



LH₂CRAFT - SAFE AND EFFICIENT MARINE TRANSPORTATION OF LIQUID HYDROGEN

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CONCEPT AND BASIC & DETAILED ENGINEERING DESIGN OF THE HDMSS

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EXECUTIVE SUMMARY

The purpose of this document is to reflect the latest detailed design of the handling, distribution and monitoring subsystems (HDMSS). This specific deliverable is the development of the work carried out within tasks T5.1 and T5.2.

The first part of this deliverable presents the concept design of the Liquid Hydrogen Handling, Distribution, Monitoring and Safety System (LH2 HDMSS) for the developed LH2 carrier. The system is designed to support the safe and efficient loading, storage, monitoring, and unloading of liquid hydrogen cargo in accordance with the vessel's operational requirements and the developed cryogenic containment technologies.

The work includes the development of high-level Process and Instrumentation Diagrams (P&IDs), the definition of key safety systems and sensors (including ventilation, gas and fire detection, fire suppression, and emergency shutdown systems), and the conceptual design of the associated electrical systems, such as power supply, protection devices, power electronics, and control systems.

In addition, the deliverable assesses LH2 port bunkering facilities and transfer methods, considering the potential use and adaptation of existing LNG terminal infrastructure.

The activities of the second part of the deliverable, include the execution of core engineering calculations covering flow rates, nominal pipe sizing, material selection, pipe stress analysis, and the dimensioning of pumps and associated system components. In parallel, a simulation model of the LH2 HDMSS is developed to evaluate and optimise overall system performance under representative operating conditions.

The design of the auxiliary systems has been reviewed both from qualitative and quantitative safety perspectives within tasks T8.2, T8.3 and T8.4. The results of both safety aspects have been well considered and reflected in the final promoted design.

All design activities are carried out in accordance with the applicable regulations, recommendations, and guidelines issued by relevant Classification Societies and maritime regulatory frameworks for hydrogen-fuelled and hydrogen-carrying vessels. The outcome of this work is a consolidated general description of the proposed LH2 HDMSS design concept, establishing the technical basis for subsequent engineering development, safety evaluation, and future system integration activities within the project.

The engineering design process has already been reviewed and approved in principle by ABS Classification Society (Task 9.1). The submitted list of documents/drawings for the thorough review is added on the Appendices section of this deliverable.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
BOG	Boil-Off Gas
CCS	Cargo Containment System
ESD	Emergency Shut Down
ESDS	Emergency Shut Down System
GCU	Gas Combustion Unit
GH2	Gaseous Hydrogen
HD	High Duty
HDMSS	Handling, distribution and monitoring subsystems
IAS	Integrated Automation System
IBS	Inter Barrier Space
IS	Insulation Space
LD	Low Duty
LH2	Liquid Hydrogen

1 INTRODUCTION

This deliverable presents the concept, basic and detailed design of the Liquid Hydrogen Handling, Distribution, Monitoring and Safety System (LH2 HDMSS) for the developed LH2 carrier, supporting the safe and efficient loading, storage, monitoring, and unloading of liquid hydrogen cargo. The design is developed in alignment with the operational requirements of liquid hydrogen carrier vessel and the integrated cryogenic containment technologies under development within the project.

The work includes the preparation of the system-level engineering concept and the definition of the main functional architecture required for nominal operating conditions. The proposed concept design encompasses the development of single-line Process and Instrumentation Diagrams (P&IDs), providing a high-level representation of the LH2 cargo handling processes, system interfaces, operational flows, and control logic.

Particular emphasis is placed on safety and risk mitigation from WP8, due to the specific properties and operational challenges associated with liquid hydrogen. The deliverable therefore defines the principal safety systems and associated sensor networks, including ventilation arrangements, gas detection systems, fire detection and suppression systems, and emergency shutdown (ESD) functionalities. These systems are designed to ensure safe operations during cargo transfer, storage, and handling activities while complying with applicable maritime safety standards and hydrogen-specific requirements.

In parallel, the concept design addresses the electrical architecture necessary to support LH2 handling operations, including power supply arrangements, power electronics, electrical protection devices, and integrated system control functions. The proposed electrical systems are intended to ensure operational reliability, redundancy, monitoring capability, and compatibility with the vessel's wider energy and automation infrastructure.

Additionally, the report includes fundamental engineering calculations such as flow rates, pipe sizing, material selection, pipe stress analysis, and the dimensioning of pumps and key system components. In parallel, a simulation model of the LH2 HDMSS is developed to evaluate system behaviour and optimise operational performance under relevant conditions.

The deliverable also assesses the feasibility of port bunkering facilities and transfer methods for LH2, taking into consideration the potential adaptation and utilisation of existing LNG terminal infrastructure. The assessment identifies key technical considerations, compatibility aspects, operational constraints, and opportunities for leveraging established LNG practices to facilitate future LH2 bunkering operations and infrastructure deployment.

All design activities are carried out in accordance with the applicable regulations, recommendations, and guidelines issued by relevant Classification Societies and maritime regulatory frameworks for hydrogen-fuelled and hydrogen-carrying vessels. The outcome of this work is a consolidated general description of the proposed LH2 HDMSS design concept, establishing the technical basis for subsequent engineering development, safety evaluation, and future system integration activities within the project.

2 PORT BUNKERING FACILITIES AND METHODS ASSESSMENT

2.1 PORT BUNKERING INFRASTRUCTURE AND PORT OPERATIONS – CASES OF KOBE AND VICTORIA INFRASTRUCTURE

The Kobe LH₂ Terminal (“Hy touch Kobe”) represents the world’s first operational maritime liquefied hydrogen (LH₂) import terminal and constitutes the central infrastructure component of Japan’s Hydrogen Energy Supply Chain (HESC) demonstration project. Developed by the CO₂-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA) in collaboration with Kawasaki Heavy Industries, Iwatani Corporation, Shell Japan, and other industrial stakeholders, the facility demonstrates the technical feasibility of a complete international liquefied hydrogen supply chain integrating hydrogen production, liquefaction, maritime transport, cryogenic unloading, storage, and redistribution [1], [2] and [3]. The Kobe installation therefore represents a first-of-a-kind demonstration platform for future international hydrogen trade and serves as one of the most advanced global reference cases for liquid hydrogen port engineering.

The terminal is located on Kobe Airport Island within the Port of Kobe, Japan, occupying an area of approximately 10,000 m² within a controlled industrial-port environment [1]. The site was selected because of its deep-water accessibility, integration with existing industrial infrastructure, hazardous materials handling capability, and proximity to future hydrogen demand centres within the Kansai industrial region. Unlike conventional LNG terminals, the Kobe LH₂ facility was designed specifically for handling hydrogen at cryogenic temperatures approaching –253°C, thereby introducing engineering challenges considerably more severe than those encountered in liquefied natural gas infrastructure.

The Kobe terminal functions as the receiving node of the HESC demonstration chain, which initially linked brown-coal-derived hydrogen production in Victoria, Australia, to liquefaction facilities at Hastings and maritime transport to Japan using the world’s first dedicated liquefied hydrogen carrier, Suiso Frontier [3]. Upon arrival at Kobe, the hydrogen is unloaded through dedicated cryogenic transfer systems and stored in a specially engineered spherical cryogenic storage tank before redistribution.

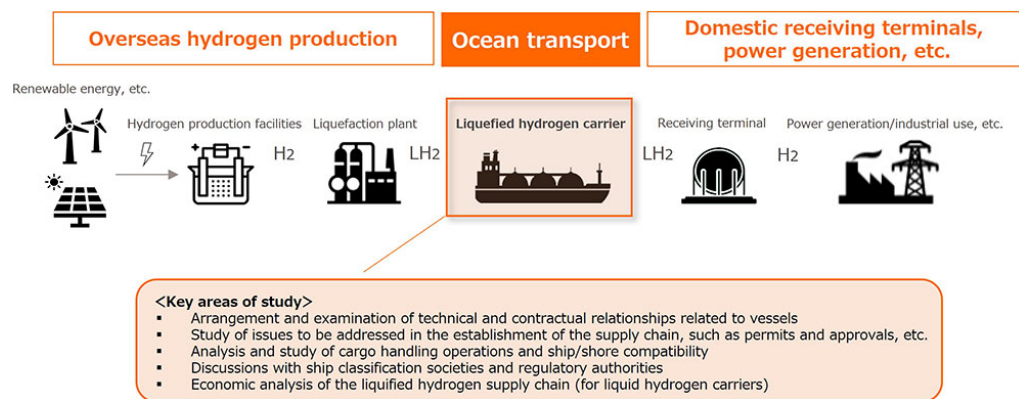


Figure 1. Simplified Hydrogen Energy Supply Chain Architecture [4]

The marine infrastructure at Kobe constitutes one of the most technologically advanced components of the project. A dedicated berth was constructed specifically for the Suiso Frontier vessel and includes cryogenic unloading interfaces, emergency shutdown systems, gas detection systems, mooring stabilization systems, and exclusion safety zones [5]. The berth was designed to manage both operational transfer conditions and emergency response scenarios associated with liquid hydrogen handling.

The Suiso Frontier itself represents a major engineering milestone in maritime hydrogen transport. The vessel is approximately 116 m in length with a gross tonnage of roughly 8,000 tonnes and incorporates a

vacuum-insulated double-shell LH₂ cargo tank with a storage capacity of approximately 1,250 m³ [3]. The ship stores hydrogen at approximately -253°C and employs technologies derived partly from Japanese aerospace cryogenic systems. Because liquid hydrogen possesses significantly lower volumetric energy density than LNG and experiences much greater boil-off sensitivity, the vessel required extensive innovations in cryogenic insulation, pressure management, and boil-off gas handling.



Figure 2. Suiso Frontier LH₂ Carrier [3]

The central fixed infrastructure element at Kobe is the 2,500 m³ spherical LH₂ storage tank constructed by Kawasaki Heavy Industries and operated by Iwatani Corporation [2]. The tank provides approximately 2,250 m³ of usable cryogenic storage capacity and is among the largest operational liquid hydrogen storage systems currently deployed in Japan. The tank employs double-shell vacuum insulation technology combined with multilayer thermal barriers to minimize conductive and convective heat transfer.

The spherical geometry of the storage tank was selected because it minimizes surface-area-to-volume ratio, thereby reducing thermal ingress and boil-off gas generation. Spherical vessels additionally provide improved stress distribution under cryogenic thermal cycling conditions compared with cylindrical alternatives [6]. Because LH₂ temperatures are approximately 90°C colder than LNG temperatures, thermal contraction, material embrittlement, and insulation performance become significantly more demanding engineering challenges [7].

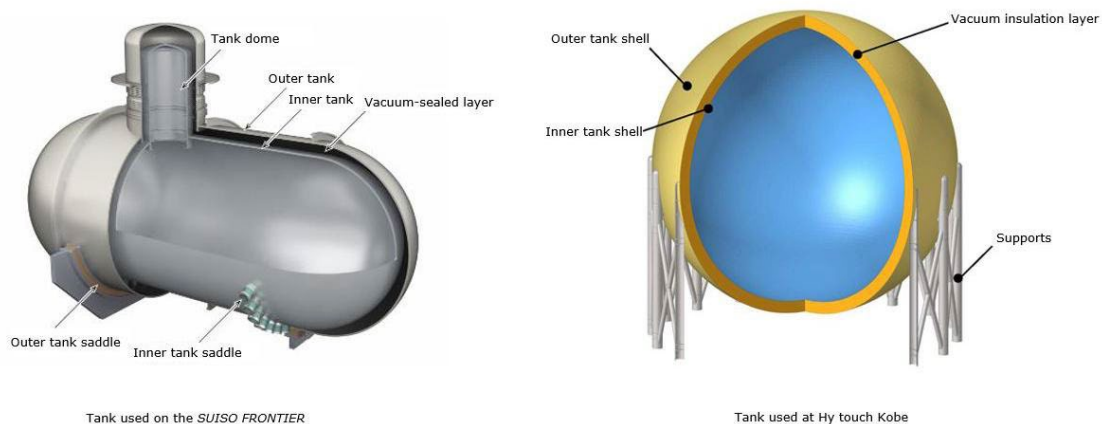


Figure 3. Kobe LH₂ Spherical Storage Tank [8]

One of the most important technological developments achieved at Kobe concerns the loading and unloading methodologies employed for ship-to-shore LH₂ transfer. The terminal has demonstrated two

principal transfer approaches: vacuum-insulated flexible cryogenic hose systems and articulated steel-pipe loading arm systems [9]. Both technologies are essential because conventional LNG transfer systems are unsuitable for operation at -253°C .

The initial demonstration unloading operations employed flexible vacuum-insulated cryogenic hoses. These systems provide several operational advantages, including mechanical flexibility, relatively low installation complexity, and accommodation of vessel movement during transfer operations. Flexible hose systems are particularly suitable for pilot-scale or demonstration operations where transfer volumes remain limited. However, such systems also present important limitations, including reduced long-term durability, susceptibility to thermal fatigue, and limitations in large-scale commercial transfer capacity.

The unloading sequence begins with vessel berthing and mooring stabilization followed by establishment of hazardous exclusion zones and inerting procedures. Prior to transfer operations, all piping systems undergo controlled cooldown procedures to prevent thermal shock and excessive boil-off generation. Once cryogenic equilibrium conditions are established, the transfer systems are connected and pressure equalization is performed before hydrogen transfer commences. During unloading, boil-off gas generated through unavoidable thermal ingress is redirected toward dedicated boil-off gas management systems.

A major advancement occurred in 2023 when Kobe successfully demonstrated the world's first articulated steel-pipe loading arm system specifically designed for liquefied hydrogen transfer [9]. This system represents a critical enabling technology for future commercial-scale hydrogen ports. The loading arm consists of vacuum-jacketed double-wall steel piping incorporating articulated cryogenic swivel joints and emergency release systems. The demonstrated system employed approximately 6-inch-diameter transfer piping and was capable of operation at temperatures approaching -253°C .



Figure 4. Conceptual LH₂ Loading Arm Configuration [8]

The engineering challenges associated with LH₂ loading arms are severe. Hydrogen embrittlement can degrade metallic structures over time, while extreme cryogenic temperatures produce substantial thermal contraction and mechanical stress. Simultaneously, vessel motions induced by wave activity introduces dynamic loading conditions on transfer systems and swivel joints. Heat ingress into the transfer lines generates boil-off gas that must be continuously managed to avoid pressure excursions.

To address these challenges, the Kobe loading arm system incorporated specialized cryogenic-compatible metallurgy, vacuum-insulated rotating interfaces, thermal isolation barriers, and advanced sealing materials [9]. Emergency Release Systems (ERS) were additionally integrated to permit safe rapid disconnection in the event of vessel drift, operational failure, or emergency shutdown conditions.

Boil-off gas (BOG) management constitutes one of the most critical operational aspects of liquid hydrogen infrastructure. Since the complete thermal isolation is physically impossible, small quantities of thermal energy are transferred to the stored LH₂, forcing it to evaporate. The Kobe terminal therefore incorporates dedicated BOG handling infrastructure including vapor return piping, compressors, pressure stabilization systems, temporary gaseous hydrogen storage systems, and controlled venting systems [10]. Effective BOG management is essential not only for operational efficiency but also for pressure stabilization and safety.

The safety architecture of the Kobe terminal reflects the unique hazards associated with liquid hydrogen. Hydrogen possesses a wide flammability range, low ignition energy, and high diffusivity. Combined with cryogenic temperatures, these characteristics introduce risks including fire, explosion, rapid phase transition events, overpressure conditions, and material fracture due to embrittlement. Consequently, the Kobe terminal integrates hydrogen leak detectors, emergency shutdown systems, pressure relief systems, vent stacks, fire protection systems, and operational exclusion zones.

Recent consequence analyses and bunkering risk assessments associated with LH₂ transfer facilities have emphasized the importance of redundancy, passive thermal protection, rapid leak isolation, and real-time monitoring systems [10]. Compared with LNG infrastructure, LH₂ terminals require substantially greater emphasis on insulation integrity, leak detection sensitivity, and cryogenic material performance.

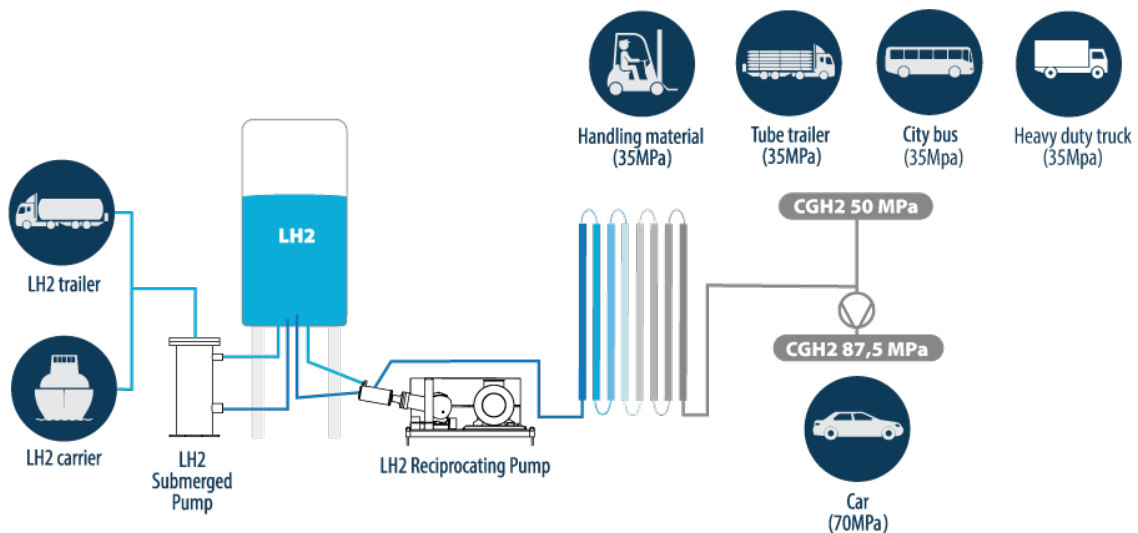


Figure 5. Simplified LH₂ Terminal Transfer and Storage Configuration [11]

Although the Kobe facility remains demonstration-scale infrastructure, it provides a critical technological foundation for future commercial hydrogen ports. Current limitations include relatively small storage volumes, limited unloading capacities, and pilot-scale transfer rates. Future commercial LH₂ systems are expected to involve carriers exceeding 40,000–160,000 m³, significantly larger storage tanks, integrated pipeline distribution systems, and high-capacity articulated transfer arms [12]. Nevertheless, the Kobe project demonstrates that maritime liquefied hydrogen transport is technically feasible and that ship-to-shore LH₂ transfer infrastructure can be successfully integrated within existing industrial port environments.

The Kobe project nevertheless demonstrates that maritime liquefied hydrogen transport is technically feasible and that ship-to-shore LH₂ transfer infrastructure can be successfully integrated within existing industrial port environments.

The Kobe receiving terminal cannot be evaluated independently from its corresponding export infrastructure in Australia, which forms the upstream component of the Hydrogen Energy Supply Chain (HESC) demonstration project. The export-side infrastructure is located at the Port of Hastings in Victoria, Australia, and is generally referred to as the HESC Hydrogen Liquefaction and Loading Terminal or Hastings Hydrogen Terminal. This facility constitutes the world's first operational liquid hydrogen export terminal and serves as the loading counterpart to the Kobe import installation.

The Hastings infrastructure was developed to process hydrogen produced in the Latrobe Valley region of Victoria through brown coal gasification combined with gas purification systems. Following production, gaseous hydrogen is transported to Hastings where it undergoes liquefaction prior to maritime export. The facility therefore integrates multiple infrastructure components including hydrogen purification systems, hydrogen liquefaction units, cryogenic storage systems, boil-off gas management systems, marine loading systems, and dedicated berth infrastructure for the Suiso Frontier vessel.



Figure 6. Port of Hastings Hydrogen Export Infrastructure [13]

The liquefaction plant at Hastings represents one of the most technologically challenging components of the supply chain because hydrogen liquefaction is highly energy intensive. Hydrogen must be cooled to approximately -253°C using multi-stage cryogenic refrigeration systems involving pre-cooling, ortho-para hydrogen conversion processes, and advanced thermal management systems. The liquefaction unit was therefore designed to achieve extremely low operating temperatures while minimizing energy consumption and boil-off generation.

Following liquefaction, the hydrogen is transferred into cryogenic vacuum-insulated storage tanks prior to loading operations. Similar to the Kobe terminal, the Hastings installation employs advanced vacuum insulation systems and cryogenic-compatible materials to minimize thermal ingress. Boil-off gas generated during storage and transfer operations is captured and redirected through dedicated vapor handling systems to prevent pressure accumulation and minimize hydrogen losses.

The marine export infrastructure at Hastings includes dedicated loading systems designed specifically for LH_2 transfer to the Suiso Frontier carrier. The loading process employs cryogenic transfer lines and insulated transfer systems capable of maintaining stable thermal conditions during loading operations. Controlled cooldown procedures are implemented prior to transfer in order to minimize thermal shock and material stress. During loading operations, pressure equalization systems and boil-off gas return lines are employed to stabilize the thermodynamic conditions between shore-side storage systems and the vessel cargo tank.

Pilot Project Supply Chain

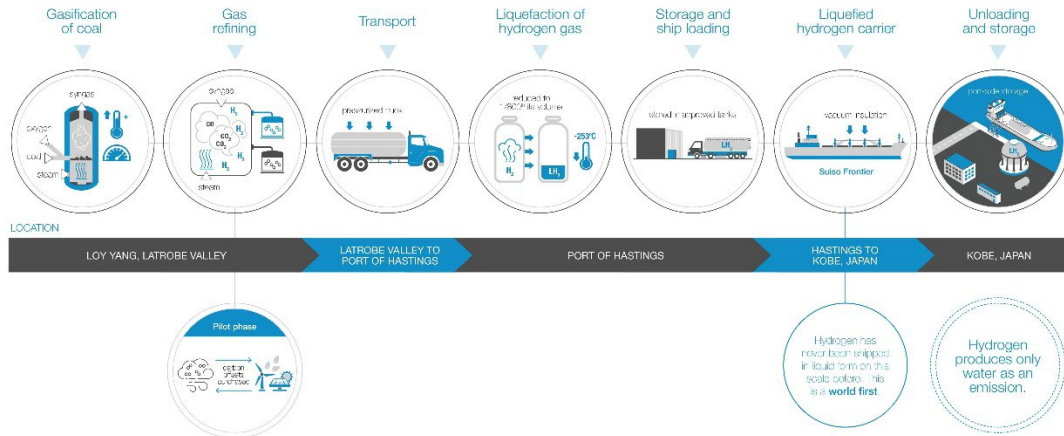


Figure 7. Simplified Australia–Japan LH₂ Export and Import Chain [14]

The Hastings export terminal and Kobe receiving terminal together constitute the first fully integrated international maritime liquid hydrogen chain ever demonstrated. The combined infrastructure therefore provides a globally significant engineering reference for future international hydrogen trade corridors involving hydrogen exporting regions such as Australia, the Middle East, North Africa, and South America supplying future hydrogen demand centres in Japan, South Korea, and Europe. As European energy systems increasingly consider hydrogen imports to support decarbonization strategies, the Kobe terminal provides a valuable engineering reference for future LH₂ receiving terminals in Rotterdam, Antwerp-Bruges, Hamburg, Marseille-Fos, and Mediterranean energy hubs.

The principal technological lessons emerging from Kobe concern the necessity of advanced vacuum insulation systems, dedicated boil-off gas management infrastructure, cryogenic-compatible materials, articulated transfer systems, and integrated safety architectures. The loading and unloading methodologies demonstrated at Kobe constitute some of the most important enabling technologies for future global hydrogen trade and are likely to influence the design basis of commercial LH₂ import terminals worldwide.

3 CONCEPT ENGINEERING DESIGN OF THE HDMSS

The current chapter intends to describe the basic operational and control philosophy for the LH2 cargo system for a safe long-term storage and long-distance transportation of LH2.

The chapter provides information about the various system components without manufacturers' specific details, which can be found at the relevant documentation.

