

D8.1: Safety Analysis Report



Composite Conformal Liquid H₂ Tank

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List of Abbreviations

Abbreviation	Meaning
AFP	Automated Fibre Placement
CFR	Code of Federal Regulations
CFRP	Carbon Fibre Reinforced Polymer
CGA	Compressed Gas Association
CTE	Coefficient of thermal expansion
DOD	Department of Defence
DOT	Department of Transportation
EASA	European Union Aviation Safety Agency
EIGA	European Industrial Gases Association
FAA	Federal Aviation Agency
FHA	Functional Hazard Assessment
HIAD	Hydrogen Incident and Accident Database
ISO	International Organization for Standardization
LLIS	Lesson Learned Information System
NFPA	National Fire Protection Association
OCED	Organisation for Economic Cooperation and Development
PRD	Pressure relief device
RCS	Regulations, Codes and Standards
TRL	Technology Readiness Level
WP	Work Package

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1 Executive Summary

The scope of this safety assessment is to provide reference and requirements for fuel storage system designers, focusing on hazards and failure modes typical of liquid hydrogen operations. The aim of the study is to better understand the hazards and associated safety objectives and requirements faced by a hydrogen storage system in a future technology readiness level (TRL) 9 architecture.

The fuel storage system has been subdivided according to its functionalities to separate the hazard assignment from any particular design configuration. Hazards associated with the system functions have been assessed systematically for different operational configurations. This was achieved by consulting literature, regulations, codes and standards (RCS), hydrogen hazard databases and by surveying the COCOLIH2T consortium members.

The hazards were subsequently categorized based on the hazard root cause. This clustering helps focusing on both specific design aspects, without losing the focus on the overall perspective and performance of the system. Another output of this analysis that is useful for the consortium is the ranked safety criteria list. This list can be used as a recommendation chart for the development of the storage demonstrator.

The preliminary functional hazard assessment (FHA) was adopted as safety approach for hazard identification. Due to limitations of time and resources, the number of hazards collected could be not exhaustive. Also, most of the identified hazards, have been obtained through the aforementioned literature review. More work on this aspect is needed, to ensure all possible hazards are found and to reduce the probability of 'unknown unknowns'.

This document supplements the "**Safety Register**" excel database where the complete list of hazards and consequent safety objectives is reported.

2 Introduction

The system under exam is an insulated container for liquid hydrogen used as aircraft fuel reservoir.

The overall approach of preliminary safety assessment defined in this document is represented in Figure 1. The assessment process is led by the collection of functional failures of the tank system, identifying the hazards related (Section 3.2) and the severity associated. For doing this, information about hydrogen behaviour, fuel management operations, knowledge of the operational environment (Section 3.1), and applicable regulatory requirements was employed. A hydrogen incident database analysis (Section 3.3) was used to understand the incidence of failure among the functions identified for the fuel storage system. The developed hazard categories (Section 3.4) have permitted a more structured identification of safety criteria (Section 3.4), which have been classified based on their Impact.

The safety criteria, delivered in terms of design recommendation, are the principal result of this assessment.

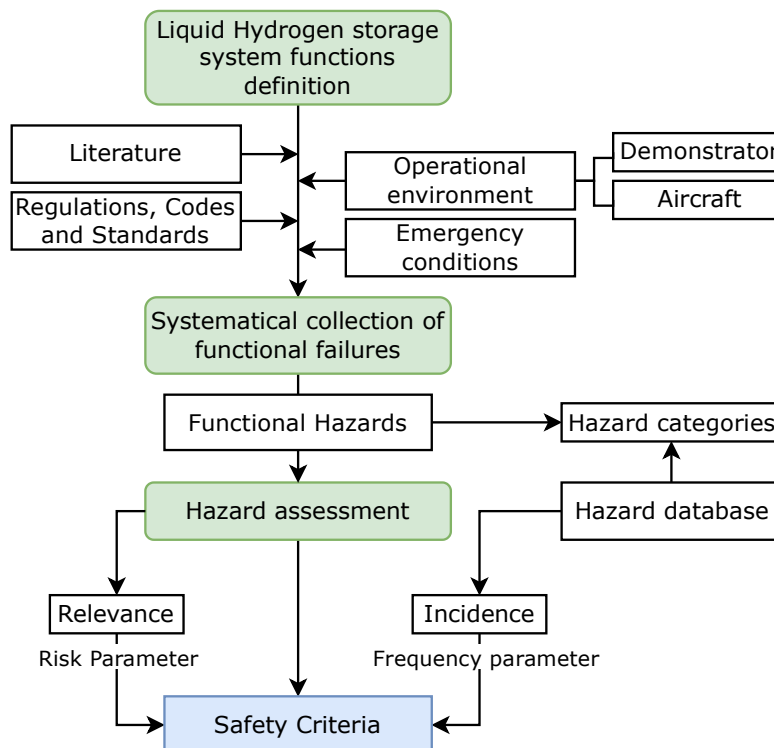


Figure 1: Safety assessment process as defined in this document.

Safety occurrences may not always result in harm or damage but, given the novelty of cryogenic hydrogen as an aviation energy storage medium, a thorough

investigation of the potential risks is required. The use of cryogenic hydrogen may call for new safety criteria to maintain or improve the safety level currently achieved in aviation. The aim of this study is therefore to identify such safety criteria.

The main objective of this study is to identify hazards and mitigation measures to minimize risks that may impact:

- People
- Property
- Equipment
- Environment

The detailed information on the **identified hazards**, as well as an overview of applicable databases, literature sources and RCS materials, and the resulting **safety criteria** has been collected into the Safety Register database. This report is provided as a supplement to that database. Table 1 gives an overview of the contents of the Safety Register, and the database entry indexing system.

Table 1: List of Safety Register information and indexes.

Information	Index
Hydrogen storage system function	#.#.#
Reference, Literature	R###
Regulation, Code and Standard	N###
Functional Hazard	H###
Hazard Database entry	D###
Hazard Category	C###
Safety Criteria	S###

3 Main section

3.1 Description of the Operational Environment

The system assessed in this study is a new storage technology for liquid hydrogen for aircraft.

The liquid hydrogen storage system is analysed under two main configurations. The first considers the tank as a subsystem of the aircraft system and the second one considers the tank as a standalone system operating for the demonstrator testing. The two conditions are referred to as aircraft configuration and demonstrator configuration.

Along with the environmental configuration description, the emergency scenarios that could arise in both cases are taken into account.

In some conditions, the impact of the environment in the aircraft configuration and the demonstrator configuration is the same, resulting in duplication of the identified hazards. For these cases, the hazards have been collected under the demonstrator configuration.

For operations that shares the same configuration and no additional information on the hazard are provided whether the environment considers the aircraft or the demonstrator, the hazards have been collected under the demonstrator configuration.

3.1.1 Configuration Considered for The Storage System As Aircraft Subsystem

The COCOLIH2T storage system comprises a single tank, placed in the aft area of the aircraft. The tank is composed of an inner tank connected in a vacuum space to an outer tank. No distinction is made whether the outer tank would be integral to the aircraft structure or not.

The **interfaces** of the tank with the aircraft system are the following:

- Fuel intake
- Fuel delivery to propulsion system
- Fuel/gas emergency unload line
- Power line in
- Monitoring data transfer to central processing unit
- Tank mechanical connections

Of the possible aircraft configuration phases, a number were considered especially relevant for hydrogen storage related hazards and therefore selected as the focus of this study. The selected phases are described below.

Aircraft configuration mode 1 – Dormancy

This configuration mode refers to the aircraft as parked at the airport waiting for the next flight. The storage system still holds a significant amount of cryogenic fuel, and the wait time is up to 24 hours. The aircraft is parked outside or in a hangar. A venting connection is used to recover boil-off hydrogen.

Aircraft configuration mode 2 – Fuelling

During this operational phase, the parked aircraft receives liquid hydrogen from the fuelling station. The operation is performed by the airport crew. Only hazards specific of airport operations are included in this configuration. For other more generic operations related to fuelling, please consider the demonstrator configuration.

