect ratio, was considered sufficient to mitigate the consequences of the potential explosion inside the dispenser).

- Location of apertures, specifically for large openings and other openings dedicated to explosion venting, to direct the hazard and limit damage and injuries. In practice this is likely to be openings located in the upper segment of the dispenser and pointing vertically upwards away from the customer refuelling the vehicle. Orientating the vent panels to a closely located wall would restrict the venting and as such would require even larger vent panels;
- Early detection of releases from filling hose and associated efficient emergency protocol (requirement: maximum detection and reaction time can vary between 2 s and 5 s depending on local regulations);
- Flow restrictor upstream of the hose to limit the flow rate in case of full-bore rupture, but compliant with vehicle filling requirements;
- Use of breakaway coupling to isolate the system and limit hydrogen inventory release in case of full-bore rupture on hose filling;
- Holsters for the dispenser;
- Limit ignition sources and combustible materials on the forecourt in a 6 m radius around the dispenser. Installation of electrical equipment must follow the Hazardous Area Classification of the installation;
- Ensure grounding of H_2 equipment;
- Canopy structure should be designed in a way that avoids accumulation of any hydrogen release (e.g. inclined canopy roof; as well as sufficient distance between dispenser roof and canopy; individual canopies per dispenser so any potential collapse is localised); and
- Electrostatic discharge protection.

The concluding section in MultHyFuel Deliverable 3.6 highlights some additional dispenser equipment measures:

- Hoses shall be free from cuts, cracks, bulges or blisters, and kinks [(ISO 19880-1, 2020) Section 8.6] and shall be tested for leaks according to the manufacturer's specific procedures requirements;
- Hoses, nozzles and breakaways shall be examined monthly or according to the manufacturer recommendations and shall be maintained in accordance with the manufacturer's instructions [(NFPA 2, 2023) Section 10.6.2.1]. During inspection, attention shall be paid to the integrity of the electrical continuity, end fittings and evidence of physical damage (EIGA IGC Doc 15/06/E, 2006);
- Pressure integrity checks in the dispenser shall be performed regularly, including all the fittings that can potentially generate a release in order to justify hole size selection for HAC; and
- Frequent maintenance and inspection of H_2 fittings are required, especially with the uncertainty surrounding hole size assumptions in the calculations for the zoning related to hazardous area classification.

5.4.2 Forecourt layout

(MultHyFuel D3.2, 2021) Tables 13 and 14 as well as its Sections 5 to 7 suggest the following example safety barriers for the forecourt layout:

- Segregation of hazardous materials;
- Separation distances;
- Crash-barrier around equipment as passive barrier to avoid external aggression (e.g. from vehicle impact) and collision sensors that automatically shut down gas equipment; and

- Firewalls to help prevent escalation/ domino effects

Pique *et al*. (2022) categorises a number of example safety barriers into classes:

- Design of refuelling station:
    - Design of canopy roof to limit degree of confinement.
    - Prefer storage with open structure on the top or placed underground.
- Management of ignition sources:
    - Comply with Hazardous Area Classification.
    - Explosive Atmosphere (ATEX)-certified devices.

Based on MultHyFuel's experimental work in Workpackage 2 and risk assessment work in Workpackage 3, a number of safety barriers (flow restrictor, venting panel) and their impact on consequence distances were analysed. The following were established within MultHyFuel's scope, in terms of forecourt layout and separation distances around the hydrogen dispenser:

- Avoid the potential for a flammable atmosphere on the HRS, where possible;
- Any potential explosive atmospheres need to be classified (Hazardous Area Classification (HAC)) for each HRS;
- Crash barriers may help prevent initiating events;
- Firewalls and explosion walls may prevent escalation/ domino effects; and
- Breakaway and Restriction Orifice can strongly reduce the hazard extents of a hose rupture.

MultHyFuel found that a high-pressure release from the filling hose in the forecourt is potentially the worst-case scenario if considering hazards originating from the forecourt alone. From the work conducted within MultHyFuel, there was no evidence to suggest larger separation distances than Compressed Natural Gas (CNG). Calculations with Schefer Approach (Schefer, Houf, Bourne, & Colton, 2006) Schefer, Houf, Williams, Bourne, & Colton, 2007) show that, considering maximum delivery pressure, specific nozzle diameter for each fuel and ensuing jet fire due to hose full bore rupture with immediate ignition, the potential flame lengths and associated effects are significantly higher for CNG compared to H_2 (around 40% higher). The most severe consequence does not come from an explosion inside the dispenser if explosion venting panels are fitted. Excluding bulk storage and processing of hydrogen, MultHyFuel experimental work showed that jet fire is potentially the worst scenario related to the H_2 dispenser upon which its basis of safety should be designed. Hence, considering the jet fire scenario, but only if ignition probability and minimum ignition energy of hydrogen are not taken into account, larger separation distances for H_2 than those existing for CNG are possibly not necessary. A separation distance of approximately 6 m for a theoretical flow rate of 120 $g.s^{-1}$ has been established by MultHyFuel within its work scope (see Table 13), on the assumption that all industry good practice, i.e. relevant risk reduction measures have been adopted. *(NB: the current French regulation Arretée* (Légifrance Arrêté 1416, 2018) *recommends a separation distance 10 m for 120 $g.s^{-1}$ and of 8 m for 60 $g.s^{-1}$).* Separation distances for other countries can be found in (MultHyFuel D1.4, 2024). It is worth noting that flame length is not necessarily adopted as the separation distance. LFL (with or without a safety factor applied) could also be adopted as the relevant separation distance. (BCGA GN41, 2020) provides some context as to the meaning of separation distance.

As part of MultHyFuel's Workpackage 3, the Hazardous Area Classification of hydrogen refuelling stations was analysed and the following key points were identified, as also reported in (MultHyFuel D3.6, 2024):

- Any equipment and section of the installation in which there are elements bearing hydrogen need to be considered as part of the Hazardous Area Classification, considering the potential leak points, operational conditions, and type of fittings/materials used in the installation.
- The type of releases need to be defined for each part of the installation;
- For primary and secondary release, the selection of the representative hole criteria is critical for the determination of the type of zone and the associated extent. For more information, refer to the benchmarking detailed in Appendix A of MultHyfuel Deliverable (MultHyFuel D3.6, 2024);
- The type of ventilation, availability and degree of dilution provided is critical for the determination of the type of zone. For instance, releases due to a leak that could potentially be present for a short duration of time may result in a Zone 1 if the degree of dilution is low (see Table D.1 of IEC 60079-10-1 (IEC 60079-10-1, 2020));
- As per IEC 60079-10-1:2020 (IEC 60079-10-1, 2020), internal releases within enclosures, for instance inside the dispenser, should be considered with a low dilution if the background concentration exceed 25% of the LFL;
- Hazardous area classification methodologies define the extent of releases to the lower flammability limit (LFL). Due to uncertainties with respect to dispersion and ignition (modelling gives an average value of concentration over time and there is variability in the instantaneous concentration of the gas), it is recommended that designers consider the application of a safety factor to the LFL (e.g. 50% LFL) or release rate depending on the characteristics of the design;
- For the naturally ventilated dispenser considered in the experimental work (WP2) and theoretical analysis (HAC example calculations documented in (MultHyFuel D3.6, 2024) Appendices) performed in WP3, a minimum of Zone 1 with natural ventilation inside the dispenser was determined. For each application, an assessment of ventilation and release rate should be performed to consider a different type of zone;
- Non-hazardous zone inside the dispenser is not possible (for the theoretical work on WP3) due to high pressure inside the dispenser and Zone 2 can only be reached with mechanical ventilation at high flow rate. Mechanical ventilation at high flow rate within the dispenser will need to be demonstrable by the duty-holder/ operator;
- Local conditions of wind and temperature need to be taken into consideration because they have a significant influence on Hazardous Area Classification, specifically for the zoning of enclosures;
- Hole size selection and justification for H_2 technologies require further research and analysis. The use of small hole sizes of 0.025 mm^2 (d = 0.18 mm) for H_2 fittings need to be justified and used with caution. It is recommended that at the very minimum, pressure integrity checks in the dispenser are performed regularly, including all the fittings that can potentially generate a release.
- Frequent maintenance and inspection of H_2 fittings are required, especially with the uncertainty surrounding hole size assumptions in the calculations for the zoning related to hazardous area classification;
- The estimated extent of the zone is directly dependent on the assumed hole size generating such releases. For instance, for hole sizes of 0.025 mm^2, a hazardous zone ranging between 1.5 m to 2 m, depending on the dispersion tool used, would be obtained. However, if the type of elements, installation and operation would not allow the justification of a 0.025 mm^2 hole, but a larger hole size is more representative instead, for example 0.1 mm^2, the estimated hazard extent could increase to approximately 4 m using Phast and 6.5 m if using Quadvent;
- Within such hazardous zones, operators must consider the control of ignition sources (e.g. including considering that members of the public may not be wearing anti-static footwear)