All personnel involved with the possible operation and handling of liquid hydrogen onboard, shall be clearly aware of the hazardous nature that LH2 is associated with. Nevertheless, the most important aspect is that all involved personnel has fully understood the system's working principles and is capable to execute with or without supervision a safe operation of the system.

3.1 RELATED RULES/REQUIREMENTS AND REGULATIONS

- International code for the construction and equipment of ships carrying liquefied gases in bulk (IGC Code)
- CCC9/14 (2023) - 'Annex 7: Draft MSC Resolution on Revised Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk'
- CCC 8-INF.17 - A study on the transportation cost of a liquefied hydrogen carrier using boil-off-gas as a fuel (Republic of Korea)
- CCC 9-7 - Draft revised Interim recommendations for carriage of liquefied hydrogen in bulk (Australia, France, Japan, Liberia, the Kingdom of the Netherlands and United Arab Emirates)
- CCC 9-INF.18 - Introduction to the development of novel designs for liquid hydrogen fuel storage tanks for ships and demonstration plan utilizing K-GTB (Green Ship Test Bed) (Republic of Korea)
- CCC 8/WP.3 Draft Interim Guidelines for the Safety of Ships using Hydrogen as Fuel
- CCC 9/WP.6 Revision of the interim recommendations for carriage of liquefied hydrogen in bulk
- CCC 9/WP.3 Amendments to the IGF code and development of guidelines for alternative fuels and related technologies
- NK Guidelines for Liquefied Hydrogen Carriers (2023)
- NK Rules for the Survey and Construction of Steel ships – Part N: Ships Carrying Liquefied Gases in Bulk (2023)
- RINA REP3 Rules for Ships - Pt C, Ch 1, App 14, Vol.1 'Hydrogen Fuelled Ships' (July 2022)
- RINA Rules for the Classification of Ships, Part E (2024)
- ABS Hydrogen Fuelled Vessels (2023)
- ABS Requirements for Liquefied Hydrogen Carriers (2023)
- ABS Liquefied Gas Carriers with Independent Tanks (2023)
- ABS Guidance Notes on Thermal Analysis of Vessels with Tanks for Liquefied Gas (2019)
- ABS Guidance Notes on Strength Assessment of Independent Type C Tanks (2022)
- BV Rules for the classification of steel ships, NR467, Part D, Chapter 9 (2024)
- BV Hydrogen-Fuelled Ships (2023)
- DNV Handbook for Hydrogen-fuelled Vessels (2021)
- DNV Gas carrier update (2018)
- DNV Part5 Ship types, Chapter 7 Liquefied gas tankers (2023)
- KR Research Report of Material Compatibility for Liquid Hydrogen Storage on Marine Application (2023)
- LR Guidance Notes for Liquid Hydrogen Systems (2023)

- LR Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases in Bulk (2023)
- ISO report ISO/TR15916: Basic considerations for the safety of hydrogen systems

3.2 PHYSICAL PROPERTIES AND CHARACTERISTICS OF LH2

Hydrogen is the lightest element, with its most common isotope consisting of only one proton and one electron. The molecular form, simply referred to as hydrogen is colourless, odourless, and tasteless and is about 14 times lighter than air. Ordinary hydrogen is the lightest substance known with high buoyancy in air and 1.2 kg/m³ density and diffuses faster than any other gas. On cooling, hydrogen condenses to liquid at -253 °C and to solid at -259 °C, and the density of liquid hydrogen at one-atmosphere pressure is approximately 800 times that gaseous hydrogen. Table 1 summarises the liquid hydrogen properties available in literature.

Table 1. Liquid Hydrogen properties (MSC.420(97))

SI No.	Properties (unit)	Value
1	Boiling temperature (K)*	20.3
2	Liquid density (kg/m ³)*	70.8
3	Gas density (kg/m ³) (Air. 1.198)**	0.084
4	Viscosity (g/cm•s × 10 ⁻⁶) Gas / Liquid	8.8 / 13.49
5	Flame temperature in air (°C)	2396
6	Maximum burning velocity (m/s)	3.15
7	Heat of vaporisation (J/g)*	448.7
8	Lower flammability limit (% vol. fraction)***	4.0
9	Upper flammability limit (% vol. fraction)***	75.0
10	Lower detonation limit (% vol. fraction)***	18.3
11	Minimum ignition energy (mJ)***	0.017
12	Auto-ignition temp. (°C)***	585
13	Toxicity	non
14	Temperature at critical (K)	33.19****
15	Pressure at critical point (kPaA)	1297****
*At their normal boiling points for comparison purpose. **At normal temperature and pressure. ***Ignition and combustion properties for air mixtures at 25°C and 101.3 kPaA. ****Normal hydrogen		

It should be noted that the IMO Maritime Safety Committee is addressing the “*Development of a safety regulatory framework to support the reduction of GHG emissions from ships using new technologies and alternative fuels*”. Several aspects of hydrogen as fuel are also fully applicable to hydrogen as cargo and the

report of the IMO Correspondence Group MSC 108/5 (based upon IMO MSC 105/2/2 and annexes to IMO CCC 9/INF.17) provides the following description:

- Hydrogen may be used as fuel for fuel cells, reciprocating internal combustion engines, gas turbines or boilers, but these technologies are still under development.
- Hydrogen is gaseous at atmospheric pressure and at temperature above -253°C.
- Hydrogen may be liquified only at temperature below its critical temperature (about -240°C)
- Gaseous hydrogen at ambient conditions is much lighter than air (0.08988 g/m³ vs 1.225 kg/m³).
- Hydrogen is very easy to ignite (minimum ignition energy of only 0.016 mJ) and shows the unusual property that the expansion is exothermal (hydrogen is heated by expansion). The flammability/explosivity range of hydrogen in the air is very wide, between 4% (LEL) and 74% (UEL). Hydrogen is typically stored as a compressed gas, or in a liquified form by cooling, or may be stored in metal hydrides at ambient temperature and low pressure (values depending on the specific metal).
- Hydrogen, in contact with certain metals, may cause their embrittlement. In case of some steels operating at elevated temperatures (typically above 400°C) in hydrogen-rich atmosphere, a phenomenon named High Temperature Hydrogen Attack (HTHA) needs to be taken into consideration as well.
- As most materials (metals and polymers) are permeable to hydrogen, hydrogen diffusion in metallic materials is difficult to grasp owing to the non-uniform compositions and material structures; further research would be necessary to enable safe application of hydrogen in future ship propulsion as well as energy storage and conversion machinery.
- In case of liquefied hydrogen, the low temperatures may cause condensation of air on exposed parts of the containment system, with a possibility of localized oxygen enrichment due to the condensation from the atmosphere.

Some relevant properties of hydrogen (from MSC 108/5):

- Flammability limit (vol%) 4.1-74.8 very broad compared to other gases
- Detonation limit (vol%) 18.3-59.0 very broad 'compared to other gases
- Min ignition energy (mJ) 0.017 very low compared to other gases
- Laminar burning velocity (cm/s) 270 very high compared to other gases
- Autoignition temperature 585°C

3.2.1 POTENTIAL HEALTH HAZARDS OF LH2

Hydrogen Risks/hazards according to IMO (Table 2)

- leak due to permeability of materials;
- fire and explosion;
- frost bite;
- material embrittlement; and
- oxygen enrichment.

Table 2. List of HAZARDS per area

Area	HAZARDS
Chemical	• Physiological (suffocation, asphyxiation, and respiratory problems - frostbite, hypothermia for LH₂), • Physical (embrittlement, failures, and phase change), • Chemical (fire, explosion) • Extremely low electro-conductivity rate - flow and agitation of hydrogen generate electrostatic charge that might trigger the spark, • Propensity for leakage of compressed hydrogen (smallest molecule), • LH₂ leak can create solidified air creating conditions for detonation. Regassified air is oxygen rich creating conditions for explosion. • LH₂ leak turns into cold vapour that if in contact with a hotter liquid create a Rapid Phase Transition explosion. • The product of combustion of hydrogen exhaust (Smoke) is water vapour – not dangerous
Bunkering	• Hydrogen release or leak • Hydrogen release or leak – hose failure/ loading arm
Navigation	• Vessel collision or grounding leading to tank rupture/damage and so to hydrogen leak/release • Grounding leading to hydrogen leak and fuel tank damage
Fuel Storage	• Hydrogen release or leak
Fuel preparation/handling system	• Hydrogen release or leak • Structure damage
Fuel Management system	• Over-pressurisation of tank
Vent System	• Internal Deflagration/detonation • Local Leakage • Over pressurisation of protected system
External risk	• Dropped objects • Cargo fire

Existing guidance documents/standards are considered to have a “Medium regulatory readiness level”.

SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through:

- SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively
- SOLAS Ch II-1 Part F (Alternative design and arrangement)
- MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455

The IGF Code does not cover hydrogen as fuel. Resolution MSC.420(97) provides interim recommendations for carriage of liquid hydrogen in bulk. Draft interim guidelines for the safety of ships using hydrogen as fuel are currently under development.

According to IMO document MEPC 80/INF.17 no marine standards are available, but ISO 14687:2019 "Hydrogen fuel quality – Product specification" is quoted in IMO document MSC 105/2/2 and also see annexes to IMO document CCC 9/INF.17.

3.3 DESIGN VESSEL PRINCIPAL PARTICULARS (WP4)

The principal particulars of the vessel are listed in the following Table 3:

Table 3. LH2 Principal particulars summary

Description	Value/description
Type of Ship	Liquefied hydrogen carrier 2G
Type of Cargo	LH2
Cargo tanks	Membrane tanks
Stem	Bulbous bow and raked stem
Stern	Twin skeg design
Classification	ABS
Length O.A.	299.06 m
Length B.P.	291.00 m
Breadth (MLD)	46.4 m
Depth (MLD)	26.5 m
Depth (Trunk)	35.5 m
Draft Design (MLD)	This value will be elaborated and included in D4.1 (Preliminary ship design and integration of LH2 CCS)
Scantling Draft (MLD)	This value will be elaborated and included in D4.1 (Preliminary ship design and integration of LH2 CCS)
Design cargo temperature	-253°C
Design cargo pressure	0.1 MPa
Insulation vapor design pressure	0.035 MPa

Important Note 1: It shall be highlighted that no re-liquefaction system is examined under the scope of this report, due to the scope of the specific report. Nevertheless, re-liquefaction system will be investigated at a basic engineering design level, in the context of desktop studies and will be reported in deliverables D4.3 (Integration solutions for alternative CCS) and D5.3 (Modularity and scalability of the HDMSS).

Important Note 2: The fuel supply system is considered out of scope for the subject document and its investigation. Thus, the document is limited only to the long-distance storage of LH2 with no fuel consumers considered.

In this chapter the following aspects are documented and examined:

- All the sub-systems of the handling, distribution and monitoring subsystems components and equipment, excluding the main engine (out of scope of this report) and the cargo containment system, which is part of WP3.

- The final process flow diagrams and systems schematics
- All the engineering calculations, including the material evaluation and selection process, pipe thickness, materials, calculations and components sizing
- A simulation model, for verification of LH₂ density, pressure, temperature and flow velocity during key operation modes.

3.4 LH2 CARGO OPERATION MODES

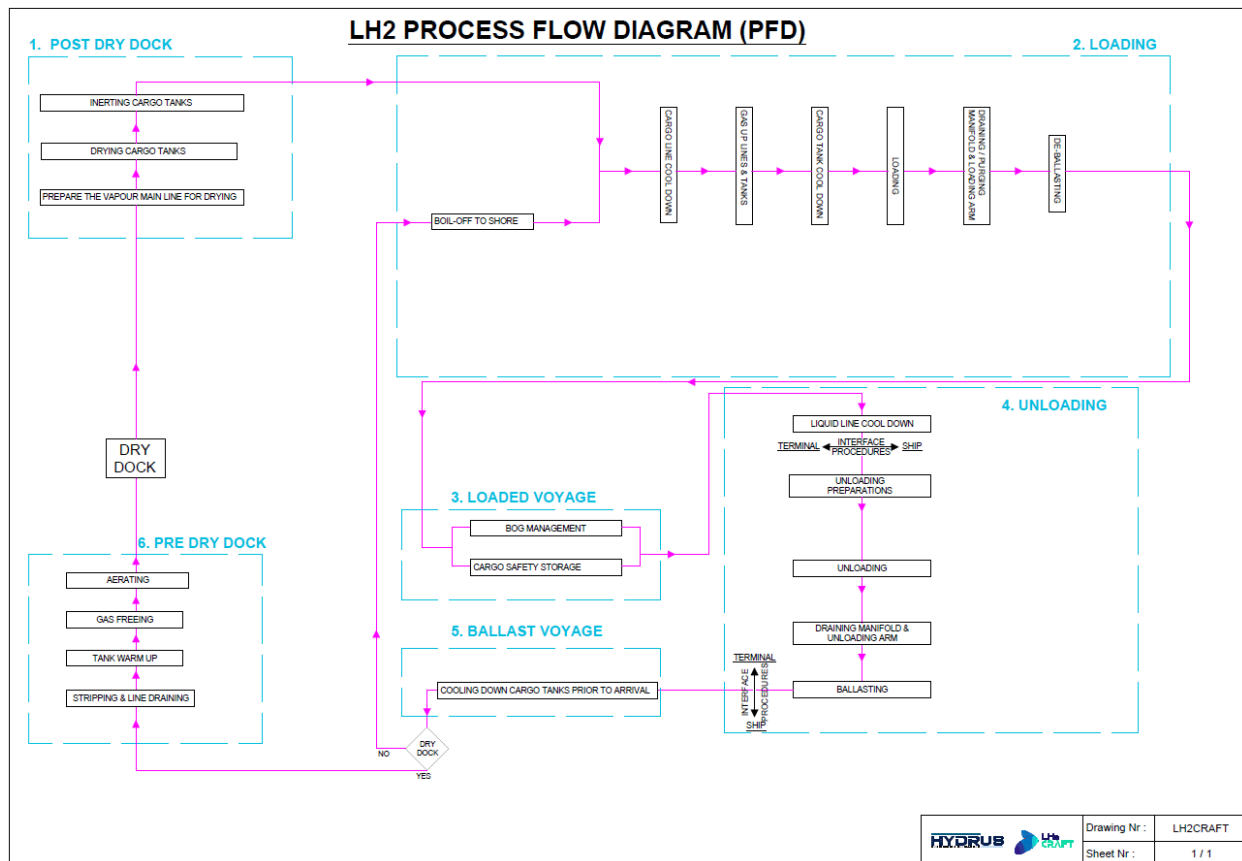


Figure 8. LH₂ cargo operation modes

3.4.1 M1.1 – DRYING OF CARGO TANKS

After the completion of various works performed at the dock, the cargo tanks which have been opened up for inspection, maintenance and potential repair works, contain humid air which must be dried out before any future cargo operation. The absence of moisture in cargo tanks is necessary in order to avoid the formation of ice during their cooling down process.

The supply of dry air is performed either from the top of the tank (gas dome & vapor main) or from the bottom (filling pipes) depending on the atmospheric condition of the surrounding environment. For instance, in the summer, when ambient air is lighter than the dry-air, the latter is supplied from the bottom, displacing the ambient air from the top of each tank via the vapor main and from No.1 inert gas vent mast eventually. On the contrary, in winter when the dry air is lighter than the ambient air, the first is introduced from the top of the tank and the latter is displaced through the filling line, to the liquid main and then vented in the atmosphere through the vent mast (this mode will not be reflected in this manual, for simplicity purposes).

Given the above, it is understood that there are deviations regarding drying operation from summer to winter.

Two crucial parameters of the drying operation are the target dew point and the duration of the process in order to achieve it, which are assumed same as those for LNG Carriers (i.e. about 20 hours of drying in order to reduce the dew point below -20°C). This is reasonably justified considering that the volume of LH2 Carrier tanks is slightly reduced compared to LNG Carrier and also that the moisture in air is minimal for temperatures below -20°C as reflected in Figure 9.

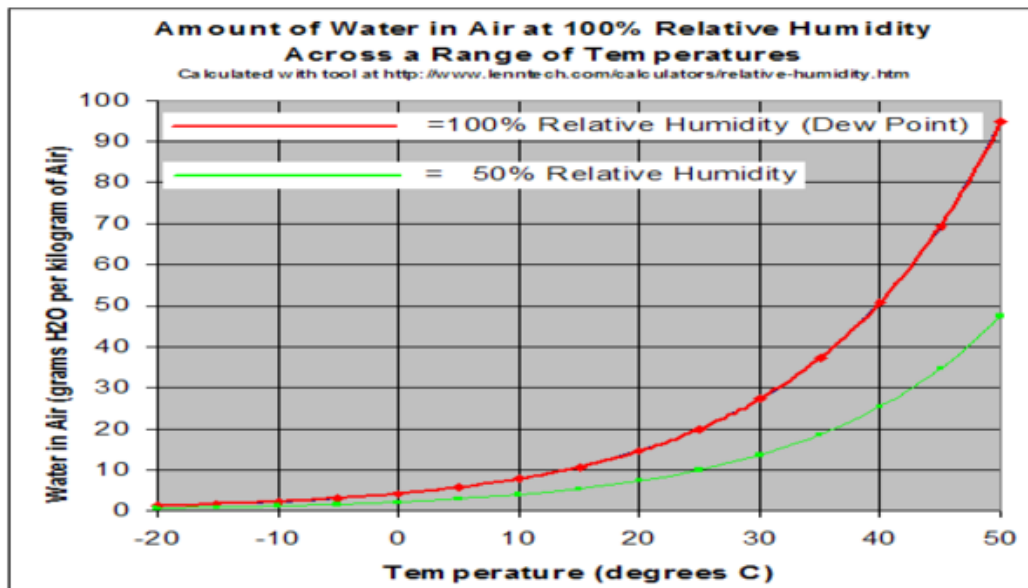


Figure 9: Air Dew Point Correlation with Temperature

3.4.2 M1.2 – INERTING OF CARGO TANKS

Given that the dew point of the tanks is below -20°C , the various processes/steps related with supply of inert gas can initiate. The target of inerting process is to reduce cargo tanks O_2 content below 1% in volume (subject to be evaluated) as well as the dew point below -20°C .

3.4.3 M2.1 – GAS UP OF CARGO LINES & TANKS WITH GH2 FROM SHORE – THROUGH GCU

After the dry-dock, the cargo lines and tanks of the LH2 carrier are filled with inert gas which shall be replaced by warm hydrogen (state, temperature & pressure of it to be evaluated) supplied by the terminal.

3.4.4 M2.2 –CARGO LINES & TANK COOL DOWN – VAPOR RETURN TO SHORE

The cargo tanks will be normally maintained at -253°C , in order to be achieved, at first the cargo lines shall be cooled down. LH2 will be inserted into the piping network through the liquid crossover at a limited flow rate. At the insertion of the liquid to the lines vapor will be generated and sent to all cargo tanks through the filling valves and the needed quantity of vapor H_2 is returned to the shore.

3.4.5 M2.3 – LOADING WITH VAPOR TO SHORE - FORCED

During loading of the cargo tank, vapor generated due to the flash evaporation of LH2 is removed to the shore, to maintain tank pressure withing nominal working limits. Before the initiation of the operation mode the following set of checks shall be done:

- Testing of the remote operation of all cargo tank valves and manifold ESD valves.
- Testing of the remote operation of the ballast valves, the water ballast pumps, safety systems and glycol water systems
- Confirmation of the operation of the hull water curtains, firefighting equipment, water spray system

3.4.6 M2.4.1 – COOLING DOWN CARGO TANKS – RETURN VAPOR TO SHORE

The scope of the subject procedure is to cool down the cargo tanks during upon arrival to the terminal and before the full loading. It is considered that at the starting point of the process all the valves are closed and that an amount of heel has been retained in all the tanks (considered minimum pump down level of each tank 0.5 m). The procedure is considered as successfully completed when cargo tank average temperature reaches -253°C.

3.4.7 M2.4.2 – COOLING DOWN CARGO TANKS – USING THE GCU

The scope of the subject procedure is to cool down the cargo tanks during upon arrival but without connection to the shore facilities. The procedure is considered as successfully completed when cargo tank average temperature reaches -253°C.

3.4.8 M3.1 – LADEN VOYAGE

In this condition all PRV cargo tanks valves shall be checked to be in a fully operable condition.

3.4.9 M3.2 – ANCHORAGE CONDITION IN LADEN MODE WITH THE USE OF GCU

Once the vessel is in anchorage condition in laden mode, the use of GCU is considered to handle the excess hydrogen vapor created.

3.4.10 M4.1 – LIQUID LINE COOL DOWN BEFORE DISCHARGING WITH THE USE OF THE GCU

The cargo lines are cooled down before arrival at the respective terminal. This mode purpose is to ensure that the discharging will commence as soon as the vessel is moored at the terminal.

The needed spool pieces along with the respective filters shall be mounted. The liquid line cool down is carried out using the spray pump in No.3 tank to pump LH2 from No.3 cargo tank through the spray main to the liquid manifold pipe network. Vapor displaced from the crossover pipe network passes through the liquid main and then back to No.2 cargo tank via the filling line. Vapor from the tanks will be supplied and burned to GCU using No.1 HD compressor (which is maintaining tank pressure) and No.2 heater.

3.4.11 M4.2.1 – UNLOADING WITH VAPOR RETURN FROM SHORE

Subject operational mode follows the completion of liquid line cooldown and is related with the discharge of LH₂ to the terminal and vapor return from shore facilities, to maintain pressure within the nominal working limits.

3.4.12 M4.2.2 – UNLOADING WITH VAPOR RETURN FROM VAPORIZER (ALTERNATIVE MODE)

Subject operational mode is an alternative operation mode to M4.2.1, in case shore connection and vapor return cannot be established. In this case, the vaporizer can be used to provide for the required vapor return function.

3.4.13 M4.3.1 – STRIPPING AND LINES DRAINING WITH SHORE FACILITIES

Subject operational procedure serves as the last stage of operations at the last unloading destination. LH₂ stripping shall take place before any warm up action of the tanks by utilizing spray pumps and considering maximum stripping of the dead heel. At the beginning of stripping procedure it is assumed that cargo pumps are closed, having already be utilized to the maximum extent in order to discharge the cargo (LH₂). Gaseous hydrogen is considered that is provided from the shore (unloading terminal) through port manifold and that the stripped (removed) LH₂ is discharged again to the shore.

3.4.14 M4.3.2 – STRIPPING AND LINES DRAINING WITH VAPORIZER

Subject operational procedure serves as the last stage of operations at the last unloading destination, but in this case no connection with the shore facilities is being established. Gaseous hydrogen is considered that is provided from usage of the vaporizer and that the stripped (removed) LH₂ is discharged to the shore.

3.4.15 M5 – BALLAST VOYAGE

Once the vessel is in ballast voyage, each tank PRV valves shall be opened in order each PRV valve to be operating at all times.

3.4.16 M6.1.1 – CARGO TANKS WARM UP

Cargo tank warm-up is part of the gas-freeing operations carried out prior to a dry docking or when preparing tanks for inspection purposes and is performed in two steps.

Step 1

Before the cargo tanks are warmed up, is necessary to take place vaporizing of any remaining LH₂ by introducing hot vapour through the filling lines to the bottom of the tanks to facilitate the evaporation.

Step 2

When the temperature of the tank tends to stabilise, it is necessary to introduce hot vapour through the vapour piping at the top of the tanks. The produced excess vapour that is generated during the warm-up operation, depending on whether the vessel is at sea or at port, is directed either to the GCU or to shore.

After all the LH₂ which cannot be pumped has been vaporised, the flow in the tanks is reversed to increase the thermal exchange. Cold gaseous hydrogen is sucked from the tank bottom and warm gaseous hydrogen is sent to the tank top so that the HD heater may be used with its maximum output. The warm-up operation continues until the temperature at the coldest point of the insulation space barrier of each tank reaches at least +5°C higher than the dew point of the inert gas that shall be applied in next stage. Subject is necessary in order to avoid the water content in the inert gas condensing in the tank. The overall warm-up operation requires a period of time depending on the amount of liquid hydrogen remaining in the tanks, as well as the temperature of the tanks and insulation spaces. Gas burning should continue as long as possible, normally until all the LH₂ has evaporated, venting has ceased and tank pressures start to fall.