Aircraft configuration mode 3 – Flight mode

This operational phase groups all flight phases together. The main characteristic is that the storage system is providing fuel to the propulsion system.

Aircraft configuration mode 4 – Maintenance mode

This operational phase describes all maintenance activities performed on the aircraft, whether planned or not.

Aircraft emergency mode 1 – Fire

The aircraft itself or the surrounding environment is ignited.

Aircraft emergency mode 2 – Electrical currents

This refers to power dissipation, shortcuts, lightning events within the aircraft or the storage system itself.

Aircraft emergency mode 3 – Mechanical impact

The aircraft hits or is hit by other bodies with significant energy. This may relate to crashes, foreign object impact, maintenance mishaps, etc.

3.1.2 Configuration Considered for The Storage System Demonstrator

The storage system is composed of an inner tank connected in a vacuum space to an outer tank. The inner tank made of carbon fibre reinforced polymer (CFRP) composite with a thermoplastic matrix manufactured with an automated fibre placement (AFP) process. The inner tank is connected to the outer tank by a temperature deformable structure. The outer tank is composed of two parts while the inner tank has an integral design. Two main openings, with minimum size depending on mandrel specifications, are closed with flanges with compatible

coefficient of thermal expansion (CTE). These flanges house connections for fuel lines and gas lines on both tanks and for data connections and vacuum depressurization and monitoring on the outer tank.

The storage **mechanical interfaces** are the following:

- Connections to the test rig that will apply acceleration during the test operations.
- Connections to the transport and handling structures.
- Fuel load connector
- Gas vent control line
- Fuel release line

The **testing facility** is being developed within WP7.2 of COCOLIH2T, details of this facility are currently not yet public.

The storage system **electrical interfaces** are the following:

- Power line in
 - Fuel gauging
 - Sensors
- Data line out
 - Pressure states
 - Valve states
 - Temperature states
 - Fuel gauging
 - Structural monitoring sensor readings
 - Vacuum state
 - Vacuum sampling system
- Commands line in
 - Emergency pressure valves
 - Fuel load and release valve

The main **goal** of the demonstrator testing is to demonstrate that the storage system designed in the COCOLIH2T meets the performance requirements set by the Clean Hydrogen Partnership. This list of requirements guides the design, manufacturing, operations and testing of the storage system demonstrator.

- Tank gravimetric efficiency [%weight]: 16% in 2024 and 35% in 2030
- LH2 tank capacity: 50-150 kilograms LH2
- Dormancy: > 24 hours
- Venting rate: < 2%/day
- Filling rate: 57 kg in 0.5 hours = 114 kg/hr average rate
- Boil-off: < 2%/day after dormancy
- Maximum diameter: < 1 meter
- Minimum operating pressure: 1 bar (pump fed) – 3 bar (pressure fed)
- Maximum operating pressure: 3 bar (pump fed) – 8 bar (pressure fed)

- Insulation Vacuum: $1 \cdot 10^{-5}$ mbar

The main configuration phases for the demonstrator are briefly described below.

Demonstrator configuration mode 0 – Manufacturing

This refers to all operations performed prior to arrival at the test station, including manufacturing of separate components and integration of the system.

Demonstrator configuration mode 1 – Handling

This refers to all handling operations performed on the storage system. This includes transportation to the test location, and possible transportation between different test rigs.

Demonstrator configuration mode 2 – Fuel loading

This refers to operations during the loading of fuel.

Demonstrator configuration mode 3 – Fuel unloading

This refers to operations during the unloading of fuel.

Demonstrator configuration mode 4 – Dormancy

This refers to all operations where hydrogen is left for a long period inside the tank.

Demonstrator emergency mode 1 – Fire

This scenario applies to the condition where fire or other intense heat sources are applied to the external structure of the demonstrator.

Demonstrator emergency mode 2 – Power loss

This scenario refers to a disconnection of the demonstrator from the main energy system.

3.2 Hazards Collection from Functional Hazard Assessment

In this section lies a crucial part of this safety assessment, the identification of hazards in term of functional failures. The level of abstraction that this approach permits, allows for catching and understanding hazards that could be possibly missed by only looking at the development at the component level. This functional hazard assessment was performed following the SAE ARP4761 standard, and [N043] as reference.

The storage system under examination has described by its functions, which have been broken down into tier 2 and tier 3 subfunctions. This operation facilitates the

separation of the hazard assessment from specific architectural configuration chosen for the COCOLIH2T demonstrators or the aircraft configuration design.

The initial list of functions was reviewed during the Preliminary Design Review meeting of October 26, 2023. The list contains more than forty functions, subdivided in four main areas described below.

- Ref.1.** Contain fuel and maintain its state.
- Ref.2.** Enable fuel transfer.
- Ref.3.** Provide information on fuel state and system health.
- Ref.4.** Provide protection against natural and induced environment.

Functions referenced by numbers 2 and 3 represent interfaces with other systems or the external environment, indicating their role in exchanging matter or information. Function reference 4 consists primarily of passive measures aimed at preventing primary hazards, while function reference 1 describes the primary functions within the fuel storage domain, including active features to maintain the required thermodynamic state of the fuel. A representation of these functions and the relation to their closest children, the tier 2 subfunctions, is provided in the annex of this document, section 6.1. For the rest of the functions, the reader is invited to check the Safety Register database, that contains a table with all the identified functions and the parent relations between each other.

For each function on the list, failure effect has been systematically investigated in the configurations, operational environment and scenario provided in the section above. The failure modes for the functions accounted for are the following.

- Loss of function
- Partial loss of function
- Function provided when not needed
- Unannounced loss of function
- Malfunction

The meaning of the list entries is straightforward, with the more generic "Malfunction" referring to a functionality that is not provided as intended. When a failure mode is analysed, the hazard effect is described with knowledge of the hydrogen behaviour, this permits to understand the effect severity. If multiple hazards may arise from a single failure mode, they are reported as single entries to permit their specific assessment. Each identified functional failure is paired with a specific index value in the Safety Register, as reported in Table 1.

For every functional failure listed, a specific description outlines the effects caused by that particular hazard. The hazards are then classified on a severity level depending on the potential effect given the hypothesized environment. Criteria are the following:

- Catastrophic

- Hazardous
- Major
- Minor
- No effect

A suggestion for a safety criterion to overcome the hazard was filed in this instance for each identified hazard. A mean for compliance verification was also suggested. Some similar hazard may need to follow the same safety criteria, section 3.5 will show how this matter is considered. Wherever possible, supporting material was reported as a reference to existing literature or guidelines that express hazard information or hazard barriers concerning a similar scenario.

The systematic evaluation of the functional hazards was conducted by the TU Delft safety analysis reference team within work package (WP) 8. Also, feedback was collected from other consortium partners in order to have a broader hazard perspective. This was done via an electronic survey. Finally, the systematic assessment listing a total of approximately one hundred entries, was reported on the respective table of the Safety Register.

Given the ten thousand combinations resulting from the failure modes in various scenarios and functions, each of which may present multiple hazards, a thorough investigation is underway to prevent overlooking any potential risks.

3.3 Hazards Collection from Incident Databases

The use of incident databases permits to learn from past operational and design errors. Careful notice should be taken that the available databases only contain self-reported cases. Therefore, this does not permit to derive reliable statistics, as no information about the total population is reported. Also, some hazards may not have been reported and a complete description of the system may not be available.

Wherever it was not possible to download the data as a single file, the information was collected from the respective website. The retrieval of the data from the following sources was performed Nov 22, 2023.

The following section gives a short description of available incident databases. Information from these databases was merged into a single COCOLIH2T safety database. Some of the available incident databases were excluded from the COCOLIH2T database due to access restrictions or lack of applicability of the data. This is also indicated in the following section.

3.3.1 Incident Databases

The **Nasa Public Lesson Learned System** (LLIS) provides access to official, reviewed lessons learned from NASA programs and projects. These lessons have been made available to the public by the NASA Office of the Chief Engineer and the NASA Engineering Network. There are currently 67 results regarding the keyword hydrogen.