and implement restrictions/ safety procedures and protocol around the dispenser within these zones in order to limit the presence of ignition sources. In addition, national/regional regulations may require control, inspection and monitoring of electrical equipment in hazardous areas;

- For external releases, several variables should be considered for the assessment, for example the wind conditions or potential physical obstructions that would result in an impeded jet;
- The methodology in Annex D of IEC 60079-10-1:2020 (IEC 60079-10-1, 2020) is not recommended for Hazardous Area Classification around Hydrogen vents for the conditions of the Hydrogen Refuelling Station (elevated pressure and release rates) because it is not possible to extrapolate and often the release rate will not be within the lines for jet, diffusive and heavy gas of Figure C.1 of the standard. So, the extent cannot be determined using this methodology;
- The only dispersion tool in this work that considers the effect of the wind is Phast or equivalent 2D-tools that can take into consideration weather and wind.

5.5 Refuelling operation

5.5.1 Operation

The (ISO 19880-1, 2020) standard (Gaseous hydrogen – Fuelling Stations – Part 1: General Requirements) defines the minimum requirements for the operation of gaseous hydrogen refuelling stations, including requirements on signage and labelling, warning signs, operational instructions, functional identification of control devices/ visual indicators/ fuelling assembly components/piping, data plate marking of equipment, training of personnel and emergency response planning. The standard also describes the important technical documentation which needs to be in place, e.g. those describing the installation (hazardous areas, venting, seismic, handling/ lifting), overview and functional diagrams, circuit diagrams, piping and instrumentation diagrams (P&IDs), parts list, maintenance and service manuals and refuelling station operating manuals.

Pique *et al*. (2022) also advises the avoidance of unloading operations during thunderstorms / inclement weather conditions.

As mentioned in Section 4.4.8, a key critical measure is to minimise the number of people in the vicinity of the dispensers during refuelling. This would mean that when a coach/ bus is refuelling at an HRS, it would be advisable for passengers to get off the bus and congregate at a safe location, before the commencement of the refuelling operation.

According to (ISO/TR 15916, 2015) 'Approved procedures' Section 7.6.2, manufacturers' operating manual and checklists shall be followed in all operations involving hydrogen systems. They should be developed by knowledgeable personnel and prepared with worker input, reviewed and approved by appropriate personnel prior to their use and should be easily accessible for who might use them. Procedures shall be established for expected service activities [(ISO 19880-1, 2020) Section 8.6].

According to H2Tools recommendations on operating procedures (H2Tools, 2024); procedures should define the personnel authorised to operate the system, the necessary training required, the PPE that shall be worn, the actions required to avoid leaks on the system and hydrogen/air mixtures – leak-free system and purging – and the emergency response to implement for safety management. They shall be reviewed periodically and a current version is recommended to be displayed in the room where the work is done or close to the H_2 facilities where operations are achieved. Regarding the hydrogen dispenser, they shall be established for the following operations:

- Leak checks;
- Start-up;
- Refuelling;
- Shut down; and
- Emergency shutdown.

In addition, checklists shall be attached to the defined procedures. They shall ensure that leak detection and fire alarm systems are available and functioning, and maintenance records are up to date.

The main operational recommendations related to the operation of dispenser equipment are listed below.

Hose:

- Before use, hose assemblies shall be tested by the component origin equipment manufacturer (OEM) or its designated representative at a pressure at least twice the maximum allowable pressure, as stated in Section 12.2 of [(ISO 19880-1, 2020)];
- Keep them in a secured place when not being used – not directly stored onto the ground; and
- Plan the distribution flexible replacement depending on its lifecycle.

Exchanger: Monitor the pressure or the cooling fluid flow in the cooling circuit using an instrumentation or an alarm commanding the compressor of the refrigeration loop to shut-down (INERIS, 2014).

Nozzle:

- Take care of the dispensing line by using the dedicated and adapted device for the H_2 tank connection – i.e. the nozzle;
- Connect and disconnect the nozzle from the dispenser without using any tools (INERIS, 2014); and
- The use of adapters shall be prohibited – i.e., an appropriate nozzle to be used at all times.

Regarding the control of the refuelling operation, the main recommendations are the following:

- Outside of normal operating hours, the hydrogen supply to the dispenser should be isolated at the source, and where appropriate, at the dispenser;
- Instructions for use of the hydrogen fuelling station dispenser by the general public shall be included on, or in the vicinity of each dispenser. These instructions shall include prohibitions against:
  — the use of adapters (e.g. 35 MPa vehicle fuelling from 70 MPa nozzle, or alternative fuel nozzles);
  — the fuelling of cylinder systems (whether in a vehicle or not) that are incompatible with the fuelling protocol employed at the station.

Regarding the control of ignition sources around the dispenser:

- Limit ignition sources and combustible materials on the forecourt in the 6 m radius around the dispenser;
- Within hazardous zones, operators must strongly consider the control of ignition sources and implement restrictions / safety procedures and protocol around the dispenser within these zones in order to limit the presence of ignition sources, including potential electrostatic ignition that may arise from members of the public carrying out the refuelling,

considering (ISO 19880-1, 2020) and (CGA H-7, 2024) Standard Procedures for Hydrogen Supply Systems; and

- For dispensing points, warning signs should be located within 3 m of the fuelling point, and should indicate [(ISO 19880-1, 2020)]:
  — no smoking, open flames, or other ignition sources;
  — power off and immobilise vehicle during fuelling; and
  — flammable gas.

Regarding the protection of people around the dispenser, the main operational recommendations are:

- Warning signs shall be placed to identify potential hazards: flammable fluids / hazardous areas / pressurised fluids / electrical hazards / hot or cold surfaces [(ISO 19880-1, 2020)];
- As a minimum, it is recommended that the pipes accessible to the public, or visible by the public, should be marked.
- Passengers of vehicles (i.e. buses or light vehicles) to get off the vehicle before refuelling operations. Only the person in charge of refuelling can stay close to the dispenser. [MultHyFuel D3.6, 2024]; and
- The fuelling station should have an emergency response plan (ERP) prepared in accordance with (ISO 14001, 2015) Clause 8.2. Emergency instructions shall be posted at the refuelling station in locations that are highly visible at each dispenser.