3.4.17 M6.1.2 – CARGO TANKS WARM UP (WITH GCU)

The purpose of this operation mode is the vaporization of the remaining liquid heel amount and warming up of the insulated spaces. This operation mode shall be performed at open sea only.

3.4.18 M6.2.1 – GAS FREEING THROUGH GCU

The purpose of this operation mode is to replace the warm gaseous hydrogen in cargo tanks with inert gas. The mixture of inert gas/GH₂ shall be sent to the GCU, until a content of GH₂ of less than 1% is achieved.

3.4.19 M6.2.2 – GAS FREEING THROUGH VENT MAST (EMERGENCY USE ONLY)

This mode shall be considered only in case of emergency, the gas from the tanks is vented from the top of the tanks through the vapor main line to each LH₂ vent mast.

3.4.20 M6.3 – AERATING

Aeration is taking place after the gas freeing operation to ensure that the atmosphere in the cargo tanks is suitable for entry and ready for any repair work to be carried out.

The cargo tanks are purged with dry air until the point at which a volume of 20% oxygen is achieved, the CO₂ content is less than 0.5% (by volume) and the CO content is 50ppm or less. Dry air is inserted into the cargo tank via the vapor main line and the dry air is discharged through the tank filling line to the liquid main line and then vented from No.1 Inert gas vent mast.

3.4.21 M7 – ANCHORAGE CONDITION IN BALLAST MODE WITH THE GCU

Subject procedure is similar with M3.2 with only addition the utilization of the following No.1 HD Compressor valves.

3.5 SINGLE LINE PROCESS AND INSTRUMENTATION DIAGRAMS (P&IDS)

3.5.1 CARGO PIPING SYSTEM ARCHITECTURE

The Liquid Hydrogen (LH₂) cargo handling system is implemented as an integrated, redundant and safety-critical network of cryogenic liquid transfer, vapour management, inerting, and boil-off gas (BOG) handling subsystems. The architecture is designed to ensure controlled cargo operations under all loading, voyage, and discharge conditions while maintaining strict thermal and atmospheric safety boundaries.

At a system level, the architecture can be described as a **closed-loop cryogenic cargo system**, consisting of four primary functional layers:

1. Liquid Transfer Layer (LH₂ loading/discharge paths)
2. Vapour Pressure Regulation Layer (tank interconnection and venting)
3. Gas Conditioning Layer (inerting and dry air systems)
4. Boil-Off Gas Management Layer (compression, routing, and disposal)

These layers are interconnected through midship crossover structures and centralised processing rooms (cargo compressor room and inert gas room), ensuring operational flexibility, redundancy, and safe segregation of hazardous functions.

1. Liquid Transfer Subsystem (LH₂ Flow Path)

The LH₂ transfer architecture is based on dual-redundant crossover lines positioned at midship, forming the primary interface between shore-based infrastructure and shipboard cargo containment systems.

Schematic flow logic

Vessel Cargo Station (port or starboard)

- Midship crossover line
- Cargo transfer line
- Individual cargo tank liquid domes

This configuration enables:

- Bidirectional operational flexibility depending on port-side infrastructure constraints
- Load balancing between tanks through controlled distribution
- Reduced dependency on a single transfer corridor

The liquid transfer subsystem is designed to minimise hydraulic losses and thermal ingress while ensuring controlled filling of each tank via its dedicated liquid dome interface.

2. Vapour Management and Pressure Regulation Layer

Each cargo tank is equipped with a vapour dome connected to a **common vapour main line**, forming a longitudinal pressure equalisation manifold across all tanks

Schematic flow logic

Cargo tank vapour dome (Tank No.1 – Tank No.4)

- Vapour Main Line (Longitudinal Header)
- Midship Vapour Crossover

- Pressure Redistribution Across Tanks / Vent Mast Interface

This configuration supports:

- Dynamic inter-tank pressure balancing during loading and discharge
- Stabilisation of vapour phase conditions during voyage
- Prevention of localised overpressure or vacuum conditions

During laden voyage conditions, dedicated LH₂ vent masts may be activated to maintain prescribed storage envelopes and ensure compliance with safe operating pressure thresholds.

3. Inerting and Gas Conditioning Layer

The inerting system provides controlled atmosphere conditioning during maintenance, commissioning, and safety-critical transitions.

Inert Gas room

- Inert Gas / Dry Air Distribution Lines
- Cargo Tanks and Associated Systems
- Dedicated Inert Gas Vent Masts (per tank)

This subsystem enables:

- Oxygen-free environment preparation prior to LH₂ operations
- Controlled drying of piping and containment systems
- Safe purging of residual vapours during maintenance activities

The system is designed to ensure full segregation between inerting operations and active cryogenic transfer functions.

4. Boil-Off Gas (BOG) Management Layer

The BOG management system constitutes a central safety and energy control subsystem located within the cargo compressor room.

Schematic BOG handling chain

- Vapour Main Line
- Cargo Compressor Room (BOG Compression Unit)
- Gas Combustion Unit (GCU)

This architecture ensures:

- Controlled capture of thermally generated boil-off gas
- Pressure stabilisation within cargo tanks
- Safe disposal of excess gaseous hydrogen via combustion under controlled conditions

The system operates continuously during cargo operations and voyage conditions, forming a key safety barrier against uncontrolled hydrogen release.

5. Spray Cooling and Thermal Conditioning Subsystem

The spray main line is integrated to provide controlled pre-cooling and thermal conditioning of cargo tanks and piping systems.

Schematic use cases

- Cargo tanks (pre-cooling/stripping/line draining operations)

Primary functions include:

- Pre-conditioning of tanks prior to first LH₂ loading after dry dock
- Controlled temperature reduction to minimise thermal shock
- Support for stripping and residual line drainage operations

This subsystem is not continuously active but is mission-critical during transitional operational phases.

6. Cryogenic Safety and Oxygen Condensation Control

A fundamental design constraint of the cargo system is the prevention of exposed surface temperatures reaching or falling below -183°C, at which oxygen condensation may occur, potentially creating oxygen-enriched hazardous atmospheres.

In accordance with classification requirements [15], the system incorporates passive and active mitigation measures:

- Thermal insulation of exposed piping and equipment
- Spatial routing to minimise exposure zones
- Installation of drip trays and cryogenic collection systems where temperature thresholds cannot be guaranteed

Safety containment logic:

- Physical containment (drip trays / barriers)
- Controlled evaporation of collected LH₂
- Prevention of oxygen-enriched local atmosphere formation

This forms a key layer of the overall hazard prevention strategy.

7. System Integration and Operational Hierarchy

All subsystems described above are integrated into a unified operational architecture governed by central cargo control logic and safety interlocks. The system is designed to ensure:

- Segregation of liquid, vapour, inerting, and BOG pathways
- Redundant pressure and thermal safety mechanisms
- Controlled transition between operational modes (loading, voyage, discharge, maintenance)

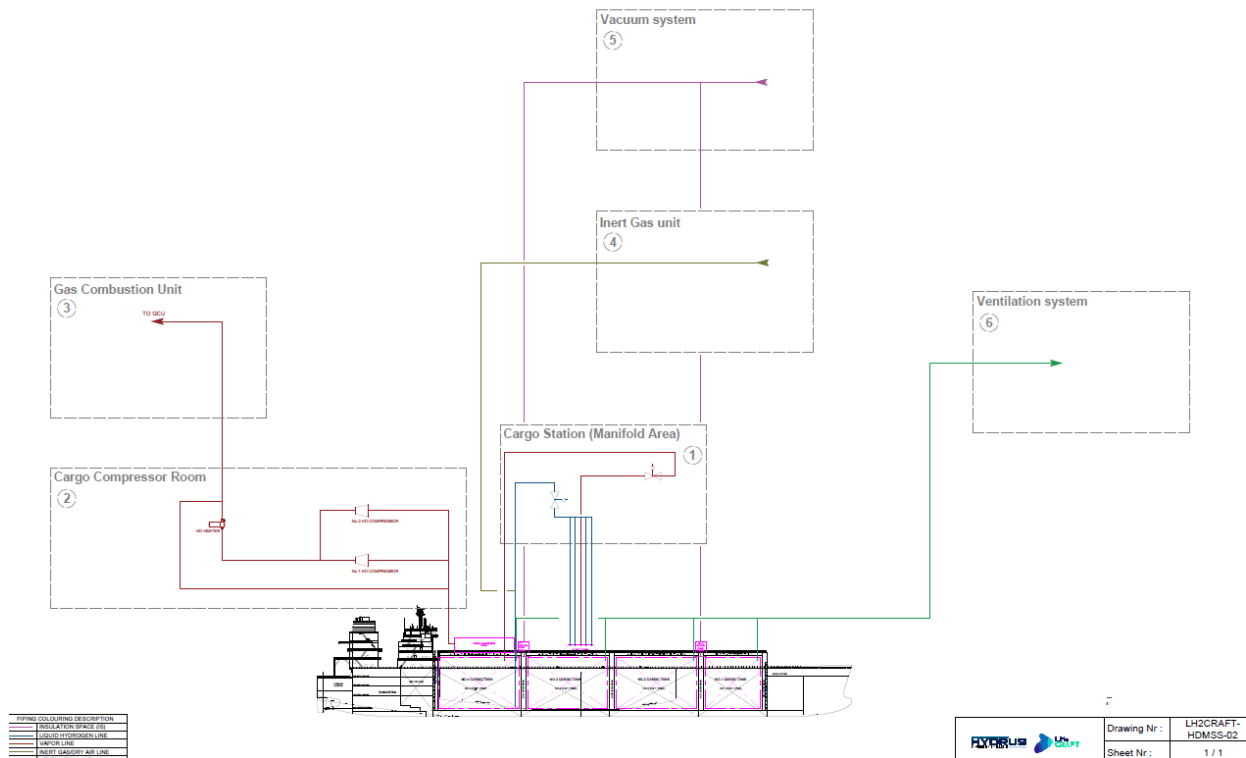


Figure 10. LH2 high-level system schematic

3.5.2 CARGO PUMPS

Each cargo tank is fitted with two cargo pumps, which will be vertical multi-stage centrifugal pumps. The characteristics of the pumps will be defined at a later stage once the flow rates are fully defined. The pumps will be driven by electric motors which will be powered from the main switchboards.

Normal cargo pump operation

- The pump should be running close to the rated flow (between minimum and maximum allowable flow rates) in continuous operation.
- As the liquid level is decreasing the discharge flow rate shall be decreased accordingly to avoid pump cavitation.
- Pumps discharge valves shall be fully open during pump operation.

Cargo Pump shutdown

- At the last stage of discharge operation, the pump shall be stopped and switched to the spray pump when the level reaches the designated pump's "stop level".

Trip and shutdown

- Pump shall be shut down when undercurrent signal is acquired
- Pump shall be shut down when overcurrent signal is acquired

The following *Table 4* summarizes the characteristics of the cargo pumps.

Table 4. Main Cargo Pumps characteristics

Main Cargo Pumps	
Rated Capacity	~ 600 m ³ /h @ 500 m
No. of sets	8 (2 per cargo tank)
Design temperature	-253°C
Design pressure	10 barg
LH2 specific gravity	0.071

3.5.3 SPRAY PUMPS

Each cargo tank is equipped with one spray pump for cooling down purposes before loading. The characteristics of the pumps will be defined at a later stage once the flow rates are fully defined. The pumps will be driven by electric motors which will be powered from the main switchboards.

Normal spray pump operation

- The pump should be running close to the rated flow (between minimum and maximum allowable flow rates) in continuous operation.
- As the liquid level is decreasing the discharge flow rate shall be decreased as well to avoid pump cavitation.
- Pumps discharge valves shall be fully open during pump operation.

Spray Pump shutdown

- At the last stage of discharge operation, pump shall be stopped and switched to the spray pump when the level reaches the designated pump's "stop level".

Trip and shutdown

- Pump shall be shut down when undercurrent signal is acquired
- Pump shall be shut down when overcurrent signal is acquired

Table 5. Spray Pumps characteristics

Spray Pumps	
No. of sets	4 (1 per cargo tank)
Design temperature	-253°C

3.5.4 HIGH DUTY COMPRESSORS

Two high duty compressors (always only one in operation and the other one standby/redundancy) will be installed in the cargo compressor room and will be used in the following modes:

- Gas-up of the cargo lines & tanks with GH2 from shore and inert gas burned in the GCU (under Mode 2.1)
- Loading with vapor (GH2) being sent to shore facilities – forced (under Mode 2.3)

- Cooling down cargo tanks prior to arrival with vapor (GH2) burned in the GCU (under Mode 2.4)
- Anchorage condition in laden mode with vapor burned in the GCU (under Mode 3.2)
- Liquid line cool down before discharge with vapor (GH2) burned in the GCU (under Mode 4.1)
- Cargo tanks warm-up (1st step) (under Mode 6.1.1)
- Cargo tanks warm-up (2nd step) (under Mode 6.1.2)
- Cargo tanks warm-up with warm vapor (GH2) burned in the GCU (under Mode 6.1.3)
- Gas freeing through GCU (under Mode 6.2.1)
- Anchorage condition in ballast mode with BOG (GH2) burned in the GCU (under Mode 7)

The compressors will be driven by electric motors which will be powered from the main switchboards.

Table 6. High duty compressors characteristics

High Duty Compressors	
Type	Centrifugal, single stage fixed speed with adjustable guide vanes
No. of sets	2

3.5.5 HIGH DUTY HEATER

A steam-heated high duty heater will be installed in the cargo compressor room to be used in the following operation modes:

- Gas-up of the cargo lines & tanks with GH2 from shore and inert gas burned in the GCU (under Mode 2.1)
- Cooling down cargo tanks prior to arrival with vapor (GH2) burned in the GCU (under Mode 2.4)
- Anchorage condition in laden mode with vapor burned in the GCU (under Mode 3.2)
- Liquid line cool down before discharge with vapor (GH2) burned in the GCU (under Mode 4.1)
- Cargo tanks warm-up (1st step) (under Mode 6.1.1)
- Cargo tanks warm-up (2nd step) (under Mode 6.1.2)
- Cargo tanks warm-up with warm vapor (GH2) burned in the GCU (under Mode 6.1.3)
- Gas freeing through GCU (under Mode 6.2.1)
- Anchorage condition in ballast mode with BOG (GH2) burned in the GCU (under Mode 7)

Table 7. High duty heater characteristics

High Duty Heater	
Type	Shell & tube
No. of sets	2

3.5.6 LH2 VAPORIZER

Two LH2 vaporizers (always only one in operation and the other one standby/redundancy). Both vaporizers shall be of steam-heated shell and tube type heat exchanger, will be installed within the cargo compressor room and will be operating in the following operation modes:

- Unloading with vapor produced & provided from LH2 vaporizer (under Mode 4.2.2)
- Stripping and lines draining with vapor produced & provided from LH2 vaporizer (under Mode 4.3.2)

Pressure control

The flow rate through the LH2 vaporizer can be controlled either by a pressure controller. The flow controller based on the flow rate will operate the inlet control valve accordingly.

Temperature control

The outlet temperature of the LH2 vaporizer is controlled by a temperature controller. The outlet temperature is regulated via the bypass control valve.

The vaporisers shall be equipped with level controllers, safeguarding that shutdown shall take place in case of low level.

Table 8. LH2 vaporizer characteristics

LH2 Vaporizer (LD)	
Type	Shell & tube
No. of sets	1

3.5.7 GAS COMBUSTION UNIT

The GCU will be used to safely combust hydrogen boil-off gas created from the storage tanks. The GCU will be used in the following operation modes:

- Gas-up of the cargo lines & tanks with GH2 from shore and inert gas burned in the GCU (under Mode 2.1)
- Cooling down cargo tanks prior to arrival with vapor (GH2) burned in the GCU (under Mode 2.4)
- Anchorage condition in laden mode with BOG (GH2) burned in the GCU (under Mode 3.2)
- Liquid line cool down before discharge with vapor (GH2) burned in the GCU (under Mode 4.1)
- Cargo tanks warm-up with warm vapor (GH2) burned in the GCU (under Mode 6.1.3)
- Gas freeing through GCU (under Mode 6.2.1)
- Anchorage condition in ballast mode with BOG (GH2) burned in the GCU (under Mode 7)

Table 9. Gas combustion unit characteristics

Gas Combustion Unit	
No. of sets	1
Minimum BOG flow limit	300 kg/h
Maximum BOG flow limit	3000 kg/h

3.5.8 NITROGEN PRODUCTION UNIT

The nitrogen generator system consists of two air compressors, two nitrogen generators and a buffer tank. Always one air compressor and nitrogen generator set is in service whereas the remaining set is for

redundancy. The produced nitrogen is stored in the pressurized buffer tank and is finally supplied to the pressurization headers through make-up regulating valves. From the headers, branches are led to the IBS and IS at the liquid dome of each tank. After flowing through the IBS and IS nitrogen is vented through its dedicated vent mast. The produced nitrogen will be used for the inerting of the IBS & IS during the dry dock maintenance/repair work.

Table 10. Nitrogen production system characteristics

Nitrogen Production System	
N2 Generator (LD)	
No. of sets	2
Set Capacity	650 Nm ³ /h
Feed air compressor	
No. of sets	2
N₂ buffer tank	
No. of tanks	1
Capacity	650 m ³
Minimum pressure	12 bar
Maximum pressure	6 bar

3.5.9 INERT GAS GENERATOR SYSTEM

A high-duty inert gas generator is considered for the inerting of the cargo tanks, while a low-duty generator is recommended for the piping system purging. Both the generators shall have inert gas and dry air mode. The generators shall be equipped with a nitrogen purity alarm to ensure the purity of nitrogen. When the sensor detects low nitrogen purity, the system shall be switched to nitrogen purging (venting) and the generated inert gas shall be vented to the atmosphere directly. In case of failure of the one of the two inert gas generators, the second shall serve as a redundancy (of course it is expected to have some deviations in terms of the available flowrate and the duration of the process compared to the normal operation given that the HD generator is sized for inerting the cargo tanks whereas the LD generator for purging purposes of the network).

The inert gas mode of HD generator is used for the following operation modes:

- Inerting of cargo tanks (under Mode 1.2)
- Gas freeing of cargo tanks through GCU (under Mode 6.2.1)
- Gas freeing of cargo tanks through Vent Mast (under Mode 6.2.2)

The dry air mode of HD generator is used for the following operation modes:

- Drying of cargo tanks (under Mode 1.1)
- Aerating of cargo tanks (under Mode 6.3)

More details will be added to the detailed engineering design phase. Also, the relevant P&ID will be added to this section.

Table 11. Inert gas generator HD characteristics

Inert Gas Generator (HD)	
Capacity	15,000 m ³ /h
No. of sets	1

Table 12. Inert gas generator LD characteristics

Inert Gas Generator (LD)	
Capacity	4,000 Nm ³ /h
No. of sets	1

3.5.10 VACUUM SYSTEM

Within IBS and IS a semi-vacuum condition will be present with the vacuum insulation space pressure to be at 1 mbar and 5 mbar for the IBS and IS respectively. Vacuum will be maintained with the usage of 6 vacuum pumps. 3 on-board pumps are to be installed at each vacuum cabinet arranged between pair of tanks to ensure redundancy. This setup allows for continued operation even if one pump fails, as the remaining pump can maintain the required pressure levels. Since the vacuum operation requires maintaining pressures in the range of 0.5–1.5 mbarA (IBS) and 4.5–5.5 mbarA (IS), low-duty vacuum pumps may be used for this operation.

Any leaks either at the primary barrier, secondary barrier or inner hull, will be traced with the usage of the following means:

- Pressure monitoring at IBS outlet
- Temperature monitoring at IBS outlet
- Pressure monitoring at IS outlet

More details will be added to the detailed engineering design phase. Also, the relevant P&ID will be added to this section.

Table 13. vacuum system characteristics

Vacuum System	
No. of pumps	6
Target pressure	1 mbarA for IBS
	5 mbarA for IS

3.6 SAFETY SYSTEMS

3.6.1 FIRE AND WASH DECK SYSTEM

The main fire system has an extensive number of hydrants in the engine room, the pump room, the accommodation area and the rest of the deck areas. The fire main line shall be always maintained in fully operational condition.

The fire water will be supplied from the engine room by the two bilge, fire & G/S pumps (centrifugal type).

An emergency fire pump will be installed in the pump room (centrifugal type).

The fire main system will be kept pressurized through the sea water hydraulic unit with the use of a fire line pressurizing pump (centrifugal type).

Crucial areas covered by fire and wash deck system during loading and unloading operations of the LH₂ carrier are the cargo manifolds (respective water curtain system in place) and the cargo compressor room (respective fire hydrants).

Relevant P&ID (**Drawing Nr. LH2CRAFT-HDMSS-04-08**) of the various fire and wash deck system components and arrangement of them in way of deck area (systems within E/R and Accommodation are not reflected since they are not related to the purposes of LH₂CRAFT and the respective HDMSS for the handling of LH₂ as cargo) is presented below.

3.6.2 DECK DRY POWDER EXTINGUISHING SYSTEM

The central CO₂ system consists of cylinders (each containing 68 liters of CO₂) located in the CO₂ room. These cylinders are connected to the discharge nozzles within the protected space through cylinder manifolds and distribution network.

Relevant P&ID (**Drawing Nr. LH2CRAFT-HDMSS-04-09**) of the various dry powder extinguishing components and arrangement of them in way of deck area is presented below.

3.6.3 CO₂ EXTINGUISHING SYSTEM

The central CO₂ system consists of cylinders (each containing 68 liters of CO₂) located in the CO₂ room. These cylinders are connected to the discharge nozzles within the protected space through cylinder manifolds and distribution network.

When the release system is activated for a particular space, a certain number of cylinders are activated depending on the space volume. The adopted concentration of CO₂ for the protected spaces under consideration is 45%.

Table 14. Required number of cylinders per protected space

Protected Space	Cylinder Quantity
Cargo compressor room	≈ 40-45
Vacuum pump room No 1	≈ 3-5
Vacuum pump room No 2	≈ 3-5

3.6.4 FIRE AND GAS DETECTION SYSTEM

The fire and alarm system will be a computerized system, which makes use of analogue type detectors. The detector loops for the system are connected to a back-up battery in order to avoid power failure events. The system is also connected with the gas sampling and alarm systems.

The system operation principle is based on the signals acquired from various sensors and detectors for the events of smoke and heat. More specifically, heat detectors used in the fire detection system are to detect a rapid rise in temperature and should be designed in accordance with recognized standards (e.g. MED, EN54-10, IEC 60092-504, IACS E10 or equivalent). As far as it is concerned, smoke detectors are devices sensing small particles in the air, which once they detect those particles above a certain level give signal for alarm. Applicable standards for smoke detectors are considered MSC.311(88), IEC 60092-505:2001 & BS EN 14604:2005. Finally, the gas detectors should identify the presence of hydrogen in an area and alerts users when dangerous concentrations are detected. They shall be designed in accordance with IEC 60079 series, ISO 21013-2, ISO 19880, ISO 22734 or equivalent.

The locations related to cargo operations where a risk of fire or hydrogen gas leakage exists and relevant detectors shall be installed, are summarized below.

Table 15. Smoke, Heat and Gas Detectors per Space

Protected Space	Smoke Detectors	Heat Detectors	Gas Detectors
No.1 Cargo switchboard room	2	2	-
No.2 Cargo switchboard room	2	2	-
Cargo compressor room	4	1	4
No.1 Vacuum Pump Room	1	1	1
No.2 Vacuum Pump Room	1	1	1
No.1 Tank liquid dome	-	-	1
No.1 Tank gas dome	-	-	1
No.1 Vent mast	-	-	1
No.2 Tank liquid dome	-	-	1
No.2 Tank gas dome	-	-	1
No.2 Vent mast	-	-	1
No.3 Tank liquid dome	-	-	1
No.3 Tank gas dome	-	-	1
No.3 Vent mast	-	-	1
No.4 Tank liquid dome	-	-	1
No.4 Tank gas dome	-	-	1
No.4 Vent mast	-	-	1
CO2 room	1	-	-
GCU room	1	1	1

CCR	2	2	-
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In addition to the above considered detectors, a number of danger alarm equipment (either visual or audible) shall be installed as per below:

Table 16. Fire Alarm Equipment per Space

Protected Space	Gas Alarm Speaker	Siren for CO2 Alarm	Air Horn for CO2 Alarm	Air Horn for Gas Alarm	Air Horn for Fire Alarm	Manual Call Point	Horn for Foam Alarm
No.1 Cargo switchboard room	3	1	1	-	-	-	-
No.2 Cargo switchboard room	3	1	1	-	-	-	-
Cargo compressor room	2	2	1	1	1	1	-
No.1 Vacuum Pump Room	-	1	-	-	1	1	-
No.2 Vacuum Pump Room	-	1	-	-	1	1	-
CO2 room	1	-	-	-	-	1	-
GCU room	1	-	-	-	-	1	1
CCR	1	-	-	-	-	1	-

As far as it concerns the arrangement of the various considered detectors and alarm equipment per space, related with cargo operation, is presented below (**Drawing Nr. LH2CRAFT-HDMSS-04-13**).