<https://llis.nasa.gov/search?page=1&query=hydrogen>

The **Hydrogen Incidents and Accidents Database** (HIAD) was firstly developed within the HySAFE Network of Excellence by the Joint Research Centre of the European Commission (JRC). Public sources of HIAD are from scientific literature, news and other public, not hydrogen-specific, databases such as French ARIA, European (SEVESO) eMARS, US CSB, NTSB, OSHA, national nuclear authorities, etc. The database is not directly available online. A recent version was requested from the project partners, resulting in the link below, accompanied by a notice for its usage. It is offered free of charge, but it must be properly cited in reports and the JRC consortium appreciates feedback on the database usage. The database contains 712 hydrogen-related incidents and at the moment of download was updated to September 2023.

<https://minerva.jrc.ec.europa.eu/en/shorturl/capri/hiadpt>

The Pacific Northwest National Laboratory developed the **Hydrogen Tools** (H2TOOLS) Portal through support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. The goal of the Portal is to support implementation of the practices and procedures that will ensure safety in the handling and use of hydrogen in a variety of fuel cell applications. The website contains relevant resources about system certification, safety planning, along with 223 lesson learned results.

https://h2tools.org/lessons?search_api_fulltext=

The **US Department of Energy** holds a collection of operational experience, lessons learned and best practises in the doeopexshare website. A number of 106 records were found matching the keyword "hydrogen". The download of reports requires an account, although the download of report titles does not. Information from this website is therefore not included in the COCOLIH2T database.

<https://doeopexshare.doe.gov/search-lessons?searchKeyword=hydrogen>

The **US Department of Labour** hosts on its website a collection of work-related injuries. Among those, some may be related to hydrogen. Due to lack of resources to extract these incidents, information from the Department of Labour database is not included in the COCOLIH2T database.

<https://www.osha.gov/data>

3.3.2 Other Analyses Pertinent to Incident Databases

A historical review of hazards derived from an analysis of NASA hydrogen mishaps reported in [N074] revealed several insights. The incidents occurred during the storage, transportation, and handling of liquid hydrogen. Table 2 provides a detailed breakdown of the component failures associated with these incidents. Please note that the percentage mentioned in the table is calculated as the total number of occurrences in each category relative to the total number of mishaps, so cannot be considered as a failure frequency in the classical meaning of the term. Also note that not all of the failures mentioned in the databases are relevant for the COCOLIH2T demonstrator architecture.

Table 2: Failures of components related to hydrogen systems.

Failure	Percentage of total
Valve malfunction/Leak	19%
Leak from connection	15%
Safety disk failure	9%
Material issues or embrittlement	9%
Excessive vent rate	9%
Cryo-pumping	9%
Air enters system	4%
Flexible coupling, bellow failure	3%
Restricted battery outgassing	3%
Tank rupture	2%
Highway traffic accidents	2%
Loss of vacuum	1%
Line rupture	1%

Among these failures, the “Cryo-pumping” phenomena needs a clarification, as the term is also used to define the cryogenic vacuum pump operating principle. In this context, it refers to instances where the temperature condition of vessels and lines produced a reduced pressure environment resulting in air being sucked in the system through leaks or faulty valves. This caused formation of flammable mixtures with hydrogen or the liquification of air that triggered other equipment failures. The “Air enters the system” failure may lead to similar consequences, but in this case the main failure source is the lack of or an improper purging.

This method of data representation does not allow for the observation of the human factor behind the failures. In fact, by looking at the root causes on the same list of failures, it has been reported that 87% of the failures involved human judgment. The four most significant failure causes were:

- Operational
- Procedural

- Design
- Planning

These results highlight the necessity of both design and operational review by a third party. With this consideration, a strict set of safety objectives should be imposed on the designer of the system under review.

The updated hydrogen hazard databases used in this study, including the HIAD database, have undergone comprehensive analysis. Detailed statistical evaluations can be found in recent reports [R021, R022, R023], while a more descriptive analysis on contributing factors can be found on the chapter 13 of a 2023 OECD report [R024].

3.3.3 Database Analysis Summary

A number of ~1000 incident events related to hydrogen have been collected from HIAD, H2TOOLS and LLIS databases as introduced in section 3.3.1. The different entries have been reformatted to a single database with the following attributes:

- Hazard index
- Database source reference
- Failure title
- Failure description
- Factors contributing to failure
- Severity of the hazard
- Function reference

Each database was holding the reformatted information under different data fields, each field is described in the paragraph below. The function reference, which refers to the functions of the COCOLIH2T storage system under exam, was added to the entries as part of this work. Depending on the source database reference, some fields may be incomplete.

The "description" field holds paragraphs of information on the accident event and the level of detail changes between the various entries. The "factors" field holds all the information on what could have caused the incident, including in some cases the lesson learned and applicable actions. Regarding the "severity" field, this is the parameter that has undergone more processing. In order to homogenize the impact level of the incident, the classification in terms of hydrogen release was employed. The four levels of severity are grouped as follows:

- Hydrogen release and ignition
- Unignited Hydrogen Release
- No Hydrogen Release
- Not specified

The latter term was adopted when no sufficient information was provided within the database entry. A "function" field has been introduced to connect each incident to a corresponding function within the storage system that may be impacted by similar hazards. For each entry, if the hazard is related to a function similar to those in the COCOLIH2T storage system, it is assigned the corresponding function index. Depending on the event description, it may be possible that none of the tank system function may be applicable. For these entries, the function reference index 5 was assigned. The database entries that lack associations with specific functions can be linked to the following functionless hazardous scenarios:

- Spontaneous hydrogen formation from biological setting.
- Spontaneous hydrogen formation from battery chemistry.
- Material specific incompatibility.
- System modification not communicated with operators.
- Operator procedures not followed.

The first two records are not applicable to the COCOLIH2T system, but the other factors should be accounted for properly. These observations will be integrated into the definition of the hazard categories and safety criteria.

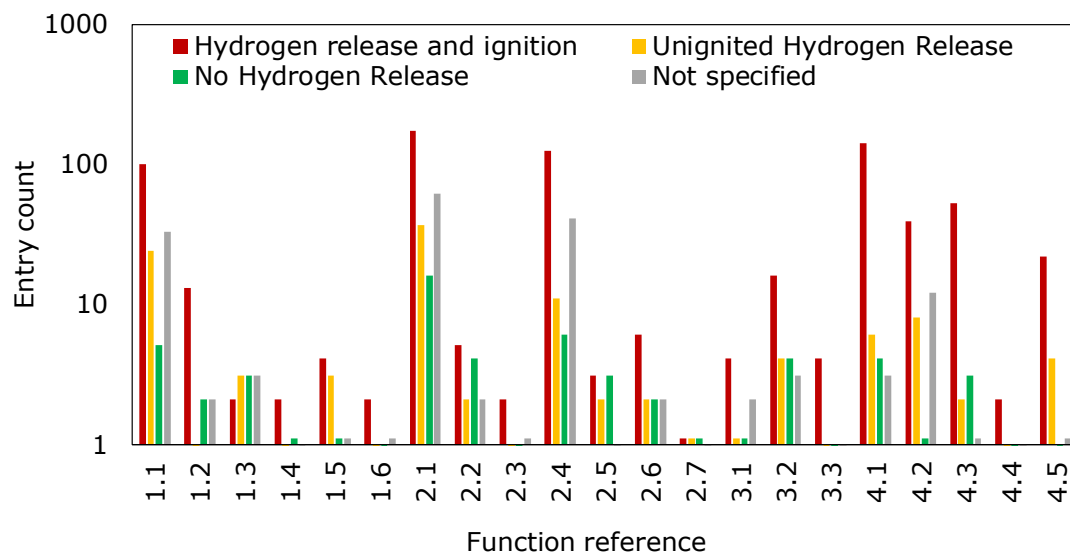


Figure 2: Overview of the hazard database entries, organized by storage system functions.