5.5.2 Inspection and maintenance

(ISO 19880-1, 2020) defines some minimum requirements for inspection and maintenance, including requirements for the inspection and maintenance programme, the testing and maintenance of gas detectors, filters and pressure release devices, hot work and if there are any modifications to the HRS and associated equipment. According to (ISO 19880-1, 2020):

- Procedures shall be established for expected service and maintenance activities. If necessary, these procedures shall address proper isolation of the system for worker safety, measures required during the maintenance or service activity to prevent contamination or air ingestion into the dispensing system, and steps required to return the system to operation;
- The dispensing system and fuelling assembly shall be visually inspected regularly to check that the assembly is free from damage. The fuelling hose shall be free from cuts, cracks, bulges or blisters, and kinks;
- The fuelling assembly shall also be periodically tested for leaks by an appropriate method, such as bubble testing or pressure decay testing. Parts such as the nozzle or breakaway coupling typically require a manufacturer's overhaul and retesting, or replacement at a regular interval. Refuelling hoses typically require replacement at a regular interval;
- Both manual and automatic isolation valves shall be periodically checked for functionality and leakage [(ISO 19880-1, 2020) §8.6];
- Pressure safety equipment shall be tested, inspected and either repaired or replaced at a regular interval, according to the manufacturer's specifications [(ISO 19880-1, 2020) §15.4]. For relief valves, this typically includes periodic lift tests, and manufacturer's overhaul and retesting, or replacement at a regular interval; and
- According to [(ISO 19880-1, 2020) §15.2], the gas detection system shall be maintained in accordance with the service requirements of the manufacturer. The service frequency shall be once per year as a minimum, or more often if specified by the manufacturer or required by the exposition of the detectors to substances reducing its lifetime.

It is also worth noting that for pressure equipment such as storage vessels or heat exchangers, inspection and maintenance programmes typically include periodic internal inspections and/or non-destructive testing, including periodic hydrostatic pressure testing. National legislation for the safe operation of pressure equipment often defines the need for third party involvement in the inspection and maintenance programme.

The MultHyFuel project HAZIDs brainstormed the following risk reduction measures for HRS inspection and maintenance [Pique *et al*., 2022]:

- Periodic control:
  Commissioning and periodic control for the integrity of H_2 equipment on the whole HRS (i.e. hoses, liquid tank or tube trailer, dispenser, piping, buffer storage).

In addition to the above measures, (MultHyFuel D3.6, 2024) suggests that:

- Frequent maintenance and inspection of H_2 fittings are required especially with the uncertainty surrounding hole size assumptions in the calculations for the zoning related to Hazardous Area Classification;
- Ensure integrity and compliance of electrical equipment with the Hazardous Area Classification of the installation during the lifetime of the dispenser; and
- Ensure the efficiency and reliability of grounding system for H_2 equipment.

NF M58-03 Sections 11.1.2 and 11.1.1 (AFNOR, 2013) stipulate that maintenance of the HRS facility must be performed by trained and authorised personnel according to procedures.

Procedures shall be established for the following maintenance operations:

- Cleaning;
- Modifications;
- Repairs; and
- Operation – what is outside normal operation, *etc*.

As for all facilities, it is recommended to set up a Management of Change (MoC) Framework for all permanent, temporary or emergency modifications to equipment, procedures and parts. It is important that all changes are reviewed and approved, by designated competent personnel, before they are implemented, and appropriate systems are in place to monitor and audit the management of change process. Roles and responsibilities of individuals and departments must be clearly defined.

According to the lessons learnt (BARPI, 2008) (FCHJU2 Hydrogen European Safety Panel, 2021) and work within MultHyFuel, the following recommendations can be established regarding maintenance:

- Keep equipment up to date and clean with appropriate inspection and maintenance regime;
- Practice preventative maintenance of equipment;
- Plan necessary and sufficient maintenance and inspection (included preventative maintenance);
- Protect hydrogen piping and equipment against potential accidental impact (by forklift trucks or water ingress or during maintenance activities); and
- Implement a safety management system (SMS) for the HRS, especially focusing on the training of maintenance staff regarding the specific risks of hydrogen and the automatic safety functions of the HRS.

6 Recommendations and technical suggestions to inform the development and/or update of Codes and Standards

This report gives recommendations on the configurations studied within the MultHyFuel project. Other possible configurations outside the scope of this project can require additional investigation.

6.1 Recommendations to inform Codes and Standards

Research **within the scope** of MultHyFuel has shown that the two most significant scenarios that require consideration when defining separation distances around a hydrogen dispenser are:

1. High pressure releases inside a dispenser, with ignition leading to a confined explosion; and
2. High pressure releases outside a dispenser, for instance from either hose rupture, or a drive-away event

In the case of a release inside the dispenser, the severity can be reduced significantly by the inclusion of sufficient apertures for natural ventilation and dedicated explosion venting panels, further recommendations are included below. When confined releases are managed adequately, and adequate measures to mitigate against releases in the event of a drive-away are in place, an external release from a hose rupture could be expected to become the dominant scenario defining the necessary separation distances.

6.1.1 Recommendations on design

Dispenser design:

- Dispenser design should incorporate openings/ apertures for natural ventilation and wind-reinforced ventilation to reduce the potential hydrogen accumulation in case of a loss of containment;
- Horizontal ventilation apertures in the upper areas of the dispenser (depending on geometry of the dispenser) are more efficient to benefit from wind, whatever the wind orientation;
- H_2 detection inside the dispenser with associated emergency protocol and actuation in case of detection and alarm at a suitable preset setpoint;
- Dedicated explosion panels
    - These should be built to one of the recognised Standards such as (BS EN 14994, 2007) or (NFPA 68, 2023), for e.g. a 1 m^3 dispenser housing as used in the experiment gives vent areas of 0.9 and 1.2 m^2 respectively;
    - Whilst the aforementioned standards offer guidance on a methodology for determining required venting panel sizes, it is recognised that standards can sometimes provide conservative results on the required vent area. Other empirical models, i.e. Molkov Model (Molkov, Dobashi, Suzuki, & Hirano, 1999) and FM Global Approach (Bauwens, Chaffee, & Dorofeev, 2011), demonstrate that smaller vent areas could lead to the same reduced pressure. Should designers wish to use these empirical standards, careful checks will need to be made to ensure that safety is not compromised;
    - In the MultHyFuel experimental setup, there was a tall (2 m height), relatively thin (0.5 m width) dispenser with a weak panel of 0.5 m^2 located on the top (equal to the entire footprint) of the dispenser. This is below that specified in the relevant standards, but extra venting was available through the natural ventilation apertures and the open bottom of the dispenser. Moreover, the dispenser also experienced some plastic deformation whilst the standards specify a vent area such that no

plastic deformations occur. Designers should consider whether the appropriate level of safety is met, in the case of damage to the dispenser, for e.g., ensuring fragments are not generated;
  - If explosion vent panels are not sized to one of these standards or according to the test configuration, there should be reliable modelling or experimental testing to demonstrate their efficiency and suitability;
  - A general principle is that dispensers should be as short as possible, however it should be taller than the average height of a person, so at least 2 m in height), and to allow for a suitably-sized explosion panel being installed above head height. Ideally these would be orientated in an upwards direction. The aspect ratio H/L/W for the studied mock-up dispenser, which was approximately 2 m/1 m/0.5 m, required the size of the explosion panel to be equal to the whole footprint of the dispenser (1 m × 0.5 m). This vent size was considered, according to the experimental results, sufficient to mitigate the consequences of the potential explosion inside the dispenser for the current aspect ratio; and
  - Integration of a dispenser onto a forecourt should take into consideration parameters that may impact the sizing and efficiency of the explosion vent panels, e.g. obstructions facing, or near the vents, for instance, walls or canopy in the forecourt.
- Early detection of releases from distributing hose and efficient associated emergency protocol(s) (requirement: maximum detection and reaction time can vary between 2 s and 5 s depending on local regulations);
- Review installation of restriction orifice, excess flow valves (in the pipework upstream of the dispenser) or potential alternative measures to limit the flow rate in case of a large leak, but compatible with vehicle filling requirements;
- Use of breakaway coupling to isolate the system and limit hydrogen inventory release in case of drive-away;
- Use of an isolation valve within the dispenser that isolates the H_2 system and limits hydrogen inventory release in case of identified loss of containment or failure of the breakaway to engage;
- Installation of electrical equipment must follow the Hazardous Area Classification of the installation;
- Ensure grounding of H_2 equipment such as the dispenser nozzle.