3.7 ELECTRICAL SYSTEMS

3.7.1 ALARM AND MONITORING SYSTEM

Alarm and Monitoring system is an integrated function within the overall integrated automation system (IAS) of the vessel. All alarms and signals from the different sub-systems of the vessel are pooled via the redundant network to form a uniform alarm system. For the specific project, only the alarms/signals related to cargo operations are considered. Subject alarms/signals are grouped in systems, as presented in the following sub chapters, and are included in **Drawing Nr. LH2CRAFT-HDMSS-11**.

3.7.2 IBS/IS PRESSURE AND TEMPERATURE MONITORING SYSTEM

Under subject system are various signals related to the monitoring of the CCS insulation space (IBS & IS). Monitoring equipment shall give warnings in case of a failure of the insulation or a leakage into the IBS and/or IS.

Table 17. IBS / IS Pressure & Temperature Monitoring System Signals

SIGNAL
No.1 CARGO TANK IS PRESSURE
No.1 CARGO TANK IBS PRESSURE
No.2 CARGO TANK IS PRESSURE
No.2 CARGO TANK IBS PRESSURE
No.3 CARGO TANK IS PRESSURE
No.3 CARGO TANK IBS PRESSURE
No.4 CARGO TANK IS PRESSURE
No.4 CARGO TANK IBS PRESSURE
No.1 CARGO TANK IS TEMPERATURE
No.1 CARGO TANK IBS TEMPERATURE
No.2 CARGO TANK IS TEMPERATURE
No.2 CARGO TANK IBS TEMPERATURE
No.3 CARGO TANK IS TEMPERATURE
No.3 CARGO TANK IBS TEMPERATURE
No.4 CARGO TANK IS TEMPERATURE
No.4 CARGO TANK IBS TEMPERATURE

3.7.3 CARGO HOLD/TANK PRESSURE MONITORING SYSTEM

The purpose of subject system is to control the cargo tank pressure, by maintaining hydrogen gas consumers in operation and adjusting their gas consumption. The related signals are presented in the following table.

Table 18. Cargo Hold/Tank Pressure Monitoring System Signals

SIGNAL
No.1 CARGO TANK PORT PUMP DISCHARGE
No.1 CARGO TANK STBD PUMP DISCHARGE
No.1 CARGO TANK SPRAY PUMP DISCHARGE
No.1 CARGO TANK CEILING
No.2 CARGO TANK PORT PUMP DISCHARGE
No.2 CARGO TANK STBD PUMP DISCHARGE
No.2 CARGO TANK SPRAY PUMP DISCHARGE
No.2 CARGO TANK CEILING
No.3 CARGO TANK PORT PUMP DISCHARGE

No.3 CARGO TANK STBD PUMP DISCHARGE
No.3 CARGO TANK SPRAY PUMP DISCHARGE
No.3 CARGO TANK CEILING
No.4 CARGO TANK PORT PUMP DISCHARGE
No.4 CARGO TANK STBD PUMP DISCHARGE
No.4 CARGO TANK SPRAY PUMP DISCHARGE
No.4 CARGO TANK CEILING

3.7.4 CARGO HOLD/TANK TEMPERATURE MONITORING SYSTEM

The purpose of subject system is to monitor the cargo tank temperature during various operation modes and identify improper performance of CCS insulation. The related signals are presented in the following table and are activated in different liquid levels (e.g. 5%, 25%, 50%, 75% and 98%).

Table 19. Cargo Hold/Tank Temperature Monitoring System Signals

SIGNAL
No.1 CARGO TANK GAS DOME VAPOR
No.1 CARGO TANK STBD SPRAY LINE INLET
No.1 CARGO TANK PORT SPRAY LINE INLET
No.1 CARGO TANK CEILING
No.2 CARGO TANK GAS DOME VAPOR
No.2 CARGO TANK STBD SPRAY LINE INLET
No.2 CARGO TANK PORT SPRAY LINE INLET
No.2 CARGO TANK CEILING
No.3 CARGO TANK GAS DOME VAPOR
No.3 CARGO TANK STBD SPRAY LINE INLET
No.3 CARGO TANK PORT SPRAY LINE INLET
No.3 CARGO TANK CEILING
No.4 CARGO TANK GAS DOME VAPOR
No.4 CARGO TANK STBD SPRAY LINE INLET
No.4 CARGO TANK PORT SPRAY LINE INLET
No.4 CARGO TANK CEILING

3.7.5 CARGO OPERATION MONITORING SYSTEM

The purpose of subject system is to monitor the pressure and the temperature in various crucial branches of the cargo operation network (i.e. manifold connections, liquid main, gas and vapor main lines etc). The related signals are presented in the following table.

Table 20. Cargo Operation Monitoring System Signals

SIGNAL
No.1 MAIN LIQUID LINE PRESSURE
No.1 MAIN LIQUID LINE TEMPERATURE
No.2 MAIN LIQUID LINE PRESSURE
No.2 MAIN LIQUID LINE TEMPERATURE
MAIN SPRAY LINE PRESSURE
MAIN SPRAY LINE TEMPERATURE
MAIN VAPOR LINE PRESSURE
MAIN VAPOR LINE TEMPERATURE
NO.1 HD COMPRESSOR INLET PRESSURE
NO.1 HD COMPRESSOR OUTLET PRESSURE
NO.2 HD COMPRESSOR INLET PRESSURE
NO.2 HD COMPRESSOR OUTLET PRESSURE
NO.1 HD HEATER INLET TEMPERATURE
NO.1 HD HEATER OUTLET TEMPERATURE
NO.2 HD HEATER INLET TEMPERATURE
NO.2 HD HEATER OUTLET TEMPERATURE
PRESSURE UPSTREAM OF HVR25
LH2 VAPORIZER OUTLET TEMPERATURE
LH2 VAPORIZER OUTLET PRESSURE
PORT CARGO STATION LH2-1001 TEMPERATURE
PORT CARGO STATION LH2-1002 TEMPERATURE
PORT CARGO STATION LH2-1003 TEMPERATURE
PORT CARGO STATION LH2-1101 TEMPERATURE
HCS38 UPSTREAM PRESSURE
HCS38 UPSTREAM TEMPERATURE
STBD CARGO STATION LH2-1004 TEMPERATURE
STBD CARGO STATION LH2-1005 TEMPERATURE
STBD CARGO STATION LH2-1006 TEMPERATURE

STBD CARGO STATION LH2-1102 TEMPERATURE
HCS19 UPSTREAM PRESSURE
HCS19 UPSTREAM TEMPERATURE

3.7.6 GAS SAMPLING SYSTEM

Subject fixed type system monitors the arranged gas sampling points in way of the vessel's hazardous gas zone. The related monitored areas are reflected in the below cumulative table of various gas sampling signals.

Table 21. Gas Sampling System Signals

SIGNAL
No.1 CARGO TANK TOP OF IBS FOR GAS DOME
No.1 CARGO TANK TOP OF IS FOR GAS DOME
No.1 CARGO TANK TOP OF IBS FOR LIQUID DOME
No.1 CARGO TANK TOP OF IS FOR LIQUID DOME
No.2 CARGO TANK TOP OF IBS FOR GAS DOME
No.2 CARGO TANK TOP OF IS FOR GAS DOME
No.2 CARGO TANK TOP OF IBS FOR LIQUID DOME
No.2 CARGO TANK TOP OF IS FOR LIQUID DOME
No.3 CARGO TANK TOP OF IBS FOR GAS DOME
No.3 CARGO TANK TOP OF IS FOR GAS DOME
No.3 CARGO TANK TOP OF IBS FOR LIQUID DOME
No.3 CARGO TANK TOP OF IS FOR LIQUID DOME
No.4 CARGO TANK TOP OF IBS FOR GAS DOME
No.4 CARGO TANK TOP OF IS FOR GAS DOME
No.4 CARGO TANK TOP OF IBS FOR LIQUID DOME
No.4 CARGO TANK TOP OF IS FOR LIQUID DOME
No.1 LH2 VENT MAST
No.2 LH2 VENT MAST
No.3 LH2 VENT MAST
No.4 LH2 VENT MAST
CARGO COMPRESSOR ROOM No.1 SAMPLING POINT
CARGO COMPRESSOR ROOM No.2 SAMPLING POINT
No.1 VACUUM PUMP ROOM
No.2 VACUUM PUMP ROOM

3.7.7 GAS DETECTION SYSTEM

In contrast to the gas sampling system, gas detection system monitors the non-hazardous gas zone areas. Signals for gas detection of monitored areas are reflected below.

Table 22. Gas Detection System Signals

SIGNAL
GCU ROOM
No.1 CARGO SWITCHBOARD ROOM
No.2 CARGO SWITCHBOARD ROOM

3.7.8 REMOTE VALVE CONTROL SYSTEM

In subject category are included the various remote operated valves of the cargo area, either of open/shut type or throttling type.

3.7.9 EMERGENCY SHUTDOWN SYSTEM

The ESD shall automatically isolate all emergency systems of the vessel and put them into a safe condition in an emergency case. The related system shall be capable of initiating either manually or automatically.

The manual way of activating the ESD is done via the manual push buttons that will be activated by the ship crew in an emergency situation. Manual push buttons shall be installed in the following areas:

- Cargo tanks liquid domes (4 sets in total)
- Manifolds port and starboard (2 sets in total)
- Forwards area (1 set in total)
- Cargo compressor room (2 sets in total)

Another way that the ESD can be activated is with the installed fusible plugs, which are melted in case of fire or explosion. The melting caused by such an event will trigger the ESD. Fusible plugs should be installed in the following locations:

- Cargo tank liquid domes (4 sets in total)
- Cargo tank gas domes (4 sets in total)
- Manifolds port and starboard (2 sets in total)
- Cargo compressor room (2 sets in total)

The above-mentioned manual push buttons as well as the fusible plugs are presented in the following table.

Table 23. ESD System Manual Push Buttons & Fusible Plugs

MANUAL PUSH BUTTON	FUSIBLE PLUG
NO.1 TANK LIQUID DOME	NO.1 TANK LIQUID DOME
NO.2 TANK LIQUID DOME	NO.1 TANK GAS DOME
NO.3 TANK LIQUID DOME	NO.2 TANK LIQUID DOME

NO.4 TANK LIQUID DOME	NO.2 TANK GAS DOME
MANIFOLD AREA PORT	NO.3 TANK LIQUID DOME
MANIFOLD AREA STBD	NO.3 TANK GAS DOME
CARGO COMPRESSOR ROOM	NO.4 TANK LIQUID DOME
	NO.4 TANK GAS DOME
	MANIFOLD AREA PORT
	MANIFOLD AREA STBD
	CARGO COMPRESSOR ROOM

In general, the ESD will be triggered in the following events:

- Case of emergency buttons manual activation
- Fusible plugs melting
- Shore/ship link system failure
- Cargo tank level high-high
- Electric power failure

Finally, the ESD shall be interlocked with the following remote operated valves of the cargo area:

4 BASIC AND DETAILED ENGINEERING DESIGN OF THE HDMSS

Liquid hydrogen (LH₂) is increasingly recognized as a strategic energy carrier for maritime decarbonization and long-distance hydrogen transport. Marine-type LH₂ cargo systems introduce significant technical challenges compared with conventional liquefied gas systems due to the extremely low operating temperature of hydrogen, hydrogen embrittlement phenomena, high diffusivity, boil-off generation, and stringent safety requirements.

This chapter summarizes the principal pipe design criteria applicable to marine LH₂ cargo systems. The document is based on the International Maritime Organization (IMO) International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), together with hydrogen-specific engineering standards and classification society guidance.

The report presents the governing design requirements related to:

- Design pressure and temperature
- Material compatibility
- Vacuum-insulated piping systems
- Thermal stress and flexibility
- Leak prevention and containment
- Pressure relief and boil-off gas management
- Surge pressure and transient analysis
- Testing and inspection requirements

The purpose of this chapter is to provide a consolidated technical reference for the conceptual and preliminary engineering design of marine LH₂ cargo transfer systems.

4.1 BACKGROUND

The maritime transport of liquid hydrogen is expected to become an essential component of future international hydrogen supply chains. Compared with liquefied natural gas (LNG), liquid hydrogen presents substantially more demanding operational and safety conditions due to its cryogenic boiling temperature of approximately 20 K (−253°C).

Marine LH₂ cargo systems require specialized piping arrangements capable of maintaining thermal integrity, minimizing boil-off losses, and preventing hydrogen leakage under marine operating conditions.

The design of marine LH₂ piping systems therefore requires the integration of:

- Cryogenic engineering principles
- Hydrogen compatibility assessment
- Marine classification requirements
- Hazardous area protection

- Process safety engineering

This report addresses the pipe design criteria applicable to marine-type liquid hydrogen cargo systems, including:

- Cargo transfer lines
- Vapor return lines
- Boil-off gas handling lines
- Process piping associated with cargo containment systems
- Vacuum-insulated piping arrangements

The report focuses on technical design principles and applicable regulatory frameworks relevant to marine LH₂ carriers

4.2 APPLICABILITY OF CODES, CLASSIFICATION SOCIETIES REQUIREMENTS, STANDARDS IN PIPE DESIGN

The primary international regulatory framework for liquefied gas cargo systems is the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).

The IGC Code establishes requirements for:

- Cargo containment systems
- Piping systems
- Pressure relief systems
- Emergency shutdown systems
- Testing and inspection
- Hazardous area classification

Chapter 5 of the IGC Code specifically governs cargo piping systems and associated process arrangements.

The IGF Code is primarily applicable to hydrogen-fueled vessels. However, selected provisions related to gaseous fuel handling, ventilation, and hazardous area protection may also support LH₂ cargo system design.

Additional guidance is provided by major classification societies, including:

- DNV
- American Bureau of Shipping (ABS)
- Lloyd's Register (LR)

These organizations provide supplemental guidance for:

- Cryogenic hydrogen systems
- Alternative fuel arrangements
- Hydrogen risk assessment
- Structural and safety evaluations

Hydrogen-Specific Engineering Standards

- ASME B31.12 – Hydrogen Piping and Pipelines

ASME B31.12 provides requirements related to:

- Hydrogen compatibility
- Material selection
- Fracture control
- Embrittlement mitigation
- Design stresses
- ISO 11326:2024

ISO 11326:2024 addresses testing and inspection requirements for cryogenic hydrogen systems and associated components.

a) The standard includes requirements for:

- Pressure testing
- Tightness verification
- Thermal performance evaluation
- Insulation system verification

4.3 PIPE VELOCITY CALCULATION AND SIZING APPROACH

For the given design certain assumptions need to be made in order to set a solid basis for the dimensioning of the relevant piping networks. The respective assumptions are summarized below:

- Loading and unloading rate: 1650 m³/h, assumed flow rate following LNG practices
- LH₂ pipe velocity: 1.5 m/s, assumed as a conservative approach from LNG industry practices
- Design pressure: 10 barg, assumed pressure at the given temperature profiles
- Design temperature: -253°C, state of LH₂

Based on the above assumptions, the required internal diameter of the cargo line shall be at least 660mm, which leads to a conservative result of the dimensioning at DN750 to accommodate unexpected events. In a similar way, the rest of the remaining piping networks have been sized.

4.4 MATERIAL EVALUATION AND SELECTION

The material of the piping shall be chosen in order to provide the best properties alleviating any embrittlement phenomena derived from the nature of liquid hydrogen. Therefore, the material which shall be chosen should comply with ABS Requirements guide for liquefied hydrogen carriers [15], as stated in section 6 chapter 2 & 3. Based on that the following pipe materials will be considered for the case of the LH2CRAFT:

- SUS 316L
- SUS 304

All above stated materials will be assessed in terms of ultimate strength in the following parameters, as described in IGC Code [16]:

R_e = specified minimum yield stress at room temperature (N/mm²).

R_m = specified minimum tensile strength at room temperature (N/mm²).

K = permissible stresses (N/mm²)

The permissible stress for carbon steel and alloy steel pipes to be considered shall be chosen as the lowest of the following values:

$R_m/2.7$ and $R_e/1.8$

The following Table 26, summarizes the above parameters for easier access and reference purposes:

Table 24. Pipe permissible stresses limits

Material	R_m (N/mm ²)	R_e (N/mm ²)	K (N/mm ²)
SUS 316L	485	170	94
SUS 304L	515	205	114

4.5 PIPE THICKNESS CALCULATIONS

Based on IACS requirements [15], [16], [17], [18], [19] the minimum wall thickness of pipes shall be calculated based on the following formula:

$$t = t_0 + b + c$$

Where:

t = minimum calculated thickness (mm)

t_0 = theoretical thickness in mm, which is calculated from the following formula:

$$t_0 = \frac{P * D}{(20 * K * e) + P}$$

Where:

P = design pressure (bar)

D = outside diameter (mm)

K = permissible stress (N/mm²)

e = efficiency factor

- value of 1 is applicable when: seamless pipes and for welded pipes delivered by manufacturers approved for making welded pipes which are considered an equivalent to seamless pipes.
- value different than 1 is applicable when: other welded pipes the Classification Society will consider an efficiency factor value depending upon the service and the welding procedure.

B = bending allowance (mm). The value of b shall be chosen so that the calculated stress in the bend, due to internal pressure only, does not exceed the allowable stress. Where such justification is not given, b shall be:

$$b = \frac{D * t_0}{2.5 * r}$$

Where:

r = the mean radius of the bend (mm)

c = corrosion allowance (mm). This value is dependent on the system that serves the purpose along with the medium flowing into the pipes.

The value of t, calculated above, does not account for any negative manufacturing tolerance. As a result, the thickness shall be increased considering the negative manufacturing tolerance by means of the following formula:

$$t_1 = \frac{t}{1 - \frac{a}{100}}$$

Where:

t₁ = minimum thickness in the case of negative tolerance (mm)

t = minimum thickness as calculated above (mm)

a = negative manufacturing tolerance for thickness (%)

Based on the above formulas, pipe wall calculations have been performed for three different design pressures (NP10) in the following table.

Table 25. Design pressure calculations and assessment for NP10 SS Pipe

DN	SUS 304			
	<u>The straight pipe minimum pipe wall thickness shall be not less than (mm)</u>	<u>Acceptability of Schedule 20S, 40, 80</u>	<u>The straight pipe minimum pipe wall thickness shall be not less than (mm)</u>	<u>Acceptability of Schedule 20S, 40, 80</u>
10	1.01	YES	0.99	YES
15	1.05	YES	1.02	YES
20	1.09	YES	1.06	YES
25	1.15	YES	1.1	YES
32	1.22	YES	1.16	YES
40	1.25	YES	1.19	YES
50	1.34	YES	1.26	YES
65	1.46	YES	1.36	YES
80	1.55	YES	1.44	YES
100	1.76	YES	1.61	YES
125	1.95	YES	1.77	YES

150	2.14	YES	1.92	YES
200	2.36	YES	2.1	YES
250	2.9	YES	2.55	YES
300	3.28	YES	2.87	YES
350	3.54	YES	3.07	YES
400	3.91	YES	3.39	YES
450	4.29	YES	3.7	YES
500	4.67	YES	4.01	YES
550	5.52	YES	4.71	YES

Table 26. Pipe sizing criteria for stainless steel piping

Nominal size DN	Outside diameter (mm)	ABS Minimum pipe wall thickness (mm)	Schedule 20S Inner diameter (mm)	Schedule 40 Inner diameter (mm)	Schedule 80 Inner diameter (mm)
10	17.3	1.6	2.0	2.31	3.2
15	21.7	1.6	2.5	2.77	3.73
20	27.2	1.6	2.5	2.87	3.91
25	34	1.6	3.0	3.38	4.55
32	42.7	1.6	3.0	3.56	4.85
40	48.6	1.6	3.0	3.68	5.08
50	60.5	2.0	3.5	3.91	5.54
65	76.3	2.0	3.5	5.16	7.01
80	89.1	2.3	4.0	5.49	7.62
100	114.3	2.3	4.0	6.02	8.56
125	139.8	2.3	5.0	6.55	9.53
150	165.2	2.3	5.0	7.11	10.97
200	198.3	2.6	6.5	8.18	12.7
250	267.4	2.6	6.5	9.27	15.1 / 12.7
300	318.5	2.9	6.5	9.53	17.5 / 12.7
350	355.6	2.9	8.0	9.53	19.1 / 12.7
400	406.4	3.6	8.0	9.53	21.4 / 12.7
450	457	4.0	8.0	9.53	23.8 / 12.7

The proper sizing of the piping is based on the above minimum pipe wall thickness calculations made within Table 27, the ABS minimum wall thickness requirements for stainless pipes shown in Table 28 and the calculations made from the following equation:

$$Q = u * A = u * \frac{\pi * d^2}{4}$$

4.6 PROPOSED PIPING

Vacuum-insulated double-wall piping systems are the reference technology for the transfer of liquid hydrogen (LH₂) in marine applications. Their primary function is to minimize thermal heat ingress from the ambient environment to the cryogenic inner pipe operating at approximately 20 K (–253°C), thereby reducing boil-off losses and maintaining safe and stable single-phase flow conditions.

Due to the extreme temperature differential between ambient marine conditions and LH₂ service conditions, conventional single-wall insulated piping systems are not suitable. Instead, vacuum-insulated piping provides a high-performance thermal barrier combined with mechanical protection and enhanced safety integrity. A vacuum-insulated double-wall pipe typically consists of the following concentric layers:

- Inner Process pipe
- Annular Vacuum space
- Multilayer Insulation
- Outer protective jacket

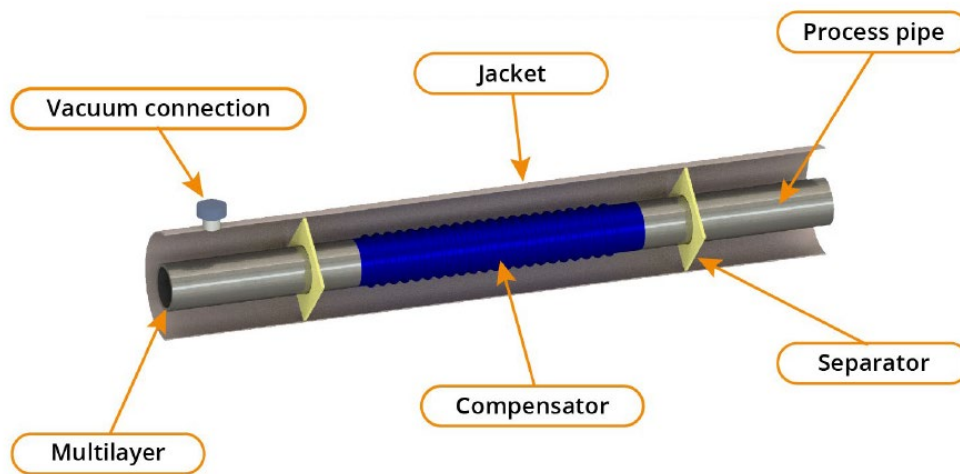


Figure 11. Vacuum insulated piping typical example [21]

4.6.1 INNER PROCESS PIPE

The inner pipe carries the liquid hydrogen and is designed for:

- Cryogenic service at ~20 K
- Internal design pressure conditions
- Resistance to hydrogen embrittlement and cryogenic fracture

Common materials include:

- Austenitic stainless steels (e.g., 304L, 316L)
- Selected nickel alloys for enhanced cryogenic performance

4.6.2 ANNULAR VACUUM SPACE

The annular gap between inner and outer pipes is evacuated to a high vacuum level to significantly reduce heat transfer by convection and conduction.