The identification of the related function for each hazard database entry allows for the generation of a hazard list specific to a particular function, which is useful for the definition of functional related failures. In this particular analysis, the number of hazard entries related to a specific function have been used to assign an "incidence" parameter for every system function. The number of hazards related to tier 2 functions (function identified by two numbers, e.g. function 4.3) have

been reported in the Figure 2 as a simplified reference to the reader. In this case tier 3 hazard counts have been included in the parent level tier 2 function.

It is clear that the severity parameter does not have a significant impact on some of the functions, as most of the incidents reported are in fact hydrogen accidents. The four levels of severity have been arbitrarily assigned to a weight coefficient as follows to obtain a weighted count of the occurrences.

$W_{HazDB} = [\text{'Hydrogen release and ignition': 1, 'Unignited Hydrogen release': 0.5, 'No Hydrogen release': 0.1, 'Not Specified': 0 }]$

In this way no-events are ruled out and the functions most frequently affected by failures are highlighted. In this way this parameter relates to a fictitious frequency of the related hazard, and it will be subsequently applied to the safety criteria as described in section 3.5, while maintaining the "incidence" naming. As seen in Figure 2, the count level is disproportionate among different functions, for this reason, the weighted count is normalized using a logarithmic function to a 1 to 2 scale to obtain the incidence parameter. The sum of weighted count for each function is processed as follows:

$Incidence_{function} = [\ln(sum) < 1: 1, \ln(sum) < 2: 1.25, \ln(sum) < 3: 1.5, \ln(sum) < 4: 1.75, \ln(sum) \geq 4: 2]$

The Incidence parameters calculated in this way for each function have been included in the function list provided in the "Safety register" document.

3.4 Hazard Categories

Hazard categorization is important for managing risks effectively. It helps to focus on the critical aspects of the system, allocate design resources efficiently, and offers a better understanding of risks. By classifying risks, specific strategies for each category can be developed, enhancing decision-making and ensuring compliance with regulatory standards. This section contains the categorization of the hazards identified for the tank system, building upon the considerations and outcomes of the functional hazard assessment outlined in section 3.2 and the hazard database processing discussed in section 3.3. First the main hazards are discussed, then the categorization is presented.

The primary risks associated with using hydrogen are linked to its release. As outlined in various safety manuals dedicated to hydrogen and cryogenic technologies [R002, R003 and R005], it is beneficial to understand hydrogen releases based on their nature. Within these categories, hazards can be further identified and classified. A flowchart describing the relationship between hydrogen release and consequent hazard is provided in Figure 3.

The major identified hydrogen release classes are Permeation, Explosive Release, Pool Vaporization, Jet Release. **Permeation** refers to the gradual and usually small-scale leakage of hydrogen through the material of the equipment. It occurs when hydrogen molecules diffuse through the material, leading to a slow release. **Jet release** involves the rapid release of hydrogen in a focused stream. This release can be purely gaseous or two-phase (involving both gas and liquid phases). It typically occurs through a breach or opening in pressurized equipment, resulting in a forceful discharge. **Pool vaporization** occurs when liquid hydrogen is spilled from the equipment onto a surface, and the spilled liquid undergoes phase transition to a gaseous state. This gaseous hydrogen then poses a hazard, as it can accumulate in the surrounding area. An **explosive** release happens when the pressure within the equipment vessel becomes excessive, leading to a catastrophic failure of the vessel. This can result in the rapid and violent disintegration of the equipment, causing a release of hydrogen with explosive force. The hazards associated with hydrogen release extend beyond combustion and explosions; they include various risks such as asphyxiation, cold burns, and jet cutting.

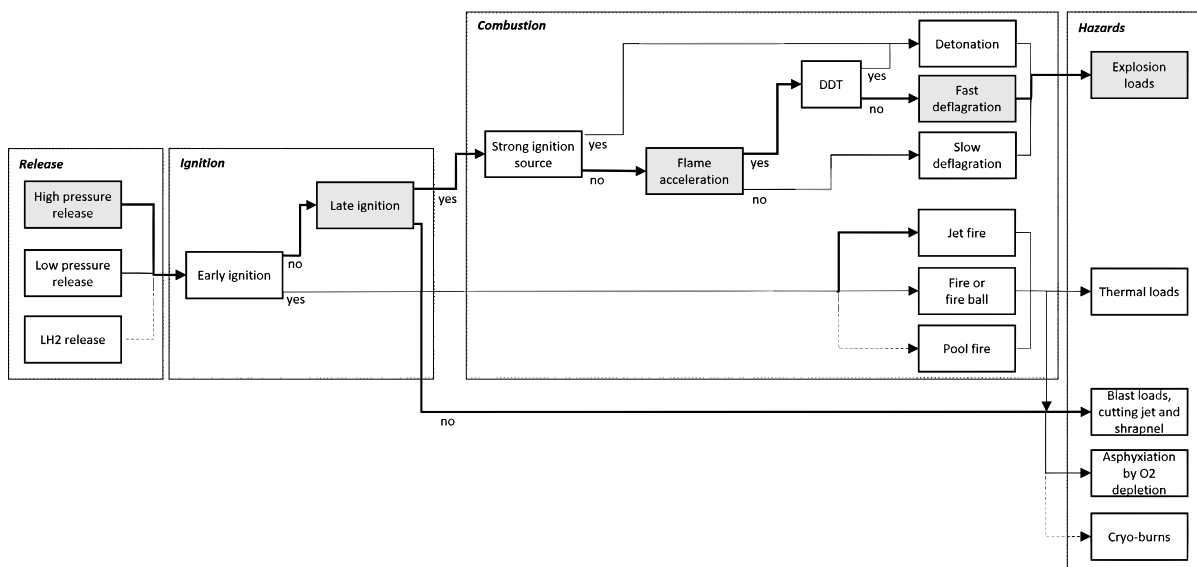


Figure 3: Potential consequences associated with hydrogen release, adapted from [R005].

In the evaluation of hydrogen release, it is crucial to recognize that the first type, permeation, is inherently unavoidable due to the atomic structure of materials and their packing density. However, permeation is also considered one of the safer modes of hydrogen release due to the slow release, as the time required to reach a flammable mixture in an air environment is high. This allows for mitigation of potential risks by implementing adequate ventilation systems. Furthermore, the

rate of leakage is unlikely to be sufficient to lead to unexpected fuel depletion during a flight.

If the storage system is made from composite materials, damage to the composite laminates can increase the rate of permeation and contribute to more complex safety scenarios. The hazard category "permeation through the skin" was defined for permeation related phenomena.

The concentration of hydrogen required to form a combustible mixture in air with available oxygen is relatively low, especially when compared to other commonly used fuels. Recognizing this, it becomes mandatory to take proactive measures to prevent significant releases of hydrogen. This involves addressing potential breaches in equipment both during the design of the system and through its operational lifetime. It is clear that the connection between components needs particular attention, a specific hazard category was defined in this case as "hydrogen release through component fitting". Overpressure of closed spaces, trapped hydrogen, loss of fuel control, and other architecture related secondary hazards will fall under this category too. It is important to address both categories in order to overcome potential cascading effects to the whole system.

The hazards related to hydrogen are strongly dependent on the operational procedures applied. This applies both to human related operations and non-human related process control. For this reason, the whole hazard category "Hazards related to fuel management operations" was defined.

Components and materials in contact with hydrogen need to be rated for this type of application, also considering the temperature and pressure conditions, as defined from RCS. Guidelines and testing methods are available and consolidated, but things may still go wrong. For this type of hazards, the category "Hydrogen incompatibility, design error" was defined. The following two cases will fit under this category too, considering that such hazards can be prevented with the right material, design and component choices, as defined by RCS. The first case includes indirect effects of an eventual unintended hydrogen discharge on the compatibility of materials and components that are not in direct contact with hydrogen during normal operation. The second case relates to hydrogen related hazards coming from the vent line, posing the risk of deflagration or detonation if not properly designed. Deflagration refers to a rapid combustion process where flames propagate through a substance at a subsonic speed, generating a shock wave but not reaching the supersonic velocities characteristic of detonation. On the other hand, detonation involves a highly explosive reaction, characterized by a shock wave moving through the substance at a supersonic speed. Proper adherence to the latest guidelines on design is essential to mitigate this potential backfire danger, ensuring the safety and integrity of the system. This type of hazard would be categorized as a hydrogen design failure, as the recommended measures and design practices to overcome these phenomena are already in place.