Canopy design:

- Canopy structure should be designed in a way that avoids accumulation of any hydrogen release (e.g. inclined canopy roof; as well as sufficient distance between dispenser roof and canopy);
- Alternatively, an individual canopy per dispenser could be considered, so that any potential collapse is localised.

6.1.2 Recommendation on estimation of likelihoods of hazardous events

Likelihood of Hydrogen release:

- Numerous probability data sources exist: formulae from expert judgment, generic data from past accidents and from different databases, *etc*.
- The evaluation carried out in the MultHyFuel example case study included those based on initiating events as developed in the project but documented in (Proust, Pique, Tarisse, & Jamois, 2023) plus the Central Feared Events (CFEs) as developed in the project;

- The different approaches to estimating the probability exemplified in MultHyFuel have their own strengths and weaknesses;
- The mechanical-probabilistic approach presented in Section 4.3.2 develops a detailed analysis of the potential degradation modes depending on the components present. This approach still requires further research before deployment at a larger scale; and
- At this stage of the project, it is proposed to use data from generic databases such as (BEVI, 2020), (SANDIA BD Ehrhart & ES Hecht, 2022) or (Offshore Norway/ Norske olje og gass PLOFAM2, 2018) because these were derived from industry experience and lessons learned from incidents, combined with potential modification factors based on expert judgement. However, the MultHyFuel working group is aware that the use of generic data presents a degree of uncertainty for the configurations studied, and due diligence would be necessary before application to any risk assessment.

6.1.3 Recommendations on consequence modelling

Consequence modelling:

From the comparison of experimental results with detailed risk assessment within the MultHyFuel project, the following approaches were established for the modelling of consequences:

- Consequence models tend to be inherently conservative and care needs to be taken not to reinforce conservatism via double-counting. The modelling tools tested within the project provided conservative estimates of hazard extents;
- There is a key need to carefully define source terms by a relevant and critical analysis of the system and associated equipment; and
- Where possible, take into consideration environment and reasonably foreseeable local weather conditions (wind) for Hazardous Area Classification and separation distance determination.

Recommended methodology for consequence assessment:

For the dispenser:

- Assess accumulation for the most critical and probable release(s);
- Assess consequences of the deflagration; and
- Limit the internal overpressure to as low as reasonably practical, and at most 200 mbar (this is the pressure considered to avoid global destruction of the dispenser housing according to the work within MultHyFuel)
    - By decreasing H_2 build-up
      e.g. with more ventilation, by limiting the flow rate, H_2 detection systems, *etc.*
    - And/or with explosion venting panels.

For the forecourt:

- Assess immediate ignition of the jet (i.e. flame) due to hose release
    - Limit the release by early detection of the release or the flame and limiting of the flow rate (if appropriate). Efficient detection systems with an appropriate emergency protocol to stop the release is recommended.

H2 accumulation in confined space:

(Linden P. F., 1999) Model is a relevant approach, but will overestimate the concentration in most cases because:

- Release is assumed to be constant, continuous and infinite;
- Concentration is the maximum reached at steady state; and
- Wind reinforced ventilation is not considered.

Deflagration in confined space:

FM Global approach (Bauwens, Chaffee, & Dorofeev, 2011) or Molkov Approach (Molkov, Dobashi, Suzuki, & Hirano, 1999) can be used, but can overestimate overpressure because:

- Concentration is considered homogeneous in the entire volume; and
- Stratification is not considered although it exists, inducing an overestimation of the amount of H_2 to be considered in the explosion.

Flame:

Schefer Approach (Schefer, Houf, Bourne, & Colton, 2006) (Schefer, Houf, Williams, Bourne, & Colton, 2007) can be used:

- The project found that it was not easy to compare model results to experimental data, since some biases are induced by the test facility (i.e. the method assumes constant release flowrate, whereas constant flowrate may not be realistic specifically where the hydrogen source is finite); and
- Nevertheless, consistency is observed with reverse calculations from corrected data (Corrected data here implies Flow rate, Q, that was not calculated from the initial release pressure and hole diameter, but from the experimentally measured Q, where it was found Q decreased with release time).

UVCE:

No data has been generated by the project to provide refined recommendations. Thus, if necessary, the recognised TNO method in the Yellow Book (Committee for Prevention of Disaster, 1995)) could be used with the Multi-Energy Method, with Blast Strength Level appropriate to the assessed phenomena and conditions. According to published studies, in most cases where there is sufficient vent area, the Multi-Energy Model using Strength Level 5 is appropriate (E Vyazmina, S Jallais, D Miller, 2016). Nevertheless, in case of high congestion levels and/ or high flow rate (> 1kg/s) the Multi-Energy Model with Blast Strength Level 6 or 7 would be more appropriate. To use the Multi-Energy Method, it is also necessary to determine the combustion energy contributing to the UVCE. This energy is obtained by multiplying the combustion energy (expressed in J/kg) by the flammable mass participating in the explosion. The combustion energy is an intrinsic property of the combustible gas (around 120 MJ/kg for hydrogen). The flammable mass involved in the explosion depends on how the flammable cloud forms and how it interacts with any obstruction in its path.

Separation distances:

Based on WP2's experimental results and Task 3.6's detailed risk assessment, a number of safety barriers (flow restrictor, venting panel) and their impact on consequence distances were analysed. The following were established, for the separation distances around hydrogen dispenser based on the current work:

- High pressure release from the filling hose in the forecourt is potentially the worst-case scenario;
- In the event of a release inside the dispenser, with sufficient openings/apertures for natural ventilation AND dedicated explosion venting panels, if ignited, the effects will potentially be contained within the dispenser with no or limited propagation outside the dispenser;
- Breakaway and Restriction Orifice can strongly reduce the hazard extents of a hose rupture;

- From the work conducted within MultHyFuel, there was no evidence to suggest larger separation distances than those for Compressed Natural Gas (CNG), which was the most recent addition to conventional refuelling stations;
- Calculations with Schefer Approach (Schefer, Houf, Bourne, & Colton, 2006) (Schefer, Houf, Williams, Bourne, & Colton, 2007) show that – considering maximum delivery pressure, specific nozzle diameter for each fuel and ensuing jet fire due to hose full bore rupture with immediate ignition – flame lengths and associated effects are significantly higher for CNG compared to H_2 (around 40% higher);
- The most severe consequence does not come from an explosion inside the dispenser if explosion venting panels are properly fitted. Jet fire is potentially the worst scenario upon which the basis of safety should be designed;
- Hence, considering a jet fire scenario, larger separation distances for H2 than those existing for CNG are possibly not necessary (because CNG jet fire scenarios give larger effect distances compared to H_2 ones for their respective typical dispenser operational conditions), but only if ignition probability and minimum ignition energy are not taken into account; and
- A flame length of approximately 6 m was found within this work for refueling flowrates of 120 g/s (please see Table 13 in Section 4.4.1), where all industry good practice, i.e. relevant risk reduction measures have been adopted (e.g. restriction orifice and 1 explosion vent panel over the whole footprint of the dispenser housing). There may be separation distances that are different to this value of 6 m in national regulations and other codes and standards, e.g. the current French regulation Arrêté (Légifrance Arrêté 1416, 2018) recommends a separation distance 10 m for 120 $g.s^{-1}$ and of 8 m for 60 $g.s^{-1}$ (in the absence of other safety measures, e.g. firewalls, *etc*.). Separation distances for other countries can be found in (MultHyFuel D1.4, 2024). It is worth noting that flame length is not necessarily adopted as the separation distance. LFL (with or without a safety factor applied) could also be adopted as the relevant separation distance. (BCGA GN41, 2020) provides some context as to the meaning of separation distance.