Key characteristics:

- Vacuum pressure typically in the range of high vacuum (10^{-3} to 10^{-6} mbar typical range)

- Optional inclusion of getter materials to maintain vacuum quality
- Instrumentation for vacuum monitoring and leak detection

The vacuum environment eliminates gaseous conduction and convection, leaving radiation as the dominant heat transfer mechanism.

4.6.3 MULTILAYER INSULATION

To further reduce radiative heat transfer, multilayer insulation is installed within the vacuum annulus.

MLI typically consists of:

- Alternating reflective metallic foils (e.g., aluminized Mylar or stainless steel)
- Low-conductivity spacer materials

The combination of vacuum and MLI significantly reduces overall thermal conductivity.

4.6.4 OUTER PROTECTIVE JACKET

The outer pipe provides:

- Structural protection
- Mechanical resistance to external loads (ship motion, impact, vibration)
- Secondary containment in certain configurations
- Support for vacuum integrity

Materials are typically carbon steel or stainless steel depending on structural requirements and corrosion protection strategy.

4.6.5 PIPE STRESS ANALYSIS

In the current section a preliminary stress analysis is conducted for the **inner process pipe**. The model consists of an automated python generation script for a 3D pipe routing analysis. The script generates a high-fidelity, three-dimensional hexahedral mesh and associated boundary conditions for finite element analysis (FEA) using the CalculiX open-source solver. The primary objective of this model is to perform a two-step sequentially coupled thermal-stress analysis. Given the extreme operating temperatures (-255 °C), the system represents a cryogenic fluid transfer line (e.g., liquid hydrogen).

Geometry & Mesh Configuration

A custom swept meshing algorithm is employed to construct the domain using standard continuous hexahedral elements (C3D8 elements). The mesh resolution is precisely controlled to ensure high-quality elements in the high-curvature elbow regions. The mesh features 61 nodes circumferentially, 15 nodes through the thickness, and 161 nodes longitudinally.

Table 27 Geometrical parameters

Geometric Parameter	Value / Dimension
Straight Segment 1 (L1)	24.0 m
Straight Segment 2 (L2)	50.0 m
Straight Segment 3 (L3)	30.0 m
Bend Radius (R_bend)	2.0 m
Outer Diameter (D_out)	0.750 m
Wall Thickness (t_wall)	0.006 m (6 mm)

Material specifications

In this preliminary pipe stress analysis, representative thermal-mechanical properties values for austenitic stainless steel were used. Table 28 below presents these input values.

Table 28 Material parameters

Property	Value
Young's Modulus (E)	210.0 GPa
Poisson's Ratio (ν)	0.28
Density (ρ)	8000.0 kg/m ³
Thermal Expansion Coefficient (α)	1.08e-5 1/K
Thermal Conductivity (k)	2.1 W/m·K
Specific Heat (Cp)	20 J/kg·K

Loads & Boundary Conditions

The internal surface of the pipe is subjected to an initial temperature of -255.0 °C and an absolute internal pressure of 101,325 Pa (~1 atm). The external surface is subjected to -252.0 °C and a near-vacuum pressure of 100 Pa, typical of a vacuum-jacketed cryogenic environment. A stress-free reference temperature of -255.0 °C is established. To resolve the common FEA issue of artificial localized stress concentrations at perfectly rigid boundaries during massive thermal contractions, the rigid clamps are replaced with an engineered web of 3D spring elements.

Solver & Execution flow

The analysis is performed in two discrete steps to correctly map the temperature gradient into the structural field. Both simulation steps are executed using CalculiX's optimized PARDISO solver:

1. Steady-State Heat Transfer: The exact thermal gradient is calculated through the 6mm pipe wall driven by the inner/outer temperature boundary conditions. Results are saved to a node file.
2. Static Thermal-Stress: The node temperatures from the heat transfer step are mapped. The resulting mechanical deformations and Von Mises stresses from thermal shrinkage and differential pressure loads are computed.

In figure 12, the structured hex mesh of the studied model is illustrated:

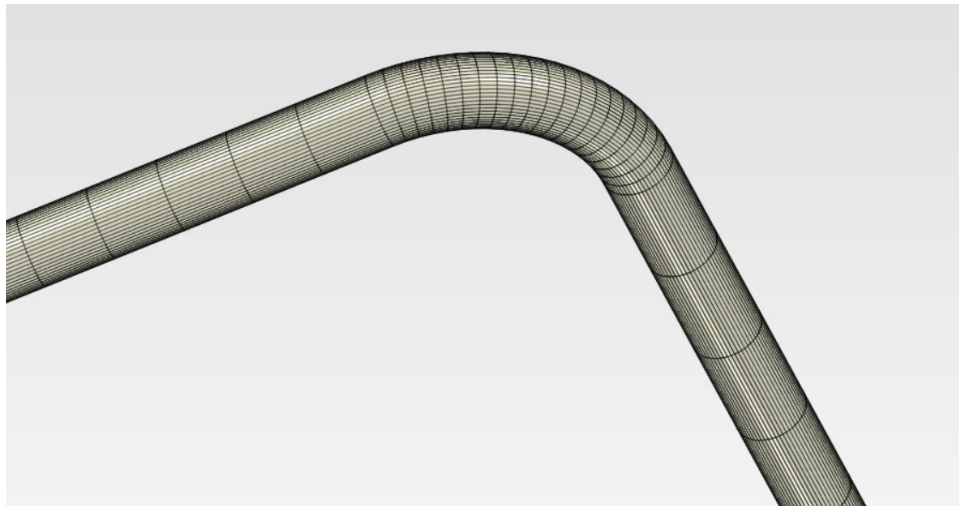


Figure 12. *Inner process pipe Hex mesh*

In figure 13 the total 3D model along with the Von Mises stress distribution is visualised. The elastic cradle supports are shown, which permit radial breathing to avoid stress singularities. The maximum Von mises stress is located in the elbow region, at the inner wall of the steel pipe. The specific location is further illustrated in figure [14].

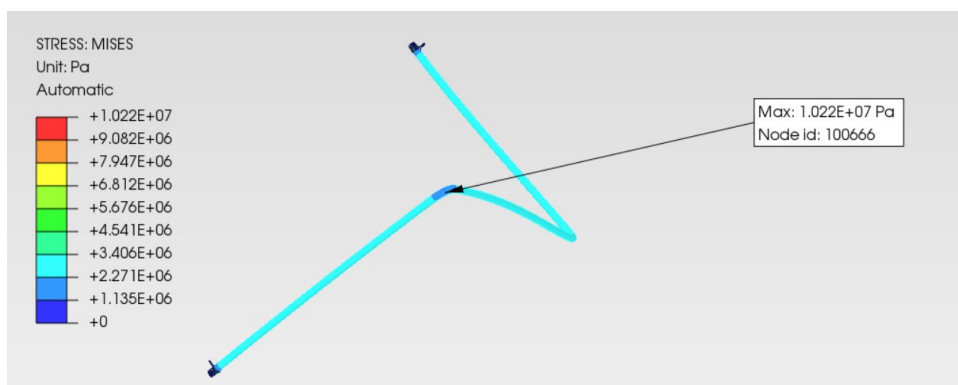


Figure 13. *3D model of the inner pipe*

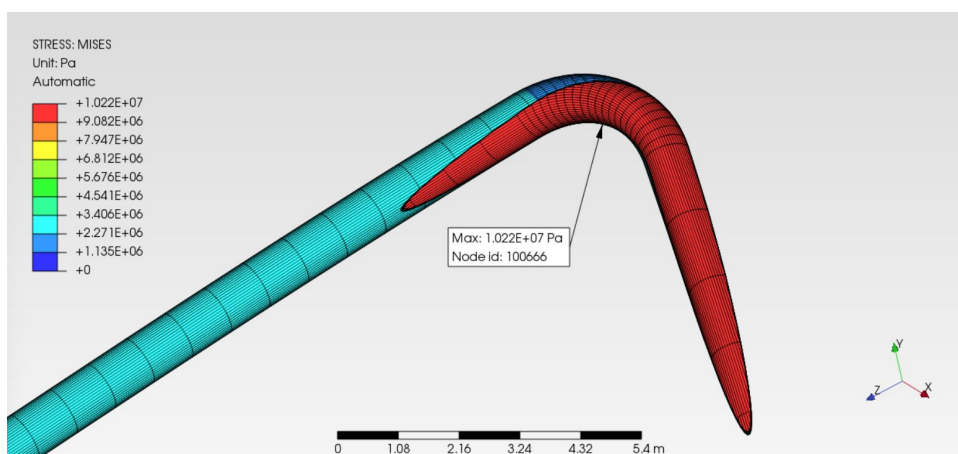


Figure 14. *Location of the maximum Von Mises stress (Section view)*

To further observe the temperature and Von Mises stress distribution across the wall thickness, figures 15 and 16 follow:

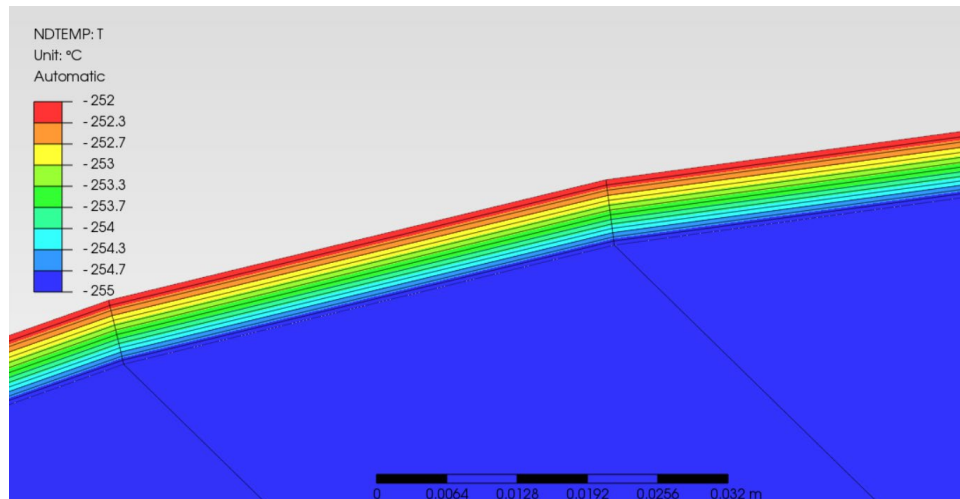


Figure 15. Temperature distribution across pipe thickness

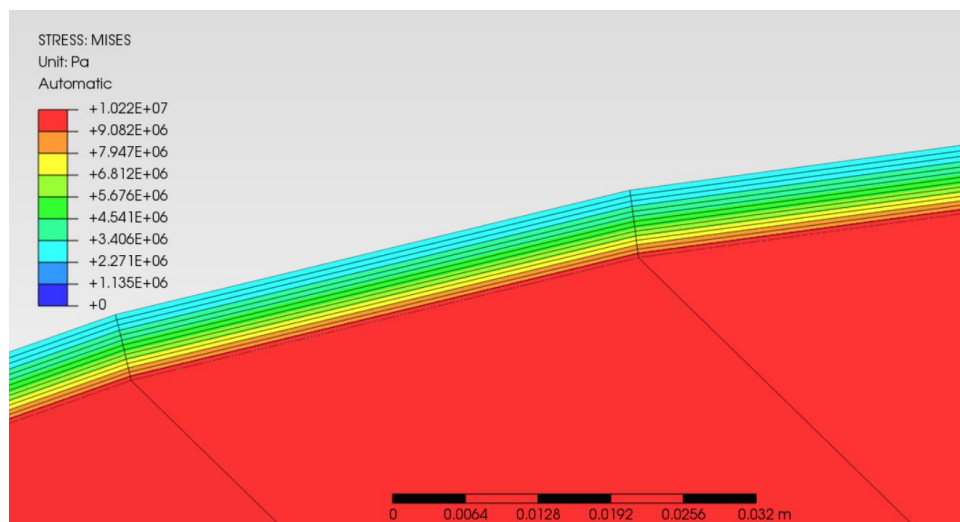


Figure 16. Von Mises stress distribution across pipe thickness

Conclusions of the analysis

After this preliminary analysis, the following conclusions can be drawn:

- The effects of temperature and pressure difference have been investigated and the maximum Von Mises stress is within acceptable margins.
- Maximum stresses occur on the inner pipe surface at the elbow regions, consistent with the stress concentration expected from curvature-induced bending and hoop stress superposition.
- A fully fixed end would prevent all thermal contraction, generating artificially large stresses and potentially singular (infinite) stress concentrations at the boundaries.
- A more detailed model needs to be evaluated, so that the whole system design can be taken into account (inner process pipe, annular vacuum space, MLI, outer protective jacket) along with its supports.
- In this study no pipe supports (receiving the metallic and fluidic weights) were simulated; only temperature & pressure difference induced loads were considered.

In a nutshell, pipe stress analysis is a mandatory engineering activity for the verification of structural integrity in cryogenic and marine piping systems, including those intended for liquid hydrogen (LH₂) service. Such analysis is required to demonstrate compliance with applicable requirements related to sustained loads, thermal expansion, dynamic effects, and occasional loading conditions, in accordance with relevant classification society rules and recognized industrial standards (e.g., ASME B31.3, ASME B31.12).

The present deliverable is prepared within the framework of a conceptual level study under Horizon Europe objectives. Its primary purpose is to establish system-level design criteria, define baseline assumptions, and support preliminary configuration development for LH₂ marine piping systems. At this stage, detailed engineering verification activities, including full pipe stress analysis, flexibility assessment, support design validation, and nozzle load evaluation, have not been performed in the overall piping but in indicative and representative branches.

Any future progression toward actual construction and fabrication shall require the execution of a complete stress analysis in accordance with the selected classification society requirements and project-specific design premises, including full load case definition, boundary conditions, and system modelling.

The current study therefore provides only the necessary input parameters and conceptual framework required to enable subsequent engineering development.

4.7 SIMULATION MODEL OF THE HDMSS FOR SYSTEM PERFORMANCE OPTIMIZATION

This section documents two dynamic simulation models of a cryogenic liquid-hydrogen (LH₂) transfer line connecting a ship-side manifold to an on-board storage tank. The first model represents the loading operation, in which hydrogen is pumped from the manifold into the tank; the second represents the unloading operation, in which the flow direction is reversed, and hydrogen is drawn from the tank towards a discharge point. Both models were built in OpenModelica using the Modelica Fluid component library, with cryogenic parahydrogen properties supplied through the ExternalMedia interface to the CoolProp property database.

The objective of the current modelling is twofold. First, to quantify the resulting temperature increase due to heat ingress into the cold fluid through the vacuum-jacketed MLI pipework, which governs boil-off and the thermodynamic state of the delivered product. Second, to establish the pressure profile along the transfer line, so that the required pump head can be read off and the margin against cavitation can be assessed at every node.

The transfer line consists of three straight pipe sections joined by two 90-degree bends, as shown in Figures 17 & 18. During loading the fluid path is: ship manifold, a 24 m horizontal deck pipe (Pipe 1), the first elbow (Bend 1), a 50 m horizontal deck pipe (Pipe 2), the second elbow (Bend 2), a 30 m vertical pipe (Pipe 3) running downward into the tank, and finally the tank itself. In the unloading direction the same hardware is traversed in the opposite order, with Pipe 3 acting as an upward riser. All three pipes are vacuum-jacketed MLI stainless-steel lines; the two deck pipes share the larger bore while the vertical pipe is of smaller bore.

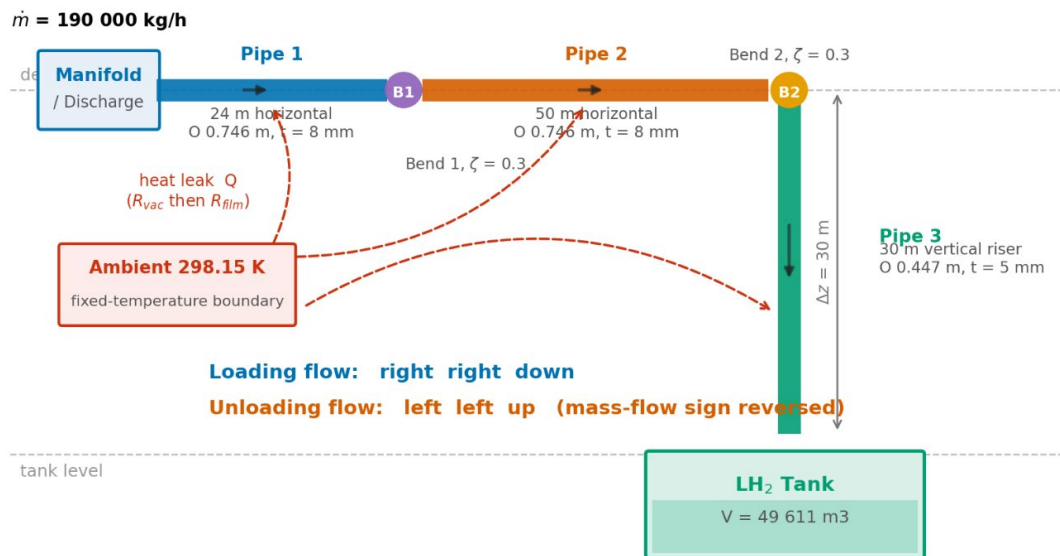


Figure 17. Topology of the LH2 transfer system

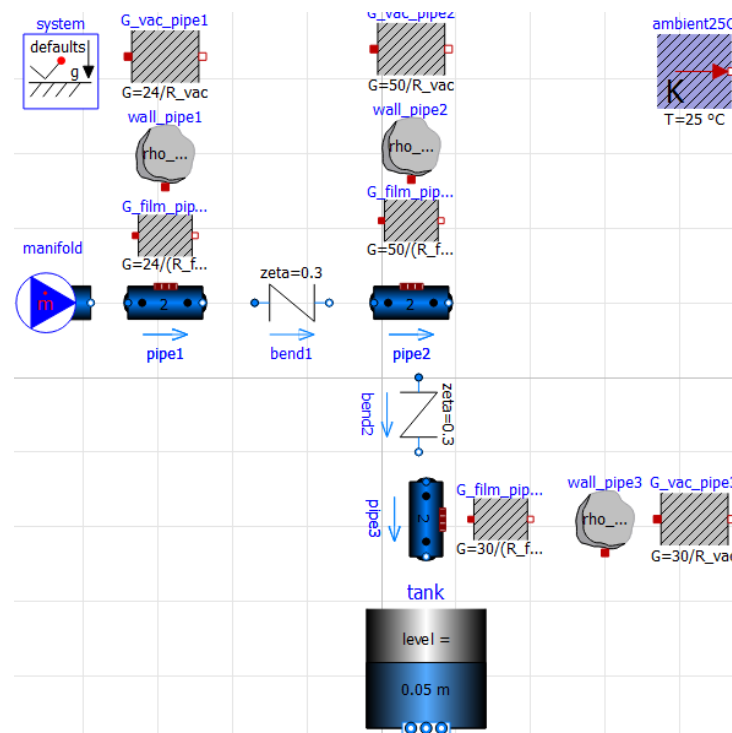


Figure 18. Model topology in OpenModelica

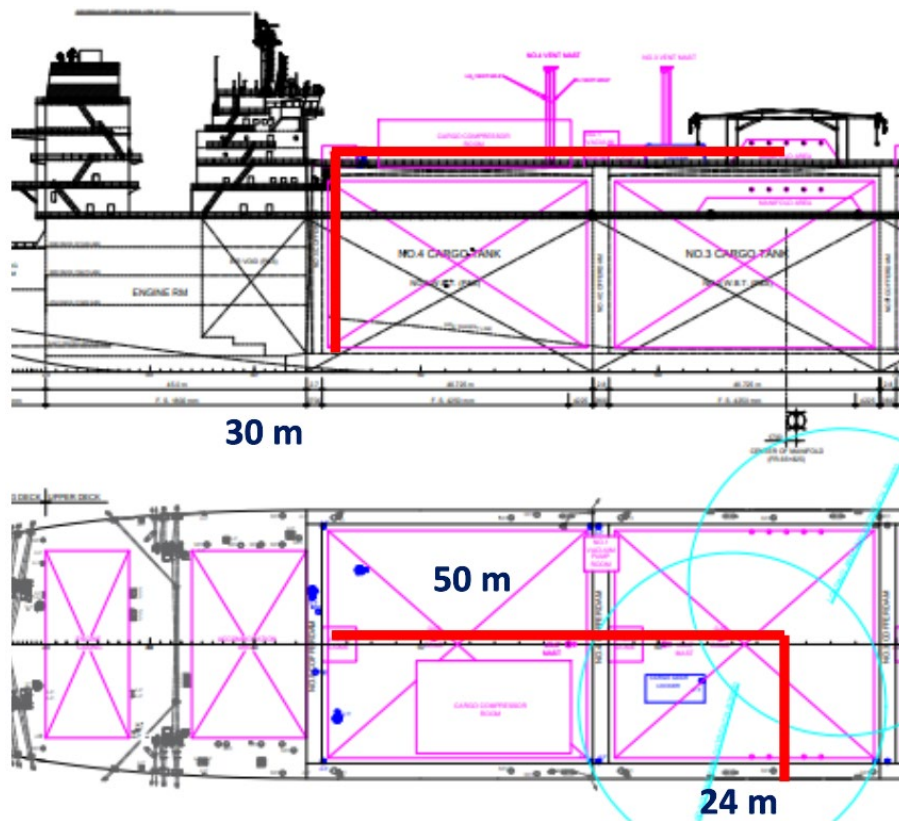


Figure 19. Simulated network on LH₂ Carrier GA

In figure 19, the simulated piping network is illustrated on the LH₂ carrier General Arrangement plan. Table 29 includes the geometric, material and operating parameters, common for both models.

Table 29. Principal parameters shared by the loading and unloading models

Parameter	Symbol / setting	Value
Mass flow rate	$\dot{m}$	190 000 kg/h (52.8 kg/s)
Working fluid	Medium	Parahydrogen
Initial fluid & wall temperature	T_{init}	18.15 K
Ambient temperature	T_{amb}	298.15 K (25 °C)
Deck pipes (1 & 2) bore	D_1	0.746 m, wall 8 mm
Vertical pipe (3) bore	D_2	0.4472 m, wall 5 mm
Pipe lengths (1 / 2 / 3)	L	24 m / 50 m / 30 m
Vertical rise of Pipe 3	Δz	30 m
Elbow loss coefficient	ζ	0.3 per bend
Vacuum-jacket resistance	R_{vac}	55.0 m·K/W
Inner film resistance	R_{film}	0.6 m·K/W
Inner process pipe wall material	ρ, c_p	8000 kg/m ³ , ≈ 20 J/(kg·K) at 20 K

Each pipe is represented by three coupled sub-models that exchange information at every solver step: a one-dimensional fluid model carrying mass, momentum and energy; a lumped thermal-mass model of the metal wall; and a thermal-resistance network that connects the warm environment to the cold fluid through the wall. The sections below describe each in turn, followed by the boundary conditions that distinguish the two operations.

The fluid in each pipe is discretised into two finite volumes (nodes). This is a deliberately coarse discretisation: the transfer line is thermally dominated by the vacuum-jacket resistance, so the axial temperature gradient inside any one pipe is small and a two-node representation captures the inlet-to-outlet behaviour adequately while keeping the model fast. Each pipe wall is represented as a single lumped thermal capacitance — one temperature per pipe — because the metal is thin and highly conductive relative to the heat fluxes involved, so an internal wall gradient would be negligible. The result is a compact model: three wall temperatures, six fluid nodes, and the associated pressures and flows.

Working fluid and properties

The medium is parahydrogen, the low-temperature equilibrium spin isomer of hydrogen, evaluated through the ExternalMedia interface to CoolProp. Pressure (p) and specific enthalpy (h) are used as the independent thermodynamic state variables: all other properties — temperature, density, viscosity, saturation pressure — are obtained as functions of the pair (p , h).

Governing equations

Each fluid finite volume obeys the three conservation laws below. They are written here in lumped (control-volume) form, which is how the Modelica Fluid DynamicPipe component assembles them.