For hazards not related to hydrogen release, such as component malfunction, reduced performance caused by unintended damage or sensor malfunction, one last category was defined. This results in the following classification, categorizing identified risks into specific groups:

- C001** Permeation through the tank skin
- C002** Hydrogen release through component fitting
- C003** Hazards related to fuel management operations
- C004** Hydrogen incompatibility, design error
- C005** Hazards unrelated with hydrogen release

With this type of categorization, it becomes more clear which type of events may be the outcomes of the different classes and what type of measures would be needed to prevent and overcome these effects. Given the complexity and diversity of potential hazards outlined, a multidisciplinary approach involving engineering, materials science, safety protocols, and ongoing risk assessment is essential to mitigate these risks effectively and ensure the safety of both personnel and equipment.

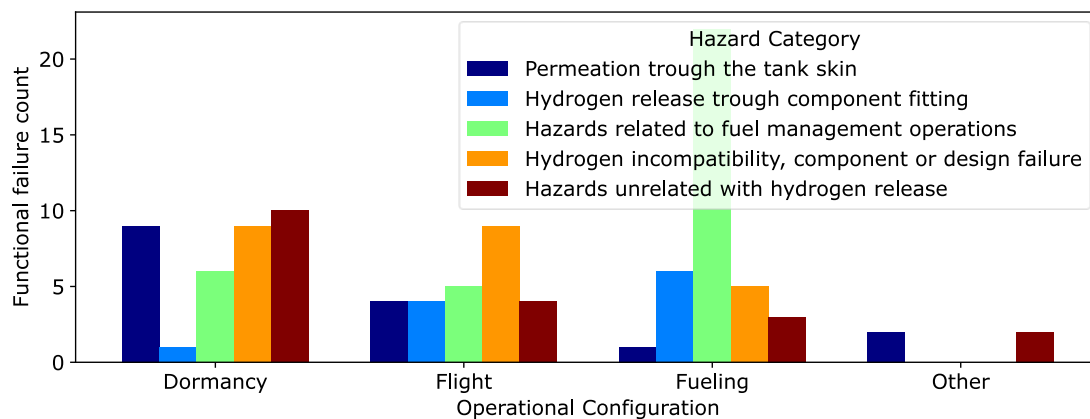


Figure 4: Distribution of Hazards collected through the FHA process, categorized based on Operational Configuration and Hazard Category.

To put these hazards in the perspective of the operating environment, a representation of the distribution of hazard categories with respect to the operational configurations is presented in Figure 4. The configuration discussed in Section 3.1 was modified for ease of representation, collating similar conditions between the aircraft and the demonstrator configurations, and incorporating the Maintenance, Manufacturing and Handling configurations in the Other configuration field. This type of representation allows for understanding the most impactful hazard type, if any, for each scenario. Also, it is helpful, during the first phase of functional failure identification, for directing the focus on areas that may have been neglected.

The comprehensive list of hazards, identified in accordance with section 3.2, is stored in the Safety Register database. A hazard category coefficient has been assigned to each entry. In cases where multiple hazard categories were identified, the hazard entry is open for assignment of additional safety criteria. Each criterion is dependent on the respective hazard category. As an example, some categorized hazards are reported here:

- **Flange Seal Leak:** CTE mismatches between flange and installation site caused a leak and subsequent fire due to different expansion coefficients (category C002 need to be addressed).
- **Hydrogen Residual in Vacuum Pump:** Despite a normally functioning vacuum pump, the presence of residual permeated hydrogen led to an unexpected explosion at the pump outlet (category C001 causes category C004, both need to be addressed).
- **Cryogenic Storage Relief Valve Malfunction:** Power outage caused a relief valve to malfunction due to frozen vacuum grease, resulting in an overpressure condition (category C004 needs to be addressed).
- **Pressure Gauge Mechanical Failure:** Mechanical failure in a pressure gauge caused a spark, igniting hydrogen during the tank filling process (categories C003 and C005 need to be addressed).

This sample shows how this type of categorization permits to break down hazards to smaller problems that can be systematically addressed. In general, managing these hazards requires an approach that integrates preventive measures, operational procedures, design considerations, and continuous monitoring, starting from the manufacturing process. For instance, to ensure the prevention of catastrophic failures, it is required to implement strict operational procedures for fuelling and defueling processes to avoid leaks, explosive mixtures, or damage to the tank itself. Valve design should have controlled dynamics to prevent shocks and ignitions, and utilizing multiple gauging devices with different technologies could be implemented to gather accurate information about tank performance. Actions needs to be employed in every step of the lifecycle of such systems. A summary of the criteria collected during this assessment, together with consideration on their application, is presented in the next section.

3.5 Safety Criteria

The definition of Safety Criteria is a strategy to reduce the risks related to hazard of hydrogen systems. General measures can be defined as the following:

- Prevent leaks
- Prevent accumulation of hydrogen
- Prevent combustible mixture
- Prevent ignition sources

- Provide hydrogen detection alarms
- Provide evacuation procedures
- Prevent operational errors
- Prevent material incompatibility
- Prevent component failures

It is clear that these intentions are broad and may result in a difficult compliance verification. For this reason, a list of specific Safety Criteria has been laid out. This was done by focusing on each hazard identified during the functional hazard assessment and, based on the function failing and the already identified safety criteria suggestion as per Section 3.2, a new safety criterion was defined or, in the case that an already identified safety criterion was applicable to the case, it was assigned to the hazard examined. Consequently, each functional hazard has only one safety criterion per hazard category and each safety criterion is related to multiple functional hazards.

The definition of safety criteria was employed to include both safety objectives and safety requirements to allow for more flexibility in the conception itself. Safety objectives in this case are represented by design recommendation or wider goals. Safety requirements, by setting a specific condition, highlight the importance of various components on the safety of the system, particularly in known and risky elements where quantitative requirements, such as the frequency “1E-X per flight hour,” need to be satisfied. These criteria transition into recommendations and design goals. These can serve as references for the TRL 4 COCOLIH2T demonstrator design, while the specific values are left to be addressed for a future particular application at TRL 9. This duality emphasizes the dynamic nature of safety considerations, balancing stringency with adaptability in different stages of development.

The identified Safety Criteria were divided in the following categories depending on the proposed recommendations.

- Operational
- Design
- Barrier
- Component
- Test

A list of the most relevant Safety Criteria is reported in the Table 3. The reader may refer to the “Safety Register” for the complete list. The list is ordered following the Impact parameter, calculated as the product of the Incidence and Risk parameters assigned to every specific Safety Criterion. The use of this coefficient permits to sort the criteria based on their relevance on the overall system safety.

The Incidence parameter associated with a Safety Criterion was obtained by applying an average on the Incidence values related to the functions and the functional failures related to the Safety Criterion under examination. In fact, with

this setting, different functional failures can share the same safety criterion. The incidence of each function was calculated as a fictitious frequency parameter from the Hazard database processing as per Section 3.3.3 and indicates the number of occurrences of a specific functional failure.

The Relevance parameter was established to convey the risk associated with a particular hazard to its resulting Safety Criterion. The Relevance parameter of a Safety Criterion is obtained by averaging the Relevance parameters of the functional failures related to it, for each of which it was calculated based on the severity level identified for the failure effect. Those severity parameters introduced in section 3.2, have been associated to the following weighting coefficients.

$$Relevance_{Hazard} = [\text{'Catastrophic': 2, 'Hazardous': 1, 'Major': 0.5, 'Minor': 0.1, 'No effect': 0}]$$

These arbitrary weighting coefficients have been chosen to focus on most impactful hazards and to have a similar range with respect to the Incidence parameter. A similar trend has been observed within the Relevance and Incidence parameter of the Safety Index.