6.1.4 Recommendations on Hazardous Area Classification

- Hazardous Area Classification methodologies define the extent of releases to the lower flammability limit (LFL). Due to uncertainties with respect to dispersion and ignition (modelling gives an average value of concentration over time and there is variability in the instantaneous concentration of the gas), it is recommended that designers consider the application of safety factor to the LFL (e.g. 50% LFL) or release rate depending on the characteristics of the design;
- Local weather conditions (including reasonably foreseeable worst case) of wind and temperature need to be taken into consideration because they have a significant influence on Hazardous Area Classification, specifically for the zoning of enclosures;
- For a naturally-ventilated dispenser considered in the experimental work (WP2) and theoretical analysis performed in this WP, a minimum of Zone 1 with natural ventilation inside the dispenser was determined. For each application, an assessment of ventilation and release rate should be performed to consider a different type of zone;
- A non-hazardous zone inside the dispenser is not possible (for the theoretical work on this WP) due to high pressure inside the dispenser but Zone 2 can only be reached with mechanical ventilation at high flow rate. Mechanical ventilation at high flow rate within the dispenser will need to be demonstrable by the duty-holder/ operator;

- Hole size selection and justification for H_2 technologies require further research and analysis. Small hole sizes 0.025 mm^2 (0.18 mm) for H_2 fittings need to be justified and used with caution. It is recommended that at the very minimum, pressure integrity checks in the dispenser are performed regularly, including all the fittings that can potentially generate a release;
- Frequent maintenance and inspection of H_2 fittings are required especially with the uncertainty surrounding hole size assumptions in the calculations for the zoning related to hazardous area classification;
- The estimated extent of the zone is directly dependent on the assumed hole size generating such releases. For instance, for hole sizes of 0.025 mm^2, a hazardous zone ranging between 1.5 m to 2 m, depending on the dispersion tool used, would be obtained. However, if the type of elements, installation and operation would not allow the justification of a 0.025 mm^2 hole, but a larger hole size is more representative instead, for example 0.1 mm^2, the estimated hazard extent could increase to approximately 4 m using Phast and 6.5 m if using Quadvent;
- Assume the worst-case conditions for the hydrogen: highest pressure and lowest H_2 temperature to remain conservative; and
- Assume the highest ambient temperature to allow conservative estimation of the flammable cloud extents.
- Within such hazardous zones, operators shall ensure control of ignition sources as per regulations; and implement restrictions/ safety procedures and protocol around the dispenser within these zones in order to limit the presence of ignition sources;
    - For external releases, several variables should be considered for the assessment, for example the wind conditions or potential physical obstructions that would result in an impeded jet;
- The methodology in Annex D of IEC 60079-10-1:2020 (IEC 60079-10-1, 2020) is not recommended for Hazardous Area Classification around Hydrogen vents for the conditions of the Hydrogen Refuelling Station (elevated pressure and release rates) because it is not possible to extrapolate and often the release rate will not be within the lines for jet, diffusive and heavy gas of the Figure C.1 of the standard. Therefore, the extent cannot be determined using this methodology; and
- Weather and wind conditions have an influence on the dispersion modelling of the hazardous zone. It is recommended to review the atmospheric conditions (including the worst foreseeable conditions) for the hazardous area classification and use the appropriate modelling tools that allow the inclusion of those conditions. EHSP Guidance on Hydrogen Safety Engineering provides information about available tools as documented in (EHSP, 2023). For this work, Phast was used.

6.2 Technical suggestions for further research and harmonisation of good practice

The pre-normative research carried out within the confines of the MultHyFuel project led to the identification of some gaps in knowledge that may need to be filled in order to inform codes and standards. There also remains some separate general knowledge gaps which were excluded from the project scope, which need consideration and investigation – some of which are already in progress by other projects (including, but not limited to HyIndoor, HyResponse, HyResponder, PRESLHY, SH2IFT, ELVHYS, (IEA Hydrogen TCP Task 43, 2024), (ISO/TC 197, 1990) including WG 24, 29, 35 and 39, CEN/CNL/ JTC 6/WG3, H2FIRST).

No data is available from the MultHyFuel project to provide technical recommendations on the modelling of liquid hydrogen releases. Nevertheless, other projects such as PRESLHY, SH2IFT, MarHySafe (Phase I and II), ELVHYS can be consulted to more specifically address liquid hydrogen scenarios, which are not in the scope of the MultHyFuel project.

The following areas should be investigated further to confirm or adjust assumptions and remove uncertainties:

Dispenser design:

- Current work is based on dispenser design as per (ISO 19880-2, 2025). For new dispenser designs/specific considerations, (e.g. from production up to distribution integrated within the dispenser housing) a dedicated assessment should be carried out by designers, engineers and manufacturers;
- For specific/atypical designs of dispenser, the design of venting explosion panels should be investigated further on a case-by-case basis; and
- For specific/atypical designs of dispenser, the impact of (higher) internal obstruction level in the upper segment of the dispenser (compared to that in MultHyFuel) may be investigated in terms of severity of the explosion in case of ignition.

Safety on the forecourt:

- Risk assessments of the installation should consider detailed information from suppliers of breakaways (failure rates and modes) and analyse potential human factors to ensure risk is kept as low as reasonably practicable.

In addition, there needs to be further research into the emergency shutdown systems on multifuel forecourts. For instance, a combination of detection and shut-off valve actioning could be investigated, with ignition of the released H_2, taking into account the response time of the system; both in the dispenser (confined case) and on the forecourt (free field case).

Risk analysis performed in the MultHyfuel project specific to multifuel stations will be communicated to HyResponse and HyResponder key contacts, where relevant, e.g. for the established protocols and emergency response to take into account, the multifuel nature of the refuelling station.

Further investigation into existing modelling approaches to reduce over-conservatism may require additional experimental data.

- Address the assumptions and limitations of the existing simple analytical models and provide recommendations where numerical simulation brings added value to inform risk assessment methodology and assumptions; and
- Carry out more detailed investigations (experimental and numerical modelling) into complex scenarios, e.g. domino effects between different fuels other than hydrogen, taking into account realistic characteristics of multifuel stations.

Investigation into the interaction between hydrogen and the other conventional fuels within a single dispenser/ compressor unit should be carried out:

- Integration of H_2 within the same dispenser as the other conventional fuels, and the necessary prevention and mitigation barriers; taking into account potential domino effects

(including flame acceleration mechanism and effects, for a single dispenser housing all types of fuels)

The work conducted within the MultHyFuel project has identified several specific areas that would benefit from further attention and exploration by relevant regulatory, codes, and standards (RCS) bodies and organisations:

Good practice could be presented via an example multifuel HRS model(s) with design layout recommendations that minimise fire and explosion risks in compliance with national regulations to protect people. e.g. reduction of leak points, hierarchy of controls (i.e. prioritising preventative and engineering controls over mitigation), promoting installations that are highly ventilated to prevent H2 accumulation, inspection of installations, *etc*. (see Section 5).

Suggestions for engagement between national regulators and relevant stakeholders:

- Harmonisation of scenarios, harm criteria thresholds; and leakage sizes for the definition of safety distances for multifuel refueling stations, noting not all regulators are prescriptive; and
- Review procedural control measures to maintain exposure to members of the public to a minimum, in line with standards and guidance.
- The Lower Explosive Limit (LEL) (with relevant safety factors) could serve as a complementary—or even primary—basis for defining hazardous zones, especially when the goal is to prevent ignition altogether rather than solely to mitigate the consequences post-ignition. Using the LEL as a reference for hazard distance aligns with a preventive safety philosophy and may help address situations where an ignition source could be present outside the visible flame envelope, but still within a flammable atmosphere. This approach could offer an additional layer of conservatism and robustness to risk assessments, particularly in complex urban or confined environments where even small flame flashes or overpressures can have significant safety implications. The work is in progress in (IEA Hydrogen TCP Task 43, 2024) and by the European Industrial Gases Association (EIGA).