Mass Conservation

For a control volume of constant geometric volume V and a fluid density ρ , the stored mass changes at the rate of the net mass inflow:

$$V \frac{d\rho}{dt} = \sum \dot{m}_{in} - \dot{m}_{out}$$

Momentum Conservation

The momentum balance for the flow between two adjacent nodes reduces, for the quasi-steady incompressible-acceleration conditions of this line, to a balance between the pressure difference, wall friction and gravity:

$$p_a - p_b = \Delta p_{friction} + \rho g \Delta z$$

The friction term is evaluated from a Darcy–Weisbach-type wall-friction correlation. With the cross-sectional area A and hydraulic diameter D , the frictional loss along a pipe of length L can be written as:

$$\Delta p_{friction} = \frac{1}{2} f \left(\frac{L}{D} \right) \rho u^2$$

$$u = \frac{\dot{m}}{\rho A}$$

where f is the friction factor (a function of Reynolds number and roughness) and u is the bulk velocity. The library blends the laminar and turbulent branches smoothly around a small reference flow so that the model remains well-behaved at and through zero flow. The gravity term $\rho g \Delta z$ is the static head: Δz is the elevation change between the two nodes, and it is this term that changes sign between the loading and unloading models.

Each 90-degree bend is modelled as a generic orifice — a localised, geometry-independent loss — using a constant loss coefficient ζ of 0.3:

$$\Delta p_{bend} = \zeta \frac{1}{2} \rho u^2$$

Energy Conservation

The energy balance for a fluid volume, states that the stored internal energy (here tracked through specific enthalpy h) changes due to the enthalpy change due to convection through the ports and heat conduction through the wall:

$$\frac{d(\rho V h)}{dt} = \sum m_{in} h_{in} - m_{out} h_{out} + Q_{wall}$$

Wall thermal mass and heat leak network

The heat path from the 298.15 K environment to the cold fluid is modelled as a series resistance–capacitance network, identical in structure for all three pipes. Working from outside in, the network consists of: the ambient fixed-temperature boundary, a conductor representing the vacuum jacket & MLI and outer structure, the lumped wall thermal capacitance, and finally a film conductor representing the wall-to-fluid heat transfer. The two thermal resistances are quoted per metre of pipe and are converted to conductance for a pipe of length L .

Wall thermal capacitance

Each pipe wall stores heat as a single lumped capacitance. Its heat capacity C is the product of the metal density, the cryogenic specific heat, and the wall volume (taken as the wall thickness multiplied by the mean circumference and the pipe length):

$$C = \rho C_p \pi D L t_{wall}$$

Series thermal resistance

The conductance of the vacuum jacket over a pipe of length L , and the conductance of the inner film, are obtained by dividing the length by the respective per-metre resistance. The film path is split equally over the two fluid nodes of each pipe so that every node receives its share of the heat leak:

$$G_{vac} = \frac{L}{R_{vac}}$$

$$G_{film,node} = \frac{L}{R_{film} n_{nodes}}$$

The heat flow through any conductor is proportional to the temperature difference across it. For instance, for the vacuum jacket, heat flow is obtained as:

$$\dot{Q}_{vac} = G_{vac}(T_{amb} - T_{wall})$$

The chosen values, $R_{vac} = 55.0$ and $R_{film} = 0.6$ m·K/W, sum to 55.6 m·K/W. This was selected so that the network reproduces manufacturer specifications of approximately 5 W/m of heat ingress at a 280 K temperature difference across the insulation — a calibration of the model against vendor data. The vacuum jacket + MLI carries essentially all of the resistance; the inner film is comparatively negligible, which is physically expected for a cryogenic vacuum-insulated line.

Cavitation reference

Liquid hydrogen near 18 K has a saturation pressure of roughly 50.8 kPa. If the local absolute pressure anywhere in the line falls below this value the liquid will flash to vapour — cavitation — which can damage pumps and disrupt flow. The unloading model therefore exports a fixed saturation-pressure reference, ($p_{sat} = 50820$ Pa), (the saturation pressure of parahydrogen at the initial temperature, obtained from CoolProp), and computes the cavitation margin at the critical nodes as the difference between the local pressure and p_{sat} . A positive margin is safe; a negative margin indicates flashing. The same constant is used as the reference line in the loading-case pressure plots for consistency.

Loading model

In the loading configuration hydrogen is delivered from the ship manifold into the storage tank. The model is driven by a prescribed mass-flow source at the manifold and terminated by the tank, which acts as the downstream pressure boundary.

Boundary Conditions

- Inlet (Ship manifold) — a mass-flow source imposing $\dot{m} = 190\,000$ kg/h at the initial temperature.
- Outlet (tank) — a tank of large cross-section, initialised almost empty (low liquid level). The tank fixes the pressure at the end of Pipe 3 and accumulates the delivered hydrogen.
- Thermal — every pipe wall is connected through its own vacuum-jacket & MLI system and film network to the common 298.15 K ambient boundary. Walls and fluid are initialised at 18.15 K (pre-chilled line).

Distinguishing feature – vertical pipe

In the loading direction the vertical pipe runs downward into the tank, so its elevation change is negative ($\Delta z = -30$ m). The static-head term $\rho g \Delta z$ is therefore a pressure gain in the flow direction: gravity assists the flow as it descends to the tank. Consequently, the pressure measured at the tank-side end of the riser is higher than at its top, and the overall pressure relationships along the line are dominated by this static recovery rather than by friction, which is small.

LOADING SCENARIO RESULTS

Figure 20 shows the pipe-wall temperatures. All three walls, starting from 18.15 K, are gradually warmed by the residual heat leak and asymptote to a steady value slightly above the initial temperature within the first few hours; the smaller-bore vertical pipe, having the least thermal mass, responds fastest.

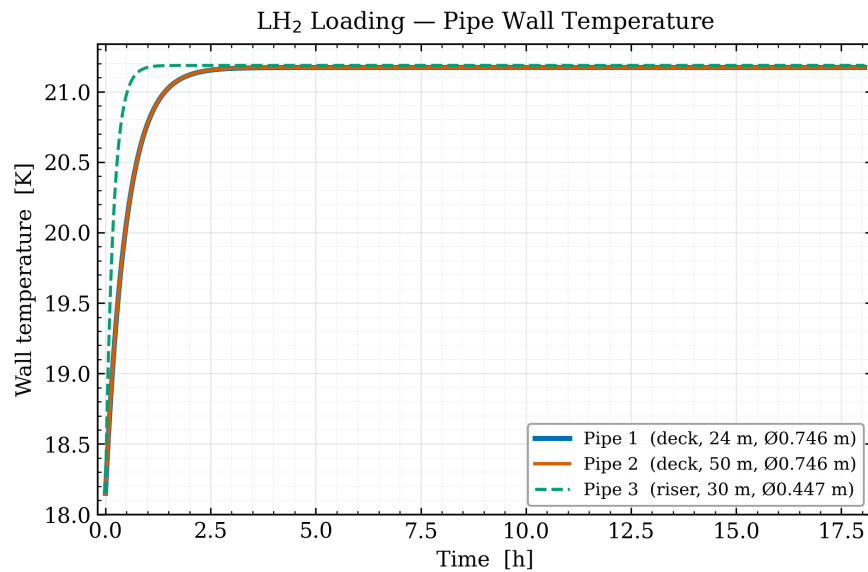


Figure 20. *Pipe wall temperatures vs time*

Figure 21 shows the heat leak into the fluid. After an initial transient the per-pipe heat flows settle at constant values; the 50 m deck pipe contributes the most simply because it is the longest, and the system total stabilises at roughly half a kilowatt — a small figure that confirms the effectiveness of the vacuum insulation and explains the very modest fluid temperature rise.

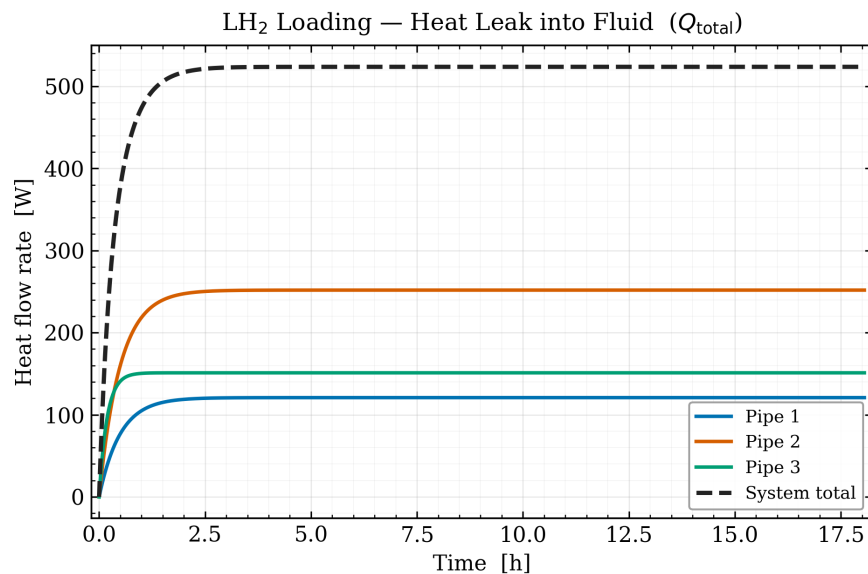


Figure 21. *Heat leak into the fluid vs time*

Figure 22 shows the pressures at the main nodes together with the cavitation reference. The node pressures remain well above the 50.8 kPa saturation line throughout, so the loading operation carries a comfortable margin against flashing.

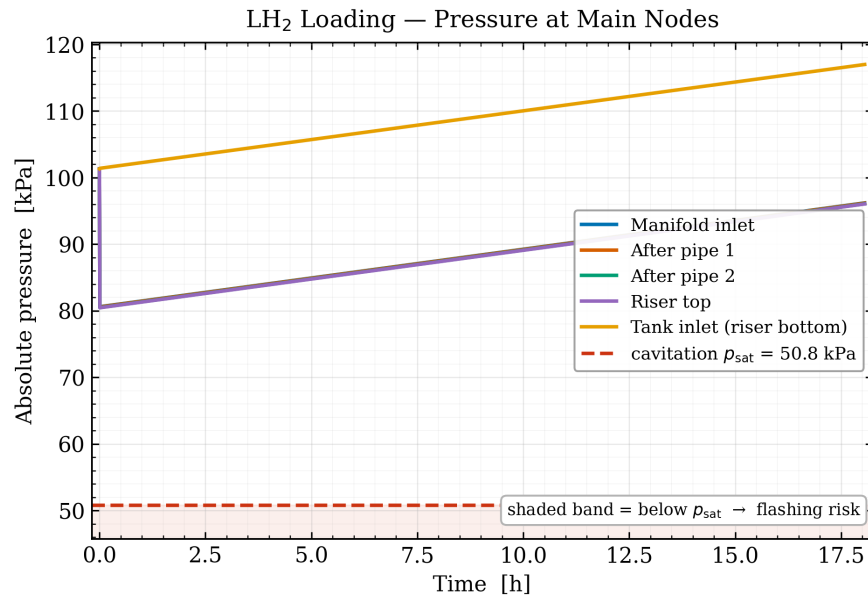


Figure 22. Nodal pressure values vs time

Figure 23 shows the temperature increase in the fluid volume across the 3 pipes. It is noted that the volume averaged temperature increase is negligible due to the dimensions of the pipes and the small temperature difference between the steel walls and fluid (due to the high resistance of vacuum and MLI).

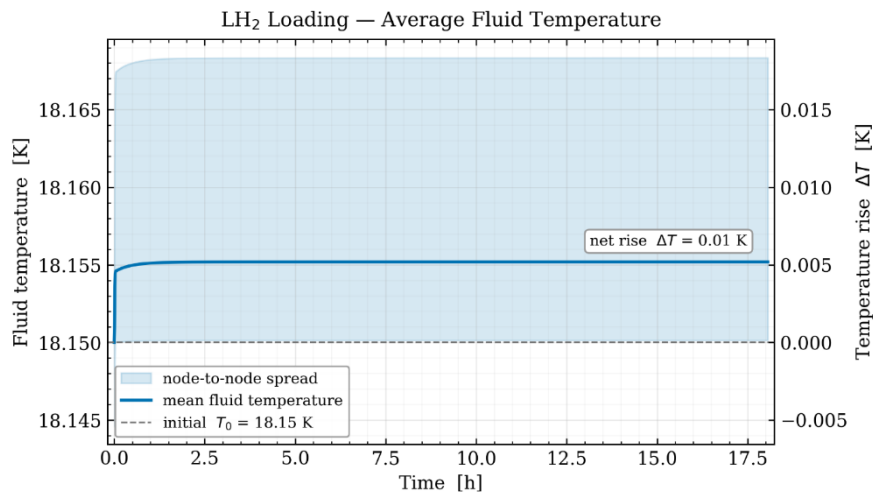


Figure 23. Fluid volume temperature increase vs time

Unloading model

In the unloading configuration the operation is reversed: hydrogen is withdrawn from a nearly full tank and delivered to a discharge point on deck. The same three pipes and two bends are used, but they are now traversed from the tank outward.

Boundary Conditions

- **Inlet (tank)** — the storage tank, initialized almost full (liquid level near the top of its 23 m height). The tank provides the upstream pressure boundary, which includes the hydrostatic head of the stored liquid.

- **Outlet (ship manifold)**— a mass-flow boundary imposing $\dot{m} = -190\,000\text{ kg/h}$. The negative sign enforces withdrawal: flow leaves the line at the discharge point at the same rate as in the loading case.
- **Thermal** — identical to the loading model: per-pipe vacuum-jacket and film networks to the 298.15 K ambient, all components initialized at 18.15 K.

Because the line now runs from the tank up to the deck, the vertical pipe is an upward riser with a positive elevation change ($\Delta z = +30\text{ m}$). The static-head term $\rho g \Delta z$ now opposes the flow: the fluid must be lifted 30 m. The model deliberately omits the transfer pump; instead, the solver computes the pressure profile that the prescribed flow demands, and the total pressure deficit across the system is reported directly as the pump rise that would be required to sustain the operation. In other words, the model converts a fixed-flow boundary condition into a required-head result.

UNLOADING SCENARIO RESULTS

In figure 24, the pressure losses can be visualized. It can become clear, that the main source of pressure losses is the riser static head.

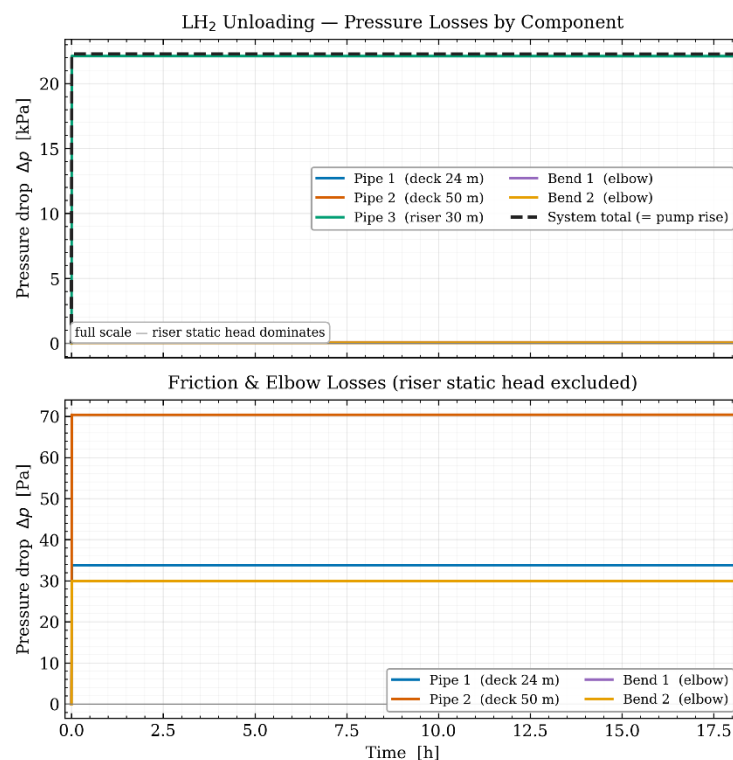


Figure 24. *Pressure losses vs time*

In table 30, the overall assessment of the 2 scenarios is illustrated. It should be noted that while the average temperature increase of the fluid is negligible, the fluid layer that is in touch with the metal wall – fluid interface will be evaporated if the critical point is surpassed.

Table 30. High level phase change risk

Loading model results						
Location	p_{local} [kPa]	T_{fluid} [K]	$T_{wall,max}$ [K]	T_{sat} [K]	$\Delta T = T_{sat} - T_{wall}$	Phase change
Pipe 1 (24 m, horiz.)	95.44	18.150	21.172	20.071	-1.101	Boiling at wall
Pipe 1 (24 m, horiz.)	95.40	18.150	21.172	20.070	-1.102	Boiling at wall
Pipe 1 (50 m, horiz.)	95.37	18.151	21.172	20.069	-1.104	Boiling at wall
Pipe 1 (50 m, horiz.)	95.30	18.151	21.172	20.066	-1.106	Boiling at wall
Pipe 1 (30 m, vert.)	95.37	18.168	21.186	20.065	-1.121	Boiling at wall
Pipe 1 (30 m, vert.)	116.22	18.161	21.186	20.743	-0.443	Boiling at wall
Unloading model results						
Pipe 1 (24 m, horiz.)	79.58	18.139	21.161	19.482	-1.679	Boiling at wall
Pipe 1 (24 m, horiz.)	79.54	18.139	21.161	19.481	-1.680	Boiling at wall
Pipe 1 (50 m, horiz.)	79.68	18.139	21.161	19.486	-1.674	Boiling at wall
Pipe 1 (50 m, horiz.)	79.61	18.139	21.161	19.484	-1.677	Boiling at wall
Pipe 1 (30 m, vert.)	101.81	18.129	21.156	20.287	-0.868	Boiling at wall
Pipe 1 (30 m, vert.)	79.71	18.138	21.156	19.488	-1.668	Boiling at wall

Conclusions of the simulation study

The loading model, driven from the manifold into a filling tank, shows a well-insulated line with a small heat leak, a modest fluid-temperature rise and a comfortable margin against cavitation, with the downward vertical section providing a static-head gain. The unloading model, driven from a full tank towards discharge, reverses the flow and the sign of the static head; with the pump deliberately omitted, it returns the required pump head directly as the system pressure deficit, and confirms that this duty is set almost entirely by the 30 m static lift rather than by friction. Together the two models provide a consistent basis for assessing heat ingress, delivered-product temperature and pump sizing across both phases of the transfer operation.

5 SAFETY AND RISK ASSESSMENT

In order to evaluate the risk and safety performance of the basic and detailed design of the LH2CRAFT, a qualitative risk analysis comprising of Hazard and Operability Analysis (HAZOP) and Failure Mode and Effects Analysis (FMEA) was carried out. The deliverables (D8.2 and D8.4) will be submitted in WP8 and will contain details of the risk assessment carried out.

The HAZOP and FMEA were carried out in the form of brainstorming guided by the relevant worksheets. The objective of the HAZOP workshop was to identify potential risks associated with the “operation” of LH2 and its associated systems. The purpose of the FMEA was to demonstrate compliance with the design philosophy for failure situations for LH2CRAFT solutions. The risk assessments were performed to the detailed up-to-date engineering design of the CCS and HDMSS systems to identify and reduce risks to acceptable/manageable levels. All consortium partners were key members of the workshops along with representatives of external advisory board participated in the workshops.

HAZOP fundamentally focused on the operational risks associated with the LH2 cargo and its associated systems designed and developed as part of the LH2CRAFT project and will be carried out for the 160,000 m³ membrane type LH₂ cargo containment system design, considering also the ship integration and the main handling, distribution and monitoring subsystems.

HAZOP was efficiently carried out in a structured manner; the overall systems were discretised into system nodes (groups). The following four system nodes were suggested for the workshop.

- Node 1: Cargo Station / Cargo handling system
- Node 2: LH2 Tank Storage / Cargo containment system
- Node 3: Vent mast / Vent system
- Node 4: Cargo compressor room / Cargo handling system

Through FMEA, the failure situations as per the detailed engineering design of the liquid hydrogen carrier vessel and liquid hydrogen cargo containment systems were identified along with risk mitigation recommendations. The FMEA has been carried out for liquid hydrogen cargo on a LH2 carrier of about 160,000 m³, and only consider LH2 as cargo (not as a marine fuel), therefore without the need of any fuel preparation unit on board. In addition, the FMEA considered only the innovative systems that have been designed and developed as part of this project.

Specifically, as part of the assessment, the overall system was discretized into system nodes (groups). The following five system nodes and their associated functional subsystems were suggested for the workshop.

- Node 1: Cargo Station
- Node 2: Tank Storage
- Node 3: CCS System
- Node 4: Vent Mast
- Node 5: Cargo Compressor Room

The risk mitigation and safety recommendations identified through these assessments were fed into the detailed designs described in D5.1.

5.1 HAZOP FINDINGS – DESIGN UPDATES

As a result of HAZOP workshop, the worksheet has been fulfilled detailing the analyses of the risk associated with operational hazards and their mitigation recommendations with a list of actions to improve the original design.

HAZOP identified 296 individual hazards in Nodes 1, 2, 3 and 4 during the workshop. Among these, most hazards had multiple likelihood and consequences scenarios as a result 192 items were risk ranked. 9 items were identified to be unacceptable risk of which all were mitigated. The breakdown of the risk score according to the nodes have been listed below.

All items were given a risk score before and after mitigation by giving appropriate recommendations. Certain items with recommendations for risk reductions will have had a change in risk score after mitigation i.e. lower risk score as a result of the recommendation being implemented after HAZOP. This will result in an increase in the number of items with lower risk scores as items with high-risk score shifts to lower risk scores as a result of mitigation actions.

Node 1: Cargo Station / Cargo handling system

Node 1 consisted of bunkering stations and fuel handling system including shore connection, bunker manifold, drip tray, bunkering lines and hoses. Node 1 had considered the 3 operating modes listed in Table 2. A total of 109 hazards were identified based on the combination of operating modes and guideword. In these hazards there were multiple consequences and therefore 51 individual items were risk ranked the breakdown is shown in Figure 25 below. Node 1 had no items in the unacceptable risk levels (intolerable area) while 42 items were in the tolerable risk category. In the acceptable risk category, there was 9 items.

		Consequence				
		C1	C2	C3	C4	C5
		Minor Injury	Major Injury	Single Fatality or Major injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely				
	L6	Very Likely				
	L5	Likely				
	L4	Unlikely				
	L3	Very Unlikely		2	9	
	L2	Extremely Unlikely		11	5	15
	L1	Remote	2	2		5

Number of items in each risk category before mitigation

		Consequence				
		C1	C2	C3	C4	C5
		Minor Injury	Major Injury	Single Fatality or Major injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely				
	L6	Very Likely				
	L5	Likely				
	L4	Unlikely				
	L3	Very Unlikely		2	8	
	L2	Extremely Unlikely		11	6	15
	L1	Remote	2	2		5

Number of items in each risk category after mitigation

Figure 25: Distribution of items in risk matrix for Node 1

Node 2: LH2 Tank Storage / Cargo containment system

The tank storage system consisted of the storage tanks on the upper deck and the lower deck (number 5 cargo hold space). Node 2 had 6 operating modes. A total of 109 hazards were identified in, and 79 items were risk ranked. In Node 2, no items were classed as intolerable risk while 62 items were classes as tolerable risk and 17 items were in the acceptable risk category.

			Consequence				
			C1	C2	C3	C4	C5
			Minor Injury	Major Injury	Single Fatality or Major Injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely					
	L6	Very Likely					
	L5	Likely					
	L4	Unlikely					
	L3	Very Unlikely	1		3	16	
	L2	Extremely Unlikely		1	14	10	19
	L1	Remote			10	3	2

Number of items in each risk category before mitigation

			Consequence				
			C1	C2	C3	C4	C5
			Minor Injury	Major Injury	Single Fatality or Major Injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely					
	L6	Very Likely					
	L5	Likely					
	L4	Unlikely					
	L3	Very Unlikely			3	15	
	L2	Extremely Unlikely	1	1	14	11	19
	L1	Remote			10	3	2

Number of items in each risk category after mitigation

Figure 26: Distribution of items in risk matrix for Node 2.1

Node 3: Vent mast / Vent system

The vent mast system had 34 hazards were identified with 32 items being risk ranked of which, 9 items were classed as intolerable risk and mitigation actions were specified. There were 22 items in the tolerable and 1 item in the acceptable regions of the risk matrix, none of these risks were mitigated. Figure 27 shows the distribution of items in the risk matrix.