Table 3: Principal Safety Objectives identified within this analysis Refer to the Safety Register for the full list of identified criteria.

index	Safety criteria	Criteria type	Hazard category	Incidence	Relevance	Impact
S005	Ensure the dormancy capability of the tank structure by verifying that the permeation of the laminate is consistently below the specified threshold required for dormancy, according to the laminate cryogenic condition and performance.	design	C001	1.8	1.6	2.8
S031	The frequency of FITTING LEAK due to improper dilatation estimation, surface preparation, pressure evaluation, vibration, retorque planning etc shall be no greater than 1E-X per flight hour.	design	C002	1.5	1.5	2.3
S024	Mark an unsafe area around the demonstrator, provide ventilation barrier protection for operators in case of hydrogen release	barrier	C003	2.0	1.0	2.0

S038	Ensure laminate-component fitting samples are cryogenic tested for leaks in the same condition of the demonstrator	test	C002	2.0	1.0	2.0
S042	Ensure the components are tightly attached (no deformation of the components). Add support for sprouting components.	design	C002	2.0	1.0	2.0
S035	Provide redundancy on Pressure relief devices and apply them to every isolated line	design	C003	1.5	1.3	1.9
S006	Provide a vacuum pump that can deal with eventual hydrogen mixture.	component	C001	1.8	1.0	1.8
S014	Provide potentially exposed electronically connection to be explosion proof according to DoD code requirements	design	C005	1.8	1.0	1.8
S034	Ensure fuel quality (purity, vapour mass fraction, spin state) before filling, preventing contaminant ingestion.	design	C003	1.8	1.0	1.8
S009	Define safe venting system as defined in CGA 5.5 or EIGA to avoid backfire, detonation, etc	design	C003	1.3	1.2	1.6
S002	Prevent the collision between the tank and other objects during test operations. Provide mechanical barrier protections.	barrier	C001	1.3	1.3	1.6
S021	Provide remote operations for hydrogen defueling as failsafe for emergency conditions, ensuring safe fuel dumping is always possible.	design	C003	1.3	1.2	1.5
S022	Ensure overflow avoidance by using different technologies for hydrogen metering and by precalculating the applicable flow from the fuel source.	design	C003	1.5	1.0	1.5
S033	Provide the demonstrator testing operations are conducted in sufficiently ventilated environment.	operational	C002	1.5	1.0	1.5
S044	Ensure a fail-safe strategy to prevent hazards in the event of fuel release in the vacuum area. E.g. PRDs on ext. tank and fuel dump	design	C005	1.5	1.0	1.5
S029	Ensure evacuation of personnel when any PRD is activated	operational	C003	1.7	0.8	1.3
S037	Ensure laminate samples are tested for permeation in the same cryogenic condition as the demonstrator	test	C001	1.3	1.0	1.3

S039	Ensure interaction between components that can generate spark and heat due to friction is prevented	barrier	C005	1.3	1.0	1.3
S043	Ensure the prevention of fuel leak through fittings using pressure locking and other failproof strategies	design	C002	1.3	1.0	1.3
S003	The frequency of VALVE FAILURE for every applicable fluid flow condition shall be no greater than 1E-X per flight hour.	component	C004	1.0	1.2	1.2
S036	Ensure parallel concurrent monitoring to prevent sensor failure consequences during operations	design	C003	1.1	1.0	1.2
S008	Define harmless tank cleaning operational procedure, material compatibility with inert gas, flow speed, etc.	operational	C003	1.1	1.0	1.1
S023	Ensure operational checklist include the connection of ground venting before tank filling.	operational	C003	1.6	0.6	1.0

Designers should refer to the applicable RCS where possible. Actions and evaluations complying with the Safety Criteria here identified should be recorded along with the related index. In this manner, design advancements in critical areas permit to achieve a better overall level of safety.

For the sake of the demonstrator operations, considering the various scenarios involving human interaction, it's critical to prioritize personnel safety by providing adequate protective measures during operations, and remote-controlled shut-off valves for emergency situations where physical proximity to hazards poses a risk.

It's essential to emphasize the importance of redundancy in safety features. The implementation of fail-safe designs, such as incorporating backup systems or parallel safety features, could significantly mitigate risks associated with hydrogen release or structural damage. Determining the required level of redundancy requires a detailed analysis of the proposed architecture of the system and therefore could not be done at this stage but should be a part of future design efforts as the system is matured to TRL 9.

The integration of technologies such as structural health monitoring and vacuum sampling can enhance the early detection of potential failures while a thoughtful design and operation following the principles identified by these safety criteria can ensure the integrity of the system.

4 Conclusions and Outlook

This Report and the "Safety register" are released as public documents to aid in the development of liquid hydrogen based aircraft propulsion systems. Within the COCOLIH2T consortium they will be used as working documents, as new functional failure and safety criteria are still identifiable as the demonstrator designs mature.

The safety criteria identified in this document are the main output of the safety assessment and are intended as design recommendations for the demonstrator, which is the goal of the COCOLIH2T project. These will be evaluated by the subsystem owners to verify applicability and potentially suggest compliance methods or alternative measures.

The effectiveness of the presented methodology increases with the quality and comprehensiveness of the list of functions of the system and the consequent systematically identified functional failures. The impact of each safety criterion is driven by the safety considerations taken during the definition of the functional failure effect severity and by addressing the incidence of similar hazards with the use of incident databases.

The methodology presented in this document permits an effective identification of hazards with a top-down approach within a new system and offers a tool to determine priorities during its design development. It synthesizes information from different publicly available databases to give an overview of known hazards and maps them onto the identified system functions. This systematic approach enables a first check that no failure modes have been overlooked during design. However, as the design matures and the system architecture becomes more defined, a systematic safety analysis process should be followed to ensure that no 'unknown unknowns' are overlooked. This can involve using tools like a fault tree analysis, or a bottom-up failure model effects and criticality analysis to identify possible interactions between failure modes of different components. Involving appropriate subject matter experts who have a full understanding of the possible failure modes and hazards of specific components will be crucial at this stage.

In conclusion, this report provides a starting point for more detailed safety analyses, both within COCOLIH2T, and for future aircraft development.

5 References

The reader is referred to the "Safety register" for the complete lists of RCS and literature references collected within the creation of this deliverable.

The references cited in this document are the following, in order of appearance.

[N074] NASA TM X-71565 Review of hydrogen accidents and incidents in NASA operations 1974

[R021] EHSP FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING *Statistics, lessons learnt and recommendations from the analysis of the Hydrogen Incidents and Accidents Database (HIAD 2.0)* 2021

[R022] J.X. Wen, M. Marono, P. Moretto, E. Reinecke, P. Sathiah, E. Studer, E. Vyazmina, D. Melideo International Journal of Hydrogen Energy *Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database*, 2022 47(38): 17082-17096

[R023] A. Campari, A.J.N. Akel, F. Ustolin, A. Alvaro, A. Ledda, P. Agnello, P. Moretto, R. Patriarca, N. Paltrinieri Computers & Chemical Engineering, *Lessons learned from HIAD 2.0: Inspection and maintenance to avoid hydrogen-induced material failures*, 2023 173:108199

[R024] OECD Risk-based Regulatory Design for the Safe Use of Hydrogen 2023

[R002] T.J. Peterson, J.G. Weisend II, Springer *Cryogenic Safety* 2019

[R003] R. Neugebauer, Springer *Hydrogen Technologies* 2022

[R005] A. Kotchourko, T. Jordan, Butterworth-Heinemann *Hydrogen Safety for Energy Applications* 2023

6 Annexes

6.1 Functions of the storage system

A simplified representation (tier 3 subfunctions are not reported) of the identified functions for the storage system of liquid hydrogen is presented in Figure A5.