Experimental research:

Modelling and Hazardous Area Classification

- Expanding validation of leakage rates for foreseeable sources through experimental data and operational experience; and
- Review Hazardous Area Classification methodology approaches to consider the specific characteristics of hydrogen technologies, including realistic release scenarios (hole size and momentum) and the dispersion characteristics.

Likelihoods:

- More operational data is needed for the validation and improvement of the AFS method developed within MultHyFuel project; and
- Review of variables affecting the probability of ignition of hydrogen to inform risk assessments and reduce over-conservatism.

Safety barriers:

- Developing inherently safe designs for multifuel dispensers;

- Testing the effectiveness of various safety barriers (e.g. the detection-to-response time of the full “stop-leak” chain including detection and required actions to stop the leakage (e.g. isolation, valve actuation) to ensure satisfactory mitigation response time;

- Determining the Confidence Level or SIL requirements for safety barriers to reduce the probability of hazardous scenarios, for e.g. review of response times of the safety function for high pressure systems;

- Reduction of electrostatic accumulation and discharge is covered in the standards ((ISO 19880-1, 2020), (CGA H-7, 2024) and (IEC TS 60079-32-1, 2013)), however, it is recommended to explore additional procedural controls and maintenance to prevent or reduce potential static accumulation, for example due to dust presence, as well as the involvement of members of the public in the refuelling operation;

- Developing ultra-rapid hazard detection and isolation devices, for e.g. acoustic detection. *etc*.

- Assessing the use of fire and/or blast walls as mitigation measures for the station backyard. Clear understanding from station designers on when and where to install fire and/or blast walls to avoid counter mitigation effects, e.g. the increase in the degree of confinement of a potential blast, leading to higher overpressures.

Inherently Safe design:

- Exploring the feasibility of a single dispenser capable of handling all fuel types, including hydrogen;

- Investigating different canopy designs for multifuel HRS facilities; and

- Adhere to the principles of inherent safety for the design of the hydrogen refuelling station and forecourt, i.e. minimisation of inventory, minimisation of operator-based tasks, eliminate opportunities for error, *etc*.

Material compatibility and maintenance:

- Examining material compatibility and potential degradation effects in hydrogen service, including piping, joints, seals, and other components, if necessary to improve the content in (ISO/TR 15916, 2015);

- Enhancing cleaning procedures for hydrogen systems; and

- Definition of maintenance regimes, including periodic leak test and inspection procedures.

Organisational measures and training:

- Establishing good practice on organisational management, including Management of Change (MOC) and standardised operating procedures, to limit passenger presence near dispensers, including regular training of personnel;

- HRS operators to develop comprehensive user training programs for station operatives and maintenance staff, to raise awareness of hydrogen-related risks; and

- Competence management and improvement of safety culture of personnel involved in the maintenance and assembly of HRS.

Risk considerations in the backyard (non-public compound containing storage, processing and compression equipment) for multifuel Stations:

- Detailed study of risks associated with all the equipment (permanent bulk, as well as temporary mobile storage, compressor and process equipment) for different fuels including conventional fuels grouped in the same area, and the potential domino effects; and
- Careful consideration of the siting of multifuel refuelling stations is of paramount importance.

These considerations emphasise the importance of thorough, multidisciplinary efforts to advance the safety, reliability, and efficiency of multifuel hydrogen refueling stations, ensuring they meet both current and future demands.

7 References

AFNOR. (2013). *Installations of systems handling hydrogen*. Paris, France: Association Francaise de NORmalisation.
ANSI/AIAA G-095A. (2017). *Guide to Safety of Hydrogen and Hydrogen Systems.* Retrieved from https://webstore.ansi.org/standards/aiaa/ansiaiaa095a2017
APEA/EI 'The Blue Book'. (2024). *Design, construction, modification, maintenance and decommissioning of filling stations Fifth Edition (The Blue Book).* Retrieved from https://apea.org.uk/shop/all-publications/guidance-for-design-construction-modification-maintenance-and-decommissioning-of-filling-stations/
BARPI. (2008). *Accidentology of hydrogen.* La defense, France: ARIA.
Batt, R. (2014). *HSE Research Report RR985: Modelling of liquid hydrogen spills.*
Bauwens, C. R., Chaffee, J., & Dorofeev, S. B. (2011). Vented Explosion Overpressures from Combustion of Hydrogen and Hydrocarbon Mixtures. *International Journal of Hydrogen Energy 36(3)*, 36(3):2329–2336.
BCGA CP33. (2012). *BCGA CODE OF PRACTICE CP 33 The Bulk Storage of Gaseous Hydrogen At Users' Premises Revision 1.* Retrieved from https://bcga.co.uk/wp-content/uploads/2021/09/CP33.pdf
BCGA CP36. (2024). *Guidance for the use, inspection, and transport of cylinders, bundles and tubes, with various design codes. Revision 1: 2024.* Retrieved from https://bcga.co.uk/bcga-issue-revision-to-guidance-note-36/
BCGA CP4. (2020). *Code of Practice 4 Gas Supply and Distribution Systems (Excluding Acetylene) Revision 5.* Retrieved from https://bcga.co.uk/wp-content/uploads/2021/06/BCGA-CP-4-Revision-5-14-02-2020.pdf
BCGA CP41. (2018). *The Design, Construction, Maintenance and Operation of Filling Stations Dispensing Gaseous Fuels Revision 2.* Retrieved from https://bcga.co.uk/wp-content/uploads/2021/09/BCGA-CP-41-Rev-2-For-Publication.pdf
BCGA GN13. (2021). *BCGA Guidance Note GN13 DSEAR Risk Assessment Guidance For Compressed Gases* Revision 1: 2021.
BCGA GN41. (2020). *Separation Distances in the Gases Industry Guidance Note 41.* Retrieved from https://bcga.co.uk/wp-content/uploads/2021/09/BCGA-GN-41-Original-03-08-2020.pdf
Betteridge, L., & Phillips, S. (2015.). Large-scale Pressurised LNG BLEVE Experiments. *IChemE Symposium Series no 160, HAZARDS 25.*
BEVI. (2020, April 1). *Handleiding Risicoberekeningen Bevi.* Retrieved from https://www.rivm.nl/sites/default/files/2020-04/Handleiding%20Risicoberekeningen%20Bevi%20versie%204.2.pdf
Birch, A. D., Hughes, D. J., & Swaffield, F. (1987). *Velocity Decay of High-Pressure Jets.* Combustion Science and Technology, 52(1-3):161–171.
Brode, H. L. (1959). Blast Wave from a Spherical Charge. *Physics of Fluids 2*, 217-229.
BS 5306-8. (2023). *Fire extinguishing installations and equipment on premises. Selection and positioning of portable fire extinguishers. Code of practice.* Retrieved from https://doi.org/10.3403/30384738
BS EN 14460. (2018). Retrieved from BS EN 14460: https://www.en-standard.eu/bs-en-14460-2018-explosion-resistant-equipment/
BS EN 14797. (2006). Retrieved from BS EN 14797:2006 Explosion Venting Devices: https://webstore.ansi.org/standards/bsi/bsen147972006
BS EN 14994. (2007). Retrieved from Gas Explosion Venting Protective Systems: https://www.en-standard.eu/bs-en-14994-2007-gas-explosion-venting-protective-systems/
BS EN 15089. (2009). Retrieved from Explosion Isolation Systems BS EN 15089: https://www.en-standard.eu/bs-en-15089-2009-explosion-isolation-systems/

BS EN 17127. (2024). *BS EN17127 Outdoor Hydrogen Refuelling Points Dispensing Gaseous Hydrogen and Incorporating Filling Protocols).* Retrieved from https://knowledge.bsigroup.com/products/outdoor-hydrogen-refuelling-points-dispensing-gaseous-hydrogen-and-incorporating-filling-protocols-1

CGA H-7. (2024, January). *Standard Procedures for Hydrogen Supply Systems.* Retrieved from https://online.standard.no/en/cga-h-7

Cirrone, D. M. (2019). Cryogenic hydrogen jets : flammable envelope size and hazard distances for jet fire. *ICHS.* Adélaïde: Hysafe.