			Consequence				
			C1	C2	C3	C4	C5
			Minor Injury	Major Injury	Single Fatality or Major injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely					
	L6	Very Likely					
	L5	Likely					
	L4	Unlikely			5		7
	L3	Very Unlikely			3		2
	L2	Extremely Unlikely					14
	L1	Remote					1

Number of items in each risk category before mitigation

			Consequence				
			C1	C2	C3	C4	C5
			Minor Injury	Major Injury	Single Fatality or Major injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extreme Likely					
	L6	Very Likely					
	L5	Likely					
	L4	Unlikely			5		
	L3	Very Unlikely			3	8	
	L2	Extremely Unlikely				6	9
	L1	Remote					1

Number of items in each risk category after mitigation

Figure 27: Distribution of items in risk matrix for Node 3

Node 4: Cargo compressor room / Cargo handling system

There were 44 hazards identified with 30 items in Node 4. All the items were in acceptable category with none in the intolerable or tolerable risk category. Figure 28 shows the breakdown of items in various risk categories.

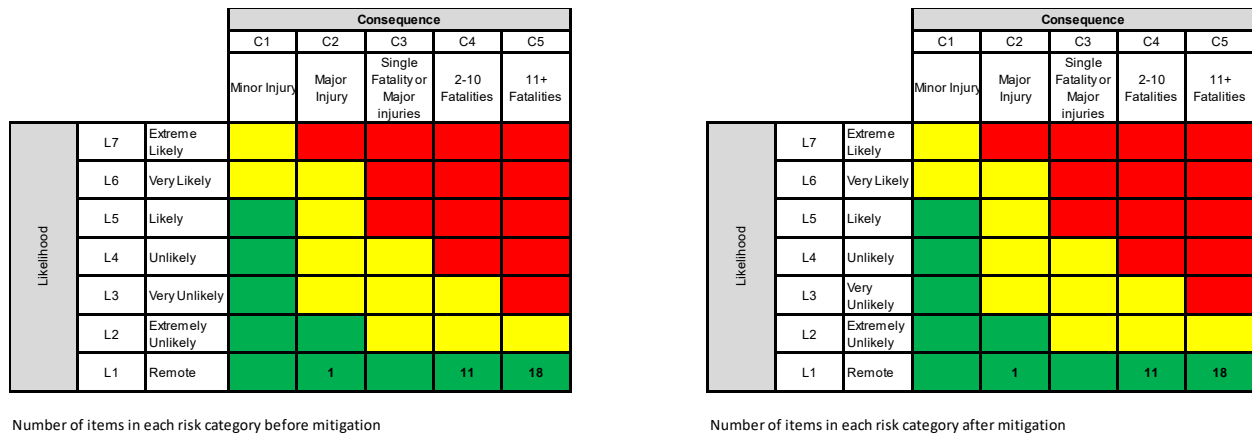


Figure 28: Distribution of items in risk matrix for Node 4

Accordingly, the following outcomes were drawn from the HAZOP workshops:

- A total of 296 individual hazards were identified in Nodes 1, 2, 3 and 4 during the HAZOP workshop. Among these, most had multiple likelihood and consequences scenarios as a result 192 items were risk ranked.
- In total, 9 items had a risk score above 15 (intolerable risk) and when mitigation actions were specified it was reduced to 0 items.
- 109 hazards were established in Node 1 and with 51 of them were risk ranked, of which, none were classed as intolerable.
- Node 2 had 109 hazards with none in the intolerable region.
- In Node 3, 34 hazards were identified with 32 items being risk ranked. 9 items were classed as intolerable risk and were mitigated through design recommendations.
- Node 4 had 44 hazards with a total of 30 risk ranked items of which none were classed as intolerable risk.
- The HAZOP recommendations and action list is provided in Appendix B. The drawings used in HAZOP was updated based on the action list prior to FMEA.

In addition, bringing together the different elements discussed earlier, a worksheet was created to document and discuss the various hazards identified during the HAZOP workshop. As an important output from the HAZOP study, the completed HAZOP worksheet is attached with this report as separate file (file title: "LH2CRAFT_HAZOP_Worksheet v1.0").

5.2 FMEA FINDINGS – DESIGN UPDATES

According to the design, each item may operate under various modes, each potentially resulting in distinct failure modes, effects, and mitigation actions. To accurately capture these during the assessment, each failure scenario was treated as a separate item for individual analysis. For example, item ID HVR31 in Node 2 exhibits three different failure scenarios across its operational modes; therefore, it was counted as three distinct item-failure scenarios in the analysis.

In summary, the total number of item-failure scenarios successfully analysed is 622, i.e.:

- Node 1: 235
- Node 2: 263
- Node 3: 48

- Node 4: 24
- Node 5: 52

Each node contains various types of components that can be broadly grouped as pressure components, temperature components, valves, components of piping system and cargo containment system, level control components, mechanical components, heating elements and other miscellaneous items.

The conclusions regarding failure effects is that no single failure has been found that can lead to a specified undesired event or hazardous situation with immediate potential for injury to persons, damage to vessels or pollution of the environment. However, there are a number of corrective or improvement actions addressed to specific consortium members that have been identified from the FMEA findings.

In addition, as can be seen in Figure 29, criticality analysis shows most items assessed was categorised in the range of very low to moderate (i.e. RPN value less than 250), no items were rated as very high (RPN value above 500). However, there are two items that have been rated as highly critical (i.e. RPN value between 250 and 500) which need to be prioritised when developing the safety strategy of the system. These items, HNS01 and HNS02, are swing check valves designed to function as outlet valves for the inert gas room. They are operated under Operation Modes M6.2.1 and M6.2.2 . The specific actions related to these items have also been included in the action list in Appendix D.

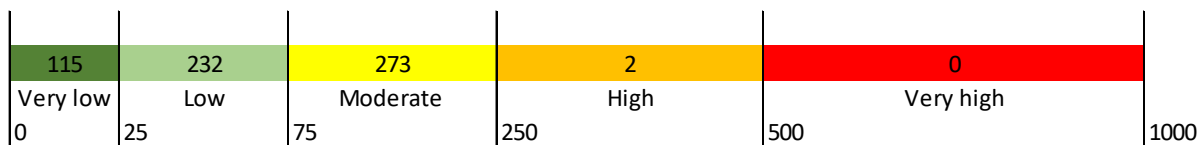


Figure 29: Total number of item-failure scenarios in each RPN category for the entire system assessed

More specifically, the final risk presents the statistics of criticality analysis results for each node. As can be seen, Nodes 1 and 5 have the highest proportion of item-failure scenarios rated as moderate level, indicating potential areas for risk reduction. Node 2 performs the best overall, with the majority of item-failure scenarios in the low and very low range, despite having the highest total item-failure scenarios assessed.

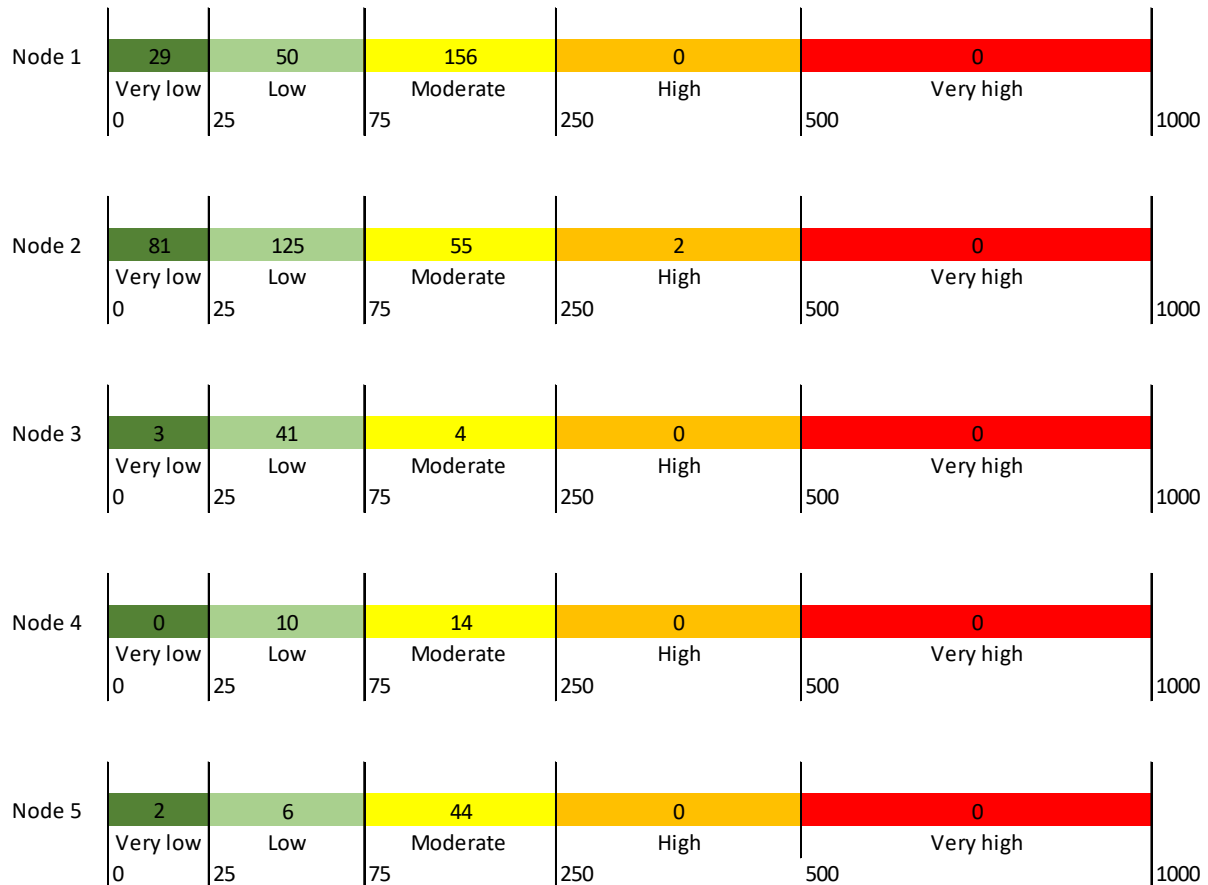


Figure 30: The number of items in each RPN category for each node

All details about the FMEA workshop outcomes that lead to the above discussed assessment results are recorded in the FMEA worksheets and attached with this report as separate file (file title: "LH2CRAFT_FMEA_Worksheet v1.0"). Accordingly, some of the general findings can be summarised as follows:

- Among all 622 item-failure scenarios assessed, 56% of them are rated low and very low critical level meaning the current safety measures are sufficient for maintaining the safe application of these items. No item is in the very high risk category. Two items are rated as highly risky and critical which requires immediate corrective action to take place. The rest items with moderate risk / critical level have also been assigned with specific corrective or improvement risk control recommendations.
- The two items that are rated as highly risky and critical are swing check valves designed to function as outlet valves for the inert gas room. The analysis shows, these items exhibited very high failure severity and low detectability, with no redundancy available.
- Based on the overall findings from the FMEA analysis, the following operational procedures should be developed and incorporated into the Operation Manual:
 - o HVR02 and HVR04: These valves must not be used as check valves, as they are not designed to allow bi-directional flow of hydrogen (H₂).
 - o HCS39, HCS40, HCS41, and Equivalent Valves in Cargo Tanks 2 and 3: Valve positions (open/closed) under various operating modes must be clearly defined, as improper configuration may result in damage to the cargo pump or tank structure.

- Y-Type Strainers and Equivalent Items in Cargo Tanks 2 and 3: As these strainers are critical components, spare units must be readily available for immediate replacement in the event of clogging.
- HVR06, HVR07, and Equivalent Valves in Cargo Tanks 2 and 3: Specific operating instructions must be provided for scenarios involving valve failure. These valves are directly connected to the gas dome and cannot be replaced unless the tank is completely emptied.
- Nitrogen and Cryogenic Liquid Hydrogen Interaction: Since nitrogen has a higher condensation temperature than liquid hydrogen, procedures must be implemented to prevent direct contact or mixing. A detailed purging process should be documented and strictly followed.
- Operating Modes M5 and M3.1: In the event of vent mast blockage, the gas dome should be opened via the gas main line as a redundancy to allow hydrogen (H₂) to flow to other tanks.
- HVR27: This valve should remain slightly open during operation to facilitate effective temperature control.
- HD Compressors No.1 and No.2: A unified operation mode list should be developed and standardized for both compressors.
- Steam Traps: Operational procedures must include detailed information regarding the associated condensation lines to ensure proper functionality.
- It should be noted that the alarm system for the IBS/IS pressure control valves is applicable exclusively to hydraulically operated valves.
- Ensure that appropriate provisions are made for pressure release, including the installation of a sufficient number of pressure relief valves (PRVs) on the cargo tanks, to effectively mitigate the risk of overpressure
- More itemised and detailed notes can be found in the attached worksheet.

5.3 QUANTITATIVE RISK EVALUATION OUTCOMES

This section offers an overview of the primary findings and design recommendations resulting from task T8.4, which focused on conducting a Quantitative Risk Assessment (QRA) study of various scenarios related to HDMSS systems and the vessel design in general. For comprehensive details, readers are encouraged to consult deliverable D8.3, entitled 'QRA reports with fire/explosion simulation and storage tank integrity '.

6.3.1 SCENARIO #1 – FIRE ANALYSIS AT VENT MAST No.3 & 4

This study aims to evaluate the potential impact of a jet fire incident originating from Vent Mast No.3 under specific wind conditions, particularly when the wind is blowing from bow to stern. Given the close proximity between Vent Mast No.3 and Vent Mast No.4, it is important to assess whether flame impingement or elevated thermal radiation could affect the surrounding area, including adjacent equipment.

The primary focus of this analysis is to determine:

- The extent and direction of flame spread under the given wind conditions.
- The temperature distribution in the vicinity of the fire, especially around Vent Mast No.4.

This evaluation will help identify potential interference between the vent masts during a fire scenario and support decisions related to fire safety design and risk mitigation.

Results and Recommendations

Hydrogen jet-fire simulations were performed under varying wind conditions to assess flame behaviour and its potential impact on surrounding structures. The cases analysed include single venting from Vent Mast No.3 with wind speeds of 1 m/s, 6 m/s, and 10 m/s, corresponding to Cases S#1-S-1, S#1-S-2, and S#1-S-3, respectively.

As shown in *Figure 31*, the flame characteristics are significantly influenced by wind speed. At low wind speed (1 m/s), the flame rises vertically with minimal horizontal displacement, resulting in concentrated thermal exposure near the vent mast. As wind speed increases to 6 m/s and 10 m/s, the flame is increasingly deflected downstream, extending horizontally and interacting with the ship's superstructure.

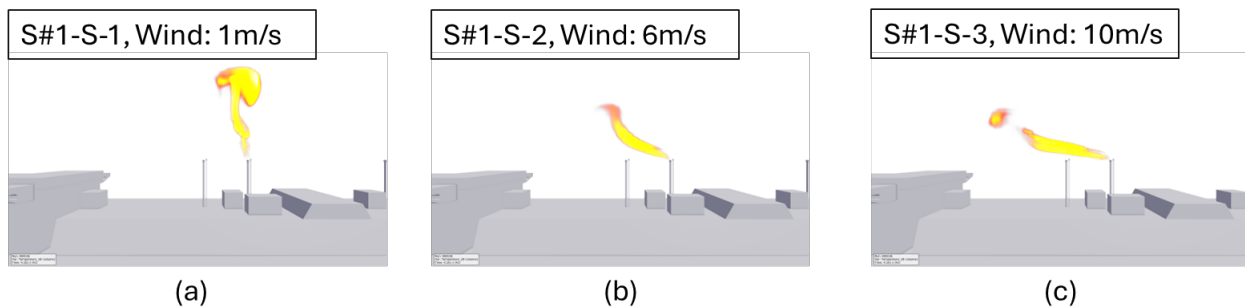


Figure 31. Hydrogen Jet-Fire Simulation Results under Varying Wind Speeds: (a) 1 m/s, (b) 6 m/s, and (c) 10 m/s. Flame behaviour and direction are visualised to assess thermal impact on surrounding structures.

In the highest wind condition (10 m/s), the flame exhibits pronounced bending and elongation. However, in the case of single vent opening, the flame does not reach the accommodation block, indicating that thermal exposure to habitable areas remains limited under this configuration. This result highlights the importance of venting configuration in determining flame reach and potential hazard zones.

Following the single venting analysis, additional simulations were conducted for the dual venting configuration, where hydrogen is released simultaneously from Vent Mast No.3 and No.4. The objective was to examine how the presence of multiple release points influences flame behaviour under varying wind conditions.

Figure 32 illustrates the flame development for wind speeds of 1 m/s, 6 m/s, and 10 m/s. At 1 m/s, the flames from both vents initially behave independently. Notably, flame formation is observed only at Vent Mast No.3 immediately after ignition. However, approximately 12 seconds later, flame propagation is also observed at Vent Mast No.4. This delayed ignition is attributed to thermal radiation and heat transfer from the initial flame, which raises the temperature around Vent Mast No.4 sufficiently to support jet-fire development. The result demonstrates that even under low wind conditions, thermal interaction between venting points can lead to secondary flame formation.

As wind speed increases to 6 m/s, the flames begin to merge and are deflected downstream, forming a broader and more coherent flame structure. Under the highest wind condition (10 m/s), the combined flame exhibits significant horizontal extension and directional bending, with increased thermal footprint across the deck area.

Compared to the single venting case, the dual venting configuration results in a wider flame base and greater overall flame length, especially under strong wind conditions. While the flame in the single venting scenario remained confined and did not reach the accommodation block, the dual venting case shows a more expansive flame trajectory. However, even in the most severe condition (10 m/s), the flame tip does

not directly impinge on the accommodation block, suggesting that the habitable zone remains outside the immediate thermal hazard range.

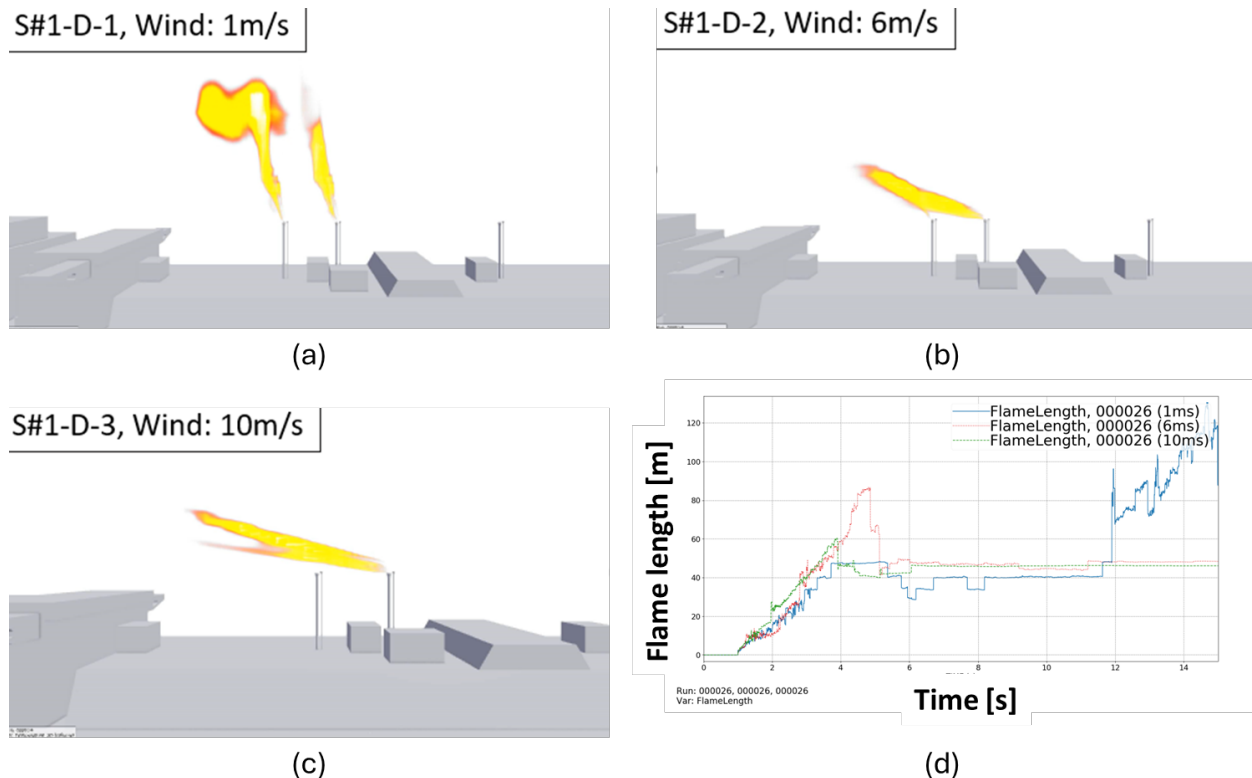


Figure 32. Hydrogen Jet-Fire Simulation Results under Varying Wind Speeds for Dual Venting: (a) 1 m/s, (b) 6 m/s, and (c) 10 m/s. Flame behaviour and direction are visualised to assess thermal impact on surrounding structures. (d) Time series of flame length for different wind speeds.

Figure 32(d) presents the time trace of flame length for each wind condition, highlighting the dynamic response of the flame to wind-induced momentum and turbulence. The dual venting setup consistently produces longer flames than the single venting case, emphasising the importance of vent configuration in fire hazard assessments.

These findings underscore the need for careful consideration of vent layout, ignition timing, and wind exposure in the design of hydrogen safety systems, particularly in scenarios involving simultaneous PRV activation and potential flame interaction.

6.3.2 SCENARIO #2 – EXPLOSION ANALYSIS AT CARGO COMPRESSOR ROOM

This scenario investigates the consequences of a fire and explosion event originating within the cargo compressor room, with a focus on its potential impact on the open deck area. The explosion is assumed to have initiated inside the cargo compressor room, and the top side of the compartment is configured with an opening to represent a ventilation inlet and outlet. Those openings allow for the release of explosion pressure and serve as a location for pressure measurement.

The purpose of this study is to evaluate the effects of fire and explosion events on the surrounding structures, particularly the LH₂ tank, as part of a Fire and Explosion Risk Assessment (FERA) and/or Quantitative Risk Assessment (QRA). The analysis aims to identify the peak explosion pressure generated

within the cargo compressor room and assess whether the resulting pressure wave could compromise the structural integrity of nearby components.

In particular, the spatial propagation of explosion pressure from the cargo compressor room toward the open deck area is examined to determine the potential for secondary accidents. This includes verifying whether the pressure levels are sufficient to affect the LH₂ tank or other critical systems located on the deck, thereby informing safety design and mitigation strategies.

Results and Recommendations

The simulation examined the pressure development resulting from hydrogen explosions within the cargo compressor room, with measurements taken at MP1, located at the centre of the room. The analysis focused on three hydrogen–air mixture concentrations: 5%, 10%, and 18% by volume.

The results, illustrated in Figure 33. , show a clear correlation between hydrogen concentration and explosion severity. As the volumetric percentage of hydrogen increases, both the peak pressure and the rate of pressure rise increase significantly. For the 5% mixture, the explosion produced a relatively low peak pressure of approximately 0.005 bar, indicating a mild deflagration. In contrast, the 10% mixture resulted in a peak pressure of around 0.5 bar, while the 18% mixture generated a much more intense explosion, reaching a peak pressure of approximately 4.5 bar.