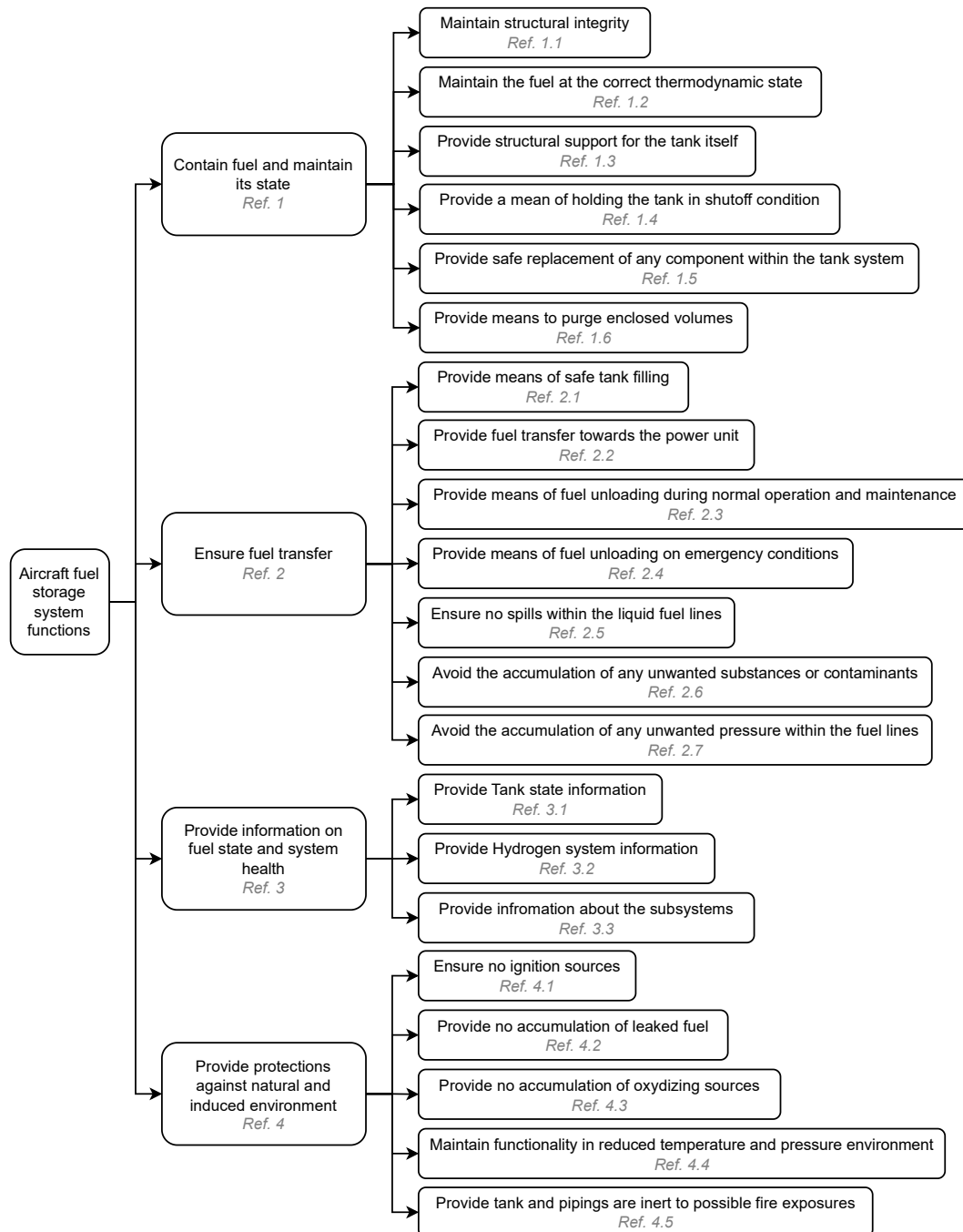


Figure A5: Representation of the storage system related functions and their relations, up to the second-tier level.

6.2 Regulations, codes and standards

This last section introduces and describes some of the main regulatory requirements within the system scope. A reference list of applicable regulatory requirements can be found in the "Safety Register". Everyone designing a component or subsystem should be aware of the related normative content, this information is thus useful for anyone involved in the design of the system or its review.

A good and updated reference for understanding the relationship between the various RCS and their applicability in the various world regions is Kotchourko and Jordan's book *Hydrogen Safety for Energy Applications* [R005]. Here will be reported the RCS related to the storage system under assessment. International, US and EU market are taken into account.

At **international level** the principal standardization bodies are ISO and IEC, the technical committees devoted to hydrogen safety are the following:

- ISO/TC 197 – Hydrogen technologies
- ISO/TC 220 – Cryogenic vessels

The United States uses model code organizations to deal with hydrogen hazards. Those are the International Code Council and the National Fire Protection Association (NFPA). NFPA 2 Hydrogen Technologies and NFPA 55 Compressed Gas and Cryogenic fluids provide high-level, hydrogen specific requirements and reference to component standards from SAE, ASME.

The **EU** does not have currently a specific law for design, deployment and testing of hydrogen systems. The system must instead comply with the regulation for explosive atmosphere, flammable gases and pressurized devices. This mainly consists of the following Directives:

- 1999/92/EC ATEX – workplace
- 2010/35/EU TPED
- 2014/34/EU ATEX – products
- 2014/68/EU PED

The ATEX (ATmosphere EXplosive) directives prioritize the prevention of explosive atmospheres, the avoidance of ignition and means to mitigate the explosion effects. The (T)PED directives concern (transportable) pressure equipment directives. In this context these are the only legally binding rules. Harmonized Standards may be voluntarily adopted unless referred by the EU legislation. Guidelines, best practice and industrial standards may be voluntarily considered

to assist the design. An example of the hierarchical structure of EU regulations and their relationship is shown in Figure A6.

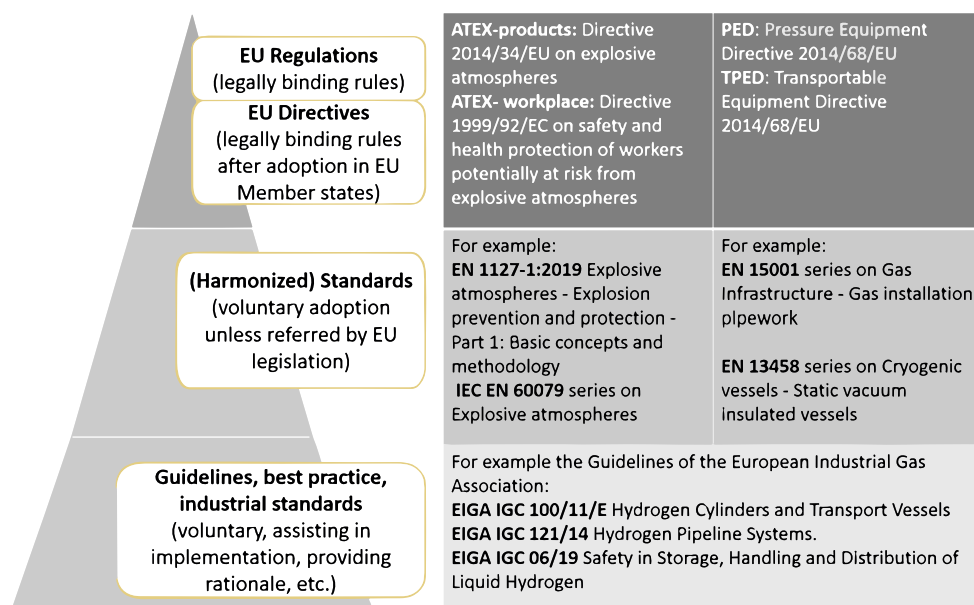


Figure A6: Hierarchical structure of the EU regulations, codes, and standards (RCS) framework. Adapted from [R005].