Committee for Prevention of Disaster. (1995). *Yellow Book - Methods for the calculation of physical effects – Third Edition, Chapter 5, pp. 5.31-5.72, 1995.*

Dienhart, K., & Verfondern, B. (1997). Experimental and Theoretical Investigation of Liquid Hydrogen Pool Spreading and Vaporization. *International Journal of Hydrogen Energy Volume 22, Issue 7*, 649-660.

DNV. (2024). *Phast 8.6.1*. Retrieved from https://www.dnv.com/software/services/plant/consequence-analysis-phast.html

E Vyazmina, S Jallais, D Miller. (2016). Effects of the ignition position on the overpressure originated from a delayed ignition of high pressure releases of hydrogen. *11th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosion (ISHPMIE).* Dalian, China.

EHSP. (2023, May 1). *EHSP Guidance on Hydrogen Safety Engineering - Guidance Document.* Retrieved from https://www.clean-hydrogen.europa.eu/system/files/2023-05/EHSP%20Guidance%20on%20Hydrogen%20Safety%20Engineering%20-%20v1-Final.pdf

EIGA Doc 75/21. (2021). *Methodology For Determination Of Safety And Separation Distances Doc 75/21 Rev 1 (Revision of Doc 75/07).* Retrieved from https://www.eiga.eu/ct_documents/doc075-pdf/

EIGA IGC Doc 15/06/E. (2006). *Gaseous hydrogen stations.* Retrieved from https://h2tools.org/sites/default/files/Doc15_06GaseousHydrogenStations.pdf

Energy Institute Guidance EI 3312. (2025, January). *EI 3312 Guidance on hydrogen delivery systems for refuelling of motor vehicles, co-located with petrol filling stations (Supplement to the Blue Book).* Retrieved from https://www.energyinst.org/technical/publications/topics/petroleum-product-storage-and-distribution/guidance-on-hydrogen-delivery-systems-for-refuelling-of-motor-vehicles,-co-located-with-petrol-fuelling-stations-supplement-to-the-blue-book

Epstein, M., & Fauske, H. K. (2003). *Flammable Mass and Length of a Variable-density Buoyant Fuel Jet: Gaussian Versus Top-hat Profiles.* Combustion Science and Technology*, 175*, 1333-1346.

EUR-Lex Directive 2006/42/EC. (2006, May 17). *DIRECTIVE 2006/42/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast).* Retrieved from https://eur-lex.europa.eu/eli/dir/2006/42/oj/eng

FCHJU project EIHP2. (2003). *Hydrogen Applications – Risk Criteria and Risk Assessment Methodology.*

FCHJU project IDEALHY. (2013). *Qualitative Risk Assessment of Hydrogen Liquefaction, Storage and Transportation - Deliverable 3-11.*

FCHJU2 Hydrogen European Safety Panel. (2021). *Statistics, lessons learnt and recommendations from the analysis of the Hydrogen incidents and accidents database (HIAD 2.0).*

H2Tools. (2024, 11 15). *Best Practices for Operating Procedures.* Retrieved from H2 tools: https://h2tools.org/bestpractices/operating-procedures

HSE GB. (2004, November). *The Selection and Use of Flammable Gas Detectors.* Retrieved from https://www.hse.gov.uk/pubns/gasdetector.pdf

IEA Hydrogen. (2024). *A Global Collaboration for Research and Innovation in Hydrogen Technologies*. Retrieved from https://www.ieahydrogen.org/

IEA Hydrogen TCP Task 43. (2024). *Task 43: Safety and RCS of Large Scale Hydrogen Energy Applications - IEA Hydrogen TCP*. Retrieved from https://www.ieahydrogen.org/task/task-43-safety-and-rcs-of-large-scale-hydrogen-energy-applications/
IEC 60079-10-1. (2020). IEC 60079-1:2020 Explosive Atmospheres – Part 10-1: Classification of areas – Explosive Gas Atmospheres. Geneva: International Electrotechnical Commission.
IEC 60079-29-2. (2015). *Explosive atmospheres - Part 29-2: Gas detectors - Selection, installation, use and maintenance of detectors for flammable gases and oxygen.* Retrieved from https://webstore.iec.ch/en/publication/21961
IEC TS 60079-32-1. (2013). *Explosive atmospheres - Part 32-1: Electrostatic hazards, guidance.* Retrieved from https://webstore.iec.ch/en/publication/651
INERIS. (2014). *Benchmark on HRS, DRA-14-141532-06227C.*
ISO 13984. (1999). *Liquid Hydrogen - Land Vehicle Fuelling System Interface.* Retrieved from https://www.iso.org/standard/23570.html
ISO 14001. (2015). *Environmental Management Systems - Requirements with guidance for use.* Retrieved from https://www.iso.org/standard/60857.html
ISO 17268. (2020). *Gaseous Hydrogen Land Vehicle Refuelling Connection Devices Edition 3.* Retrieved from https://www.iso.org/standard/68442.html
ISO 19880-1. (2020). *Gaseous hydrogen – Fuelling Stations – Part 1: General Requirements.* Retrieved from https://www.iso.org/standard/71940.html
ISO 19880-2. (2025). *Gaseous hydrogen — Fuelling stations Part 2: Dispensers and dispensing systems Edition 1.* Retrieved from https://www.iso.org/standard/85839.html
ISO 19885-1. (2021). *Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles Part 1: Design and development process for fuelling protocols.* Retrieved from https://www.iso.org/standard/82556.html
ISO 26142. (2010). *Hydrogen Detection Apparatus - Stationary Applications.* Retrieved from https://www.iso.org/standard/52319.html
ISO/TC 197. (1990). *Hydrogen technologies Technical Committee.* Retrieved from https://www.iso.org/committee/54560.html
ISO/TR 15916. (2015). *Basic considerations for the safety of hydrogen systems Edition 2.* Retrieved from https://www.iso.org/standard/56546.html
LaChance, J. B. (2008). *Data for the use in Quantitative Risk Analysis of Hydrogen Refueling Stations.* Sandia National Laboratory Report SAND2009-0874.
Leachman, J. W., Jacobsen, R. T., Penoncello, S. G., & Lemmon, E. W. (2009). *Fundamental Equations of State for Parahydrogen, Normal Hydrogen and Orthohydrogen*. Journal of Physical and Chemical Reference Data 38 (3), 721-748.
Légifrance Arrêté 1416. (2018). *Arrêté du 22 octobre 2018 relatif aux prescriptions générales applicables aux installations classées pour la protection de l'environnement soumises à déclaration sous la rubrique n° 1416 (station de distribution d'hydrogène gazeux) de la nomenclature des.* Retrieved from https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000037519292
Légifrance Arrêté. (2005). *Arrêté du 29 septembre 2005 relatif à l'évaluation et à la prise en compte de la probabilité d'occurrence, de la cinétique, de l'intensité des effets et de la gravité des conséquences des accidents potentiels dans les études de dangers des installations c*. Retrieved from https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000245167
Legifrance Circulaire n° 3 . (1985, May 9). *Circulaire n° 3 du 9 mai 1985 relative au commentaire technique des décrets n° 84-1093 et n° 84-1094 du 7 décembre 1984 concernant l'aération et l'assainissement des lieux de travail.* Retrieved from https://www.legifrance.gouv.fr/download/pdf/circ?id=1800
Legislation, U. (2002). *The Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR).* Retrieved from https://www.legislation.gov.uk/uksi/2002/2776/contents/made