For aviation specifically, the **European Union Aviation Safety Agency (EASA)** and the **Federal Aviation Administration (FAA)** are the key organisations involved in setting regulations. At present they have not published regulations or guidance material specifically related to the use of liquid hydrogen. However, such material is actively being developed. For example, EASA participates in the Clean Aviation Partnership, in which certification experts and research teams are working closely with the Clean Hydrogen initiative, building a European research area for clean hydrogen. EASA is also actively involved in activities of **WG-80**, the **EUROCAE** workgroup developing guidelines to support the use of Hydrogen Fuel Cell Systems for aircraft applications.

These collaborations will bring in the near future requirements more suitable for the development of hydrogen aircraft.

6.3 Recommended reference documents

Important **guidelines** can be found on ISO/TR 15916 Basic considerations for the safety of hydrogen systems.

The National Renewable Energy Laboratory (NREL) host several **recommendations** on hydrogen safety, among which the NREL/TP-5400-60948 with title Hydrogen Technologies Safety Guide.

The **detection** of flammable gases is regulated by the standard IEC 60079-29 Explosive Atmospheres. A specific standard dedicated to hydrogen detectors is ISO 26142:2010 Hydrogen detection apparatus – stationary applications.

Regarding specifically **liquid hydrogen** technologies, the standards ISO 19385:2006 and 19384:1999 have been withdrawn, to avoid regulation making reference to them, as the technology matured. These standards referenced to outdated fuelling mating surfaces and boil-off strategies. A new set of standards for the transport, on-board storage, use of LH2 is still needed, as reported in [R005].

In Europe, the **EIGA's** Code of Practice for liquid hydrogen safety isn't mandatory but highly regarded. This comprehensive guideline has been recently updated with a performance-based focus, offering a thorough approach to storage, handling, and distribution safety.

The main European code for developing **transport category aircraft** is the certification specification CS-25, with last update Amendment 27 from January 2023. This code lists the main requirements for such aircraft, while setting limits for hazard frequency based on the severity of effects, particularly in CS 25.1309 and the associated acceptable means of compliance.

Another important document to reference is the SANDIA SAND2012-7321, a Technical Reference for hydrogen **compatibility of materials**.

In 2017, the **Energy Supply Device Aviation Rulemaking Committee** of the Federal Aviation Administration (FAA) issued a report [DOT/FAA/TC-19/16] containing findings and recommendations for **airworthiness standards** of hydrogen fuel cells in transport aircraft. Sections D.4.2 and D.5 of the document offer a list of standards and certification rules applicable to a liquid hydrogen tank system and its components. The committee urged actions from FAA safeguarding hydrogen tanks and fuel lines from unsafe temperatures during crash landings, suggesting proper positioning to minimize rupture risks. It advocates for fuselage fuel lines designed for deformation without leakage. Additionally, the committee proposes installing hydrogen leakage detection systems in areas where hazardous hydrogen accumulation is possible on the airplane.

The main document developed in US for managing the **safety of hydrogen** system is the American National standard G-095-2017, derived from the NASA Technical Memorandum NSS 1740.16 from 1977. A Brief analysis follows of the annex B of the specified standard.

6.4 Brief report on hydrogen safety guidelines

The American National Standard "Guide to Safety of Hydrogen and Hydrogen Systems" classifies regulatory requirements basing on their functionality. The categories identified are the following.

- Pressure vessels codes and standards
- Codes and standard for pressure piping
- Standards and regulations for the commercial, industrial and non-propellant use of hydrogen
- Standards for the propellant use of liquified hydrogen
- Regulations for transportation equipment and the transport of hydrogen.

Here are some considerations reported from the standard under exam, with a shortened title reference to improve readability.

6.4.1 Pressure Vessels

B.1: *"... Hydrogen storage is separate in two categories in this Guide: nonpropellant and propellant use.*

- *The nonpropellant category involves the storage of GH₂ and LH₂ in which the main safety consideration is release and possible burning of H₂ in air.*
- *The propellant category involves the storage and use of LH₂ in an experimental or test facility or launch complex as a propellant, for which the primary safety consideration is pressure rupture and/or rapid combustion, or detonation, of a hydrogen and oxidizer mixture. ..."*

Comment: We may consider that the storage system in the demonstrator configurational mode fits the first description, as hydrogen won't be used as a propellant.

B.2.1: *"... 29 CFR1910.103 specifies that LH₂ storage containers shall comply with and be designed, constructed, and tested in accordance with appropriate requirements of ASME BPVC, Section VIII – Unfired pressure vessels. ..."*

6.4.2 Pressure Piping

B.3.1: *"... Sections A13.1, B31.1, and B31.3 of ASME B31 are the most applicable to hydrogen systems. ..."*

Comment: Code for cryogenic piping was incorporated in ASME B31.3

B.3.2: "... B31.12 is applicable up to and including the joint connecting the piping to associated pressure vessels and equipment but not to the vessels and equipment themselves. ..."

B.3.3: "... Piping, as used in ASME B31.3, includes pipe, tubing, flanges, bolting, gaskets, valves, relief devices, fittings, and the pressure-containing portions of other piping components. ..."

B.3.4: "... The information on CGA G-5.4 is general in nature and intended for use by designers, fabricators, installers, users and maintainers of hydrogen piping systems and should be of interest to safety personnel, fire departments, building inspectors, and other emergency personnel. CGA G-5.4 specifies piping systems should be designed in accordance with ASME B31.3. ..."

6.4.3 Non-Propellant Hydrogen

B.4.1: "... NFPA 50A and NFPA 50B have a narrow scope of application. They cover bulk storage vessels from the point of fill connection to the point at which hydrogen enters the distribution piping. ..."

"... NFPA 2 Hydrogen technologies, published in 201 that incorporates hydrogen guidance previously located in separated NFPA standards. ..."

"... Guidelines ... such as DoD 6055.9-STD primarily established for explosives and propellants for missile and rocket applications, were considered in the formulation of the NFPA standards for industrial applications. ..."

B.4.1.3: "... NFPA 50B covers the requirements for the installation of LH2 systems on consumer premises for which the hydrogen supply to the consumer premises originate outside the consumer premise, and is delivered by mobile equipment..."

Comment: This applies to the case of the demonstrator testing.

B.4.2: "... The CFR ... is divided into titles, which represent broad areas ... The titles that are of primary interest to the use of hydrogen include Title 29-Labor and Title 49-Transportation. ..."

B.4.2.2: "... NFPA 50A and 50B for GH2 and LH2 storage were incorporated almost completely into 29 CFR 1910.103. ..."

6.4.4 Propellant Hydrogen

B.5.1: "... A standard that applies to LH2 installations where liquid propellants are present and covers all types of liquid propellant storage areas, including missiles,

rockets, and multi compartment tanks in which liquid fuels and liquid oxidizer are stored is DOD 6055.9-STD. ..."

Comment: This case does not apply to the demonstrator testing, but the cited regulation contains several protective measures that can be useful to mitigate hydrogen hazards.

6.4.5 Hydrogen Transport

B.6.1: *"... Regulations related to transportation equipment and to the transport of hydrogen, are given in 49 CFR, Subtitle B, Chapter I, Subchapters A, B, C. ..."*

B.6.2: *"... Subchapter C prescribes the requirement of the DOT governing the transportation of hazardous materials. ..."*

Comment: Subchapter C (HAZARDOUS MATERIALS REGULATIONS) ranges from Part 171 to Part 180, including cryogenic liquids and aircraft transportation.

6.5 External resources and links

A valuable resource is the European database "Hylaw" that groups some of the regulatory requirements relating to hydrogen.

<https://www.hylaw.eu/>

The International Association for Hydrogen Safety, also known as "Hysafe" is a non-profit organization with the mission of facilitating the international coordination, development and dissemination of hydrogen safety knowledge by being the focal point for hydrogen safety research, education and training. Some resources are available in the link below.

<https://hysafe.info/references/>

The European Hydrogen Observatory hosts a list of applicable Policies and Standard at the website:

<https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/policies-and-standards>

The actual Codes and Standards listed are ISO, IEC, EN and OIML. The application area of the hundred codes and standards listed is various and ranges from the production of hydrogen, its distribution and storage, to end-use applications, Safety, Quality and fuel measurements.