Linden, P. F. (1999). *The Fluid Mechanics of Natural Ventilation.* Annual review of fluid mechanics*, 31(1)*, 201–238.
Molkov, V., & Saffers, J.-B. (2013). Hydrogen Jet Flames. *International Journal of Hydrogen Energy Volume 38, Issue 19, Hydrogen Jet Flames*, 8141-8158.
Molkov, V., Dobashi, R., Suzuki, M., & Hirano, T. (1999). *Modelling of vented hydrogen-air deflagrations and correlations for vent sizing*. Journal of Loss Prevention in the Process Industries*, 12(2*, 147-156.
MultHyFuel D1.2. (2021, September). *Permitting Requirements and Risk Assessment Methodologies for HRS in the EU (First version).* Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/MHYF_WP1_D12_Permitting_requirements_and_risk_assessment_methodologies_20210930_03.pdf
MultHyFuel D1.4. (2024). *Permitting Requirements and Risk Assessment Methodologies for HRS in the EU (Final version).* Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/MHYF%20-%20D1.4%20-%20Permitting%20requirements%20in%20the%20EU.pdf
MultHyFuel D2.4. (2024). *Fire and Explosion Hazard Assessment Report*. Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/MultHyFuel%20D2.4%20-%20Fire%20and%20explosion%20hazard%20assessment%20summary%20report%20-%20Final.pdf
MultHyFuel D3.1. (2021). *State of the Art on Hydrogen Technologies and Infrastructures regarding a Multi-fuel Station Environment - Deliverable 3.1.* Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/D31_-_State_of_the_art_-_Technologies.pdf
MultHyFuel D3.2. (2021). *Benchmarking of Risk Assessment Methodology Applied to Refuelling Stations.* Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/D32_-_State_of_the_art_-_Risk_assessment.pdf
MultHyFuel D3.6. (2024). *Layout Recommendations for Multifuel Stations (Separation Distances/Hazardous Area Classification)*. Retrieved from https://multhyfuel.eu/images/event-documents/deliverables/MultHyFuel%20D3.6%20-%20Risk%20assessment%20review%20of%20critical%20scenarios%20and%20hazardous%20area%20classification%20-%20Public%20-%20Final.pdf
MultHyFuel Project. (2021). Retrieved from https://multhyfuel.eu/
NFPA 2. (2023). *Hydrogen Technologies Code.* Retrieved from https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2
NFPA 68. (2023). *Standard on Explosion Protection by Deflagration Venting.* Retrieved from https://www.nfpa.org/codes-and-standards/nfpa-68-standard-development/68
Offshore Norway/ Norske olje og gass PLOFAM2. (2018, December 6). *Process leak for offshore installations frequency assessment model - PLOFAM2 Main Report.* Retrieved from https://www.offshorenorge.no/contentassets/253ea4d863ac428c8a1cf73b0bcec486/main-report---process-leak-for-offshore.pdf
Pique, S., Quesnel, S., Weinberger, B., Nouvelot, Q., Houssin, D., Vyazmina, E., . . . Saw, J. L. (2022). *Preliminary Risk Assessment of Hydrogen Refuelling Stations in a Multifuel Context.* Chemical Engineering Transactions, 90, 229-234.
PRESLHy. (2021). *Novel guidelines for safe design and operation of LH2 systems and infrastructure, D6.2.*
Proust, C. P., & Studer, E. (2011). *High Pressure Hydrogen Fires*. International Journal of Hydrogen Energy.

Proust, C. P., Pique, S., Tarisse, A., & Jamois, D. (2023). A New Method to Quantify the Leakage Scenarios (frequencies and flowrates) on Hydrogen High Pressure Components. *ICHS conference.* Québec: HySafe.

SANDIA BD Ehrhart & ES Hecht. (2022, April). *SANDIA Report - Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 4.1 Technical Reference Manual.*

Schefer, R. W., Houf, W. G., Bourne, B., & Colton, J. (2006). *Spatial and radiative properties of an open-flame hydrogen plume*. International Journal of Hydrogen Energy*, 31(10):1332–1340,*, 31(10):1332–1340.

Schefer, R. W., Houf, W. G., Williams, T. C., Bourne, B., & Colton, J. (2007). *Characterization of High-pressure, Underexpanded Hydrogen Jetflames*. International Journal of Hydrogen Energy, 32(12):2081–2093.

TS 19889-1. (2025). *Hydrogen Technologies – Interoperability – Part 1: Interface Between Gaseous Hydrogen Trailer and Hydrogen Fuelling Station.* Retrieved from https://www.iso.org/standard/65492.html

UK Government. (2016). *The Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations 2016*. Retrieved from https://www.legislation.gov.uk/uksi/2016/1107/contents

UNECE. (2015). Retrieved from https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2015/R134e.pdf

Venetsanos, A. (2018). *Homogeneous Non-equilibrium Two-phase Choked Flow Modelling.* International Journal of Hydrogen Energy*, 43(50)*, 22715-22726.

W, C. C. (1978). *On the Decay of Vertical Buoyant Jets in Uniform Environment*. Proceedings of 6th International Heat Transfer Conference, (pp. 97-102).

Yellow Book - CPR, C. (1995). *Methods for the Calculation of Physical Effects : Due to Releases of Hazardous Materials.* In Yellow Book Third Edition (pp. Chapter 5 pp. 5.31-5.72).

8 Appendix A – Comparative analysis between hydrogen and compressed natural gas

A quick and simple comparison was made between hydrogen (H_2) and compressed natural gas (CNG) currently used in the transport sector.

Maximum delivery pressures for each fuel were considered:

- 700 bar for Hydrogen Fuel Cell Electric Vehicles (H_2 FCEV)
- 250 bar for Compressed Natural Gas Vehicles (CNGV)

Parameters of the scenario for the comparison were as follows:

- Full bore rupture of the hose,
- 5.3 mm diameter hose for H_2,
- 8 mm diameter hose for CNG,
- Immediate ignition of the release – i.e. Flame / Jet Fire – without considering potential flow restrictor.

Table 17 presents the characteristic values for a jet fire considering hydrogen and methane releasing from a circular nozzle of 5.3 mm diameter at the maximum pressure.

Table 17 - Comparison of jet fire characteristics and associated effects for a hose full bore release for hydrogen and compressed natural gas at maximum pressure

Parameters for jet fire severity assessment	Hydrogen	Compressed natural gas
Pressure	**700 bar**	**250 bar**
Diameter	5.3 mm	8 mm
Release flow rate ($NL.min^{-1}$)	$5.5 \cdot 10^5$	$1.6 \cdot 10^5$
Release flow rate ($g.s^{-1}$)	827	1850
Flame length	**16.1 m**	**23.6 m**
Distance 8 $kW.m^{-2}$	20.1 m	28.3 m
Distance 5 $kW.m^{-2}$	22.8 m	31.8 m
Distance 3 $kW.m^{-2}$	26.4 m	36.8 m
Distance 1.6 $kW.m^{-2}$	32.4 m	44.8 m

What is MultHyFuel?

The goal of MultHyFuel is to contribute to the effective deployment of hydrogen as an alternative fuel by developing a common strategy for implementing Hydrogen Refuelling Stations (HRS) in multifuel contexts, contributing to the harmonization of existing laws and standards based on practical, theoretical and experimental data as well as on the active and continuous engagement of key stakeholders.

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Further information can be found under https://www.multhyfuel.eu.

For feedback on the MultHyFuel project or the published deliverables, please contact info@multhyfuel.eu.

The MultHyFuel Consortium