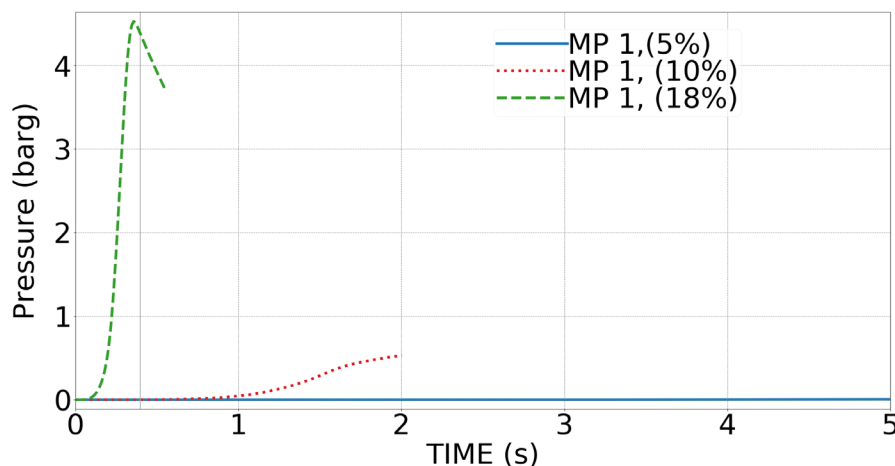


Figure 33. Pressure-Time Histories at MP1 (on the centre-facing wall surface) for Different Hydrogen Concentrations (5%, 10%, and 18%) within Cargo Compressor Room.

The time required to reach peak pressure also decreased with increasing hydrogen concentration. The 18% case exhibited a rapid pressure escalation immediately following ignition, suggesting highly reactive combustion dynamics. This behaviour highlights the increased risk associated with higher hydrogen concentrations, particularly in confined spaces.

The pressure-time curves further reveal that the initial pressure rise becomes steeper as the concentration increases, indicating faster flame propagation and more energetic combustion. These findings underscore the importance of controlling hydrogen accumulation and ensuring adequate ventilation in enclosed environments to mitigate explosion hazards.

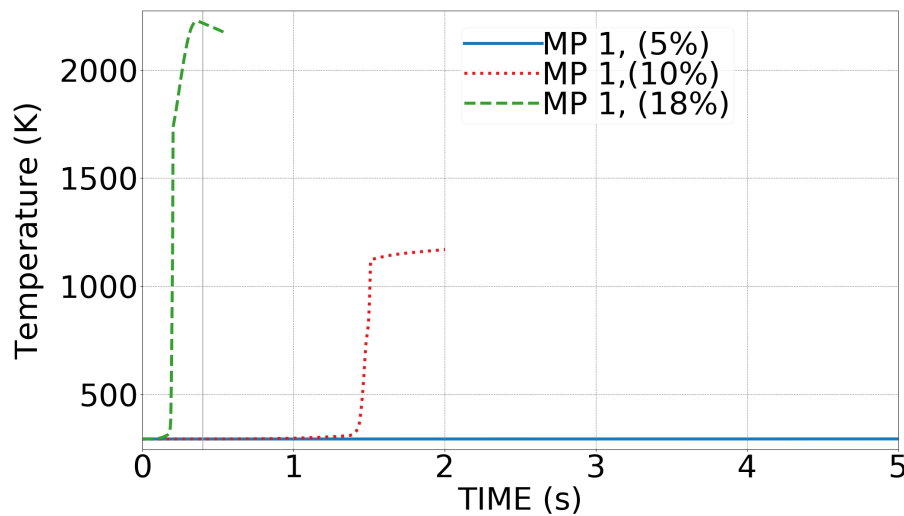


Figure 34. *Temperature-Time Histories at MP1 (on the centre-facing wall surface) for Different Hydrogen Concentrations (5%, 10%, and 18%) within Cargo Compressor Room*

Figure 34. presents the temporal progression of temperature for MP 1 at three different concentrations: 5%, 10%, and 18%. The simulation results reveal a strong dependence of thermal behaviour on concentration.

At a concentration of 5% (blue solid line), the temperature remains nearly constant at approximately 294 K, indicating the absence of significant exothermic reactions. In contrast, the 10% concentration case (red dotted line) exhibits a delayed temperature rise, reaching a peak of approximately 1169 K slightly after 1 second, suggesting the onset of moderate thermal activity. The most distinct behaviour is observed at 18% concentration (green dashed line), where the temperature rapidly escalates to a peak of 2224 K almost immediately after ignition, indicating a highly reactive or potentially explosive regime.

These findings underscore the critical influence of concentration on the thermal response of MP 1, with higher concentrations leading to significantly more intense and rapid temperature rises.

FIGURE 35 illustrates the progression of temperature distribution following the ignition of a hydrogen-air mixture with 18% hydrogen concentration. Initially, no thermal activity is observed (a), but localised heating begins at (b). A significant temperature rise and flame propagation are evident from (c) to (h), with the combustion front expanding and intensifying over time. The sequence highlights the dynamic nature of hydrogen combustion and the rapid development of high-temperature regions within a few seconds.

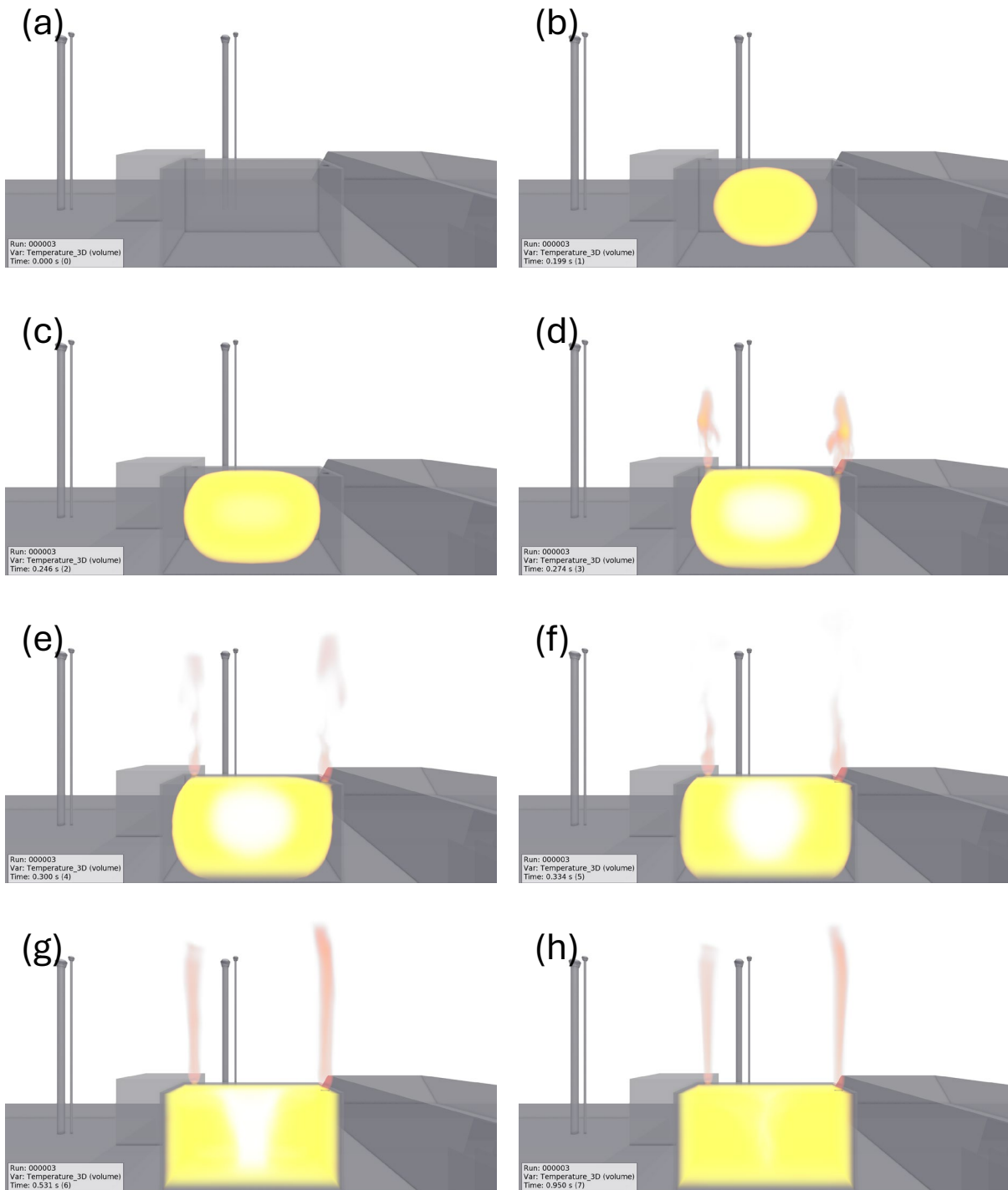


Figure 35. Temperature evolution in a domain containing 18% hydrogen concentration at selected time steps. (a) $t = 0$ s, (b) $t = 0.20$ s, (c) $t = 0.25$ s, (d) $t = 0.27$ s, (e) $t = 0.30$ s, (f) $t = 0.33$ s, (g) $t = 0.53$ s, (h) $t = 0.95$ s)

6.3.3 SCENARIO #3 – JET FIRE ANALYSIS AT PRESSURE RELIEF VALVE

In liquefied hydrogen (LH₂) carriers, pressure relief valves (PRVs) are essential components for maintaining system safety under overpressure conditions. However, mechanical failure or improper sealing in the PRV or adjacent piping may lead to unintended hydrogen leakage. When such a release occurs in the presence of an ignition source, it can result in a jet fire, characterised by high-velocity, high-temperature flame propagation.

Scenario #3 addresses this critical failure mode by analysing the thermal consequences of a jet fire initiated near the No.3 PRV. The scenario assumes that hydrogen leakage originates either directly from the PRV or from the connected pipeline, and that ignition occurs shortly thereafter. The resulting jet fire poses a significant threat to nearby shipboard structures, particularly the cargo compressor room and the adjacent open deck area.

The primary objective of this study is to evaluate the thermal impact of the jet fire on these vulnerable regions. Through computational simulation, the temperature distribution and heat flux levels are assessed to determine the extent of thermal exposure and potential structural damage. This analysis provides essential insight into the fire resilience of LH₂ carrier designs and supports the development of effective risk mitigation strategies for cryogenic hydrogen transport systems.

Results and Recommendations

Figure 36. presents the total heat flux distribution on the wall of the cargo compressor room resulting from a jet fire initiated by a 2 mm hydrogen leak located 0.5 metres from the structure. The simulation snapshot corresponds to approximately 7 seconds after the onset of release ($t \approx 6.95$ s), representing the early-stage thermal impact of the jet flame.

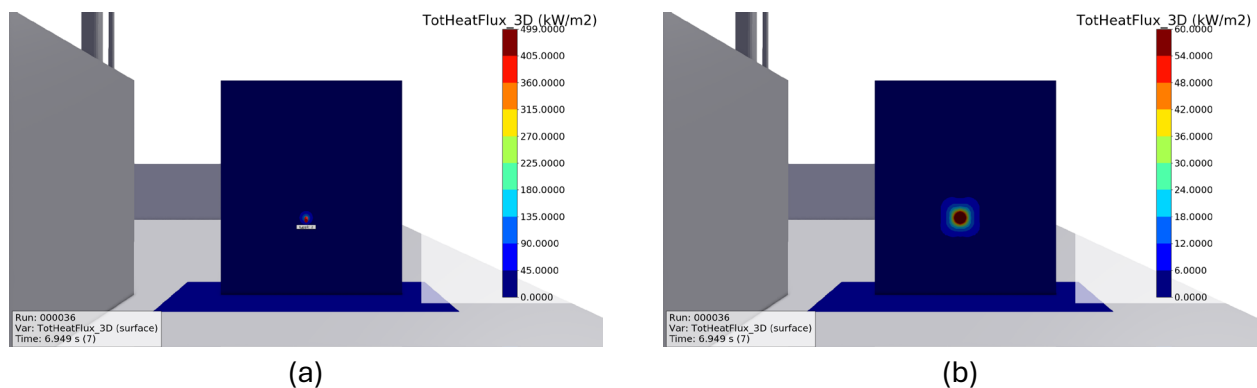


Figure 36. Total heat flux distribution on the cargo compressor room wall at $t \approx 7$ s for a 2 mm hydrogen leak located 0.5 m from the structure: (a) full-scale legend, (b) capped at 60 kW/m².

Figure 36. (a) displays the full range of heat flux values, including the maximum observed intensity. The distribution indicates widespread thermal exposure, with peak values approaching 500 kW/m², suggesting severe localised heating. Figure 36. (b) applies a capped legend with a maximum value of 60 kW/m², allowing clearer visualisation of the extent of high-risk zones. It is evident that a substantial portion of the wall surface exceeds this threshold, highlighting the potential for structural damage or failure under such conditions.

These results demonstrate that within a short duration—less than 7 seconds—the jet fire can generate intense thermal loads on adjacent structures. The findings underscore the importance of evaluating flame impingement scenarios and implementing appropriate thermal protection measures in LH₂ carrier designs.

Figure 37. presents the total heat flux distribution on the cargo compressor room wall for the case in which the hydrogen leak occurs at a distance of 2 metres from the structure. The simulation snapshot corresponds to approximately 6.08 seconds after release initiation. Compared to the previous case (Figure 36.), the thermal impact is significantly reduced, with the maximum heat flux values remaining below 3 kW/m².

The colour map indicates that only a small central region experiences elevated thermal exposure, while the majority of the wall surface remains within low heat flux levels. This result confirms that increased separation between the leak point and the structure leads to a substantial reduction in flame impingement and thermal load.

These findings reinforce the importance of spatial configuration in mitigating fire hazards. Even with identical leak characteristics, the proximity of the release source to critical structures plays a decisive role in determining the severity of thermal effects.

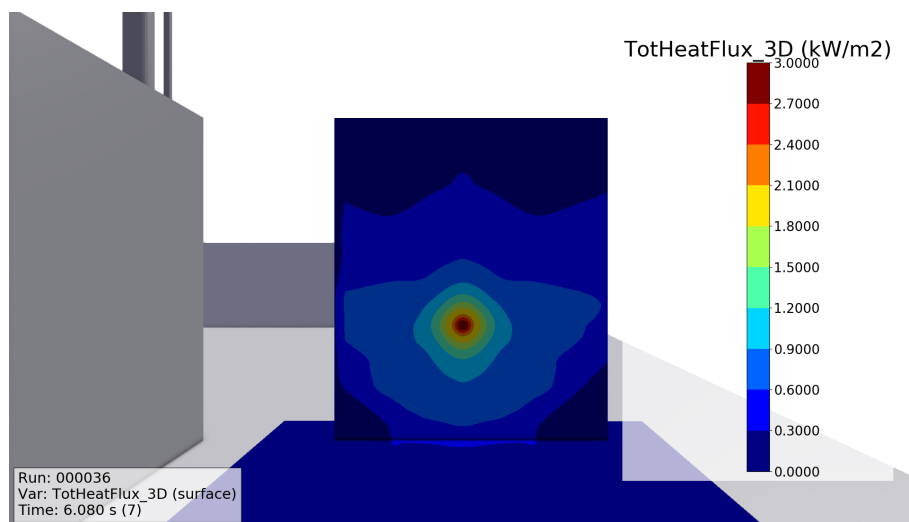


Figure 37. Total heat flux distribution on the cargo compressor room wall at $t \approx 6$ s for a 2 mm hydrogen leak located 2 m from the structure.

6.3.4 SCENARIO #4 – LH2 SPILL ANALYSIS

This study of Scenario #4 investigates the risk of liquid hydrogen (LH₂) spilling onto the seawater surface due to a collision or tank damage. The dispersion analysis of LH₂ is based on CFD simulations, considering the spill behaviour and the formation of a vapour gas cloud caused by the large temperature difference between the liquid hydrogen and seawater. This study aims to predict the behaviour of leaked LH₂ from a damaged tank spilling onto the sea. The main focuses are the size, shape, and location of the flammable gas cloud, as well as the shape, location, and size of the resulting pool.

The phenomenon of pool spreading and vaporisation of LH₂ has been analysed theoretically by comparison with other liquid fuels, such as liquefied natural gas (LNG). Cryogenic liquid spills behave differently depending on the ground type. On liquid surfaces, the pool area and vaporisation rate remain roughly constant, whereas on solid ground, the vaporisation rate decreases. Therefore, in the scenario of an LH₂ spill on seawater, the vaporisation rate is expected to stay nearly constant due to the natural convection caused by the large and steady temperature difference, along with stable film boiling. Additionally, LH₂ has a density of 70.8 kg/m³, which is significantly lower than LNG's density of 438 kg/m³. As a result, only about 7% of spilled LH₂ penetrates the water, compared to around 40% for LNG. The mixing of LH₂ with water is minimal. Moreover, the phenomenon of Rapid Phase Transition (RPT) is unlikely to occur with LH₂ spills, as

its Leidenfrost temperature (-245°C) is far lower than the temperature of water, which is close to its freezing point (0°C). The predicted peak pressure generated by LH₂ during RPT events is only 17% of that produced by LNG, and the estimated explosive energy per unit volume is just 5% of LNG. Hence, RPT resulting from an LH₂ spill on water is considered a minor safety concern.

An experiment conducted by Verfondern and Dienhart provides a brief understanding of the phenomenon of LH₂ spill on water surface. The findings from the experiment are:

- a. A closed pool was formed, clearly visible and hardly covered by the white cloud of condensed water.
- b. The equilibrium pool radius moved forward and backward within the range of 0.4 to 0.6 m.
- c. Single small floes of ice escaped the pool front and moved outwards.
- d. After cutting off the source, a massive ice layer was identified where the pool was boiling.

Based on the literature review, a general understanding can be formed of what may occur when LH₂ spills onto the sea surface. This study focuses on investigating the formation of the vaporised gas cloud and its behaviour under varying conditions, such as different damage hole sizes and wind speeds.

Results and Recommendations

Initial simulations were carried out for a pool spill with a leak radius of 0.2 m and a mass flow rate of 92.14 kg/s, over a spill duration of 80 seconds. To capture the complete process from gas cloud formation through to dispersion below the safety threshold concentration (4%), the total simulation time was extended to 160 seconds. Figure 38. presents a sequence of 3D visualisations showing the evolution of hydrogen gas cloud concentration contours over time following a LH₂ pool spill onto a water surface. The images display simulation snapshots at 40 s, 80 s, 110 s, and 140 s.

The location of the LH₂ pool significantly influences the spatial distribution of the resulting vapour cloud around the vessel. When the wind flows across the ship, and the pool is located in the downstream region, the flow over the ship geometry induces separation and recirculation zones. This results in a highly unsteady vapour cloud behaviour, characterised by pronounced fluctuations and an increased dispersion surrounding the vessel, as illustrated in Figure 38.

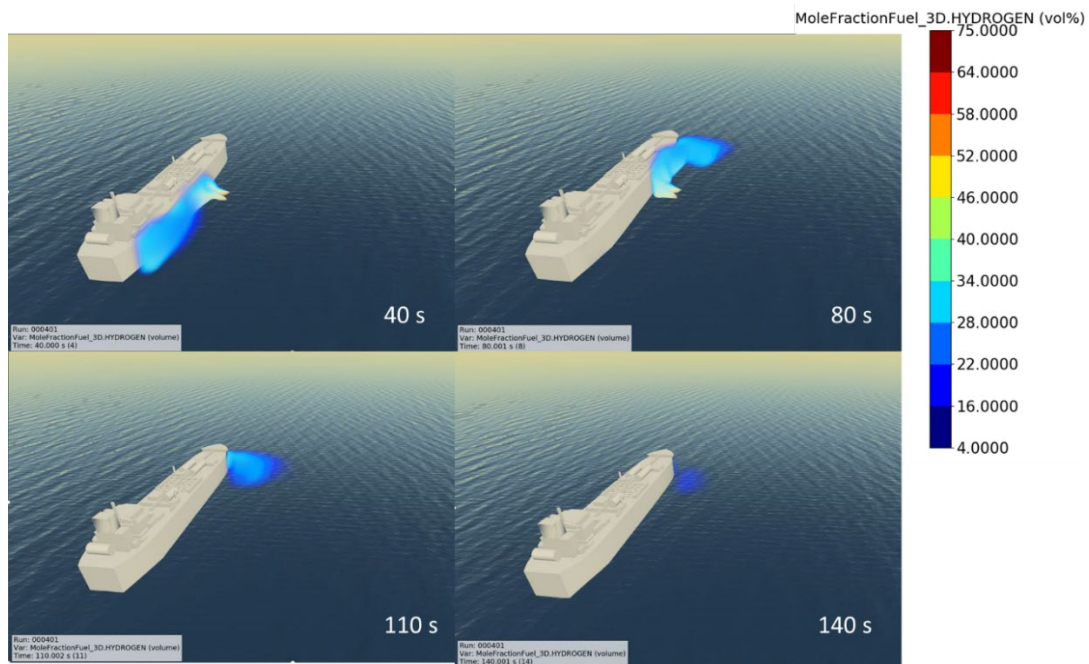


Figure 38. 3D plot for hydrogen gas cloud concentration contour development after LH2 pool spill.

Figure 39. presents a sequence of 2D horizontal cross-section contour plots close to the ground, showing the concentration of hydrogen following an LH2 pool spill at 40 s, 80 s, 110 s, and 140 s. The x-axis represents the downwind distance from the spill source. The y-axis represents lateral spread from the plume centreline. Colour contours show hydrogen concentration from 4% (blue) to 75% (dark red). Each plot illustrates the evolution of the hydrogen cloud as it develops and disperses over the sea surface. The cloud builds up during the active spill phase (0–80 s), after which it begins to spread and dilute downstream following the termination of the release. Ship-induced wake effects play a significant role in shaping the plume behaviour in the near-field region, particularly close to the source, where strong flow disturbances influence the initial dispersion pattern.

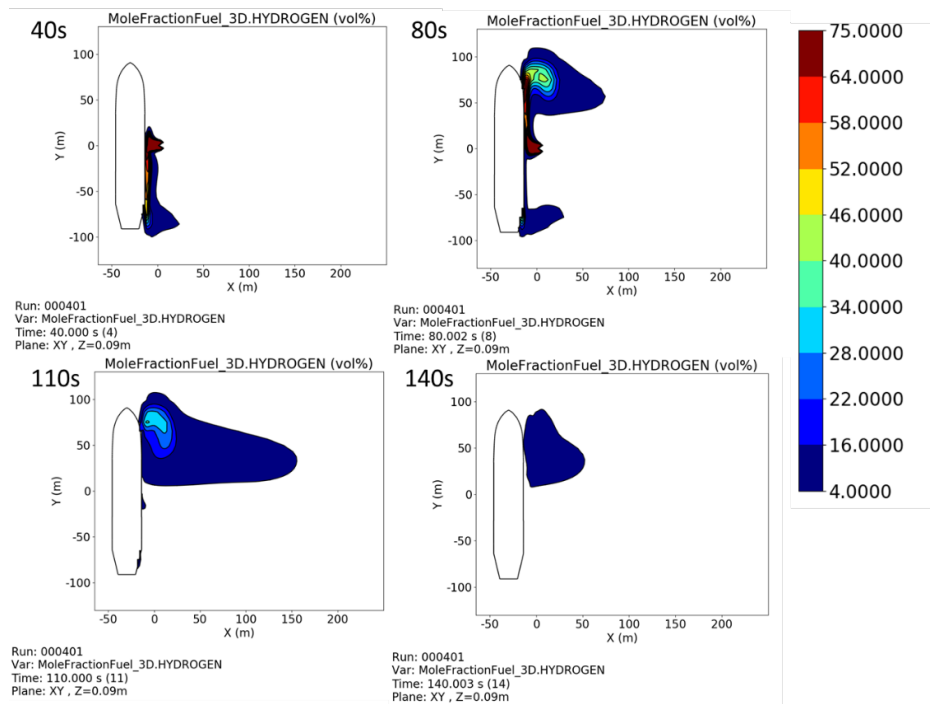


Figure 39. Horizontal cross-section contour plots after LH2 pool spill at times 40 s, 80 s, 110 s, 140 s.

Figure 40. shows a sequence of vertical cross-sectional contour plots illustrating the evolution of hydrogen gas concentration in the X-Z plane. These plots provide insight into the vertical height and downwind dispersion of the gas cloud. The results clearly show a buoyant hydrogen plume interacting with both the ambient wind field and the ship geometry. The gas initially rises rapidly from the spill location, forming a curved, elevated plume due to buoyant effects. It then transitions into a diluting, downstream-advected cloud with minimal ground-level concentration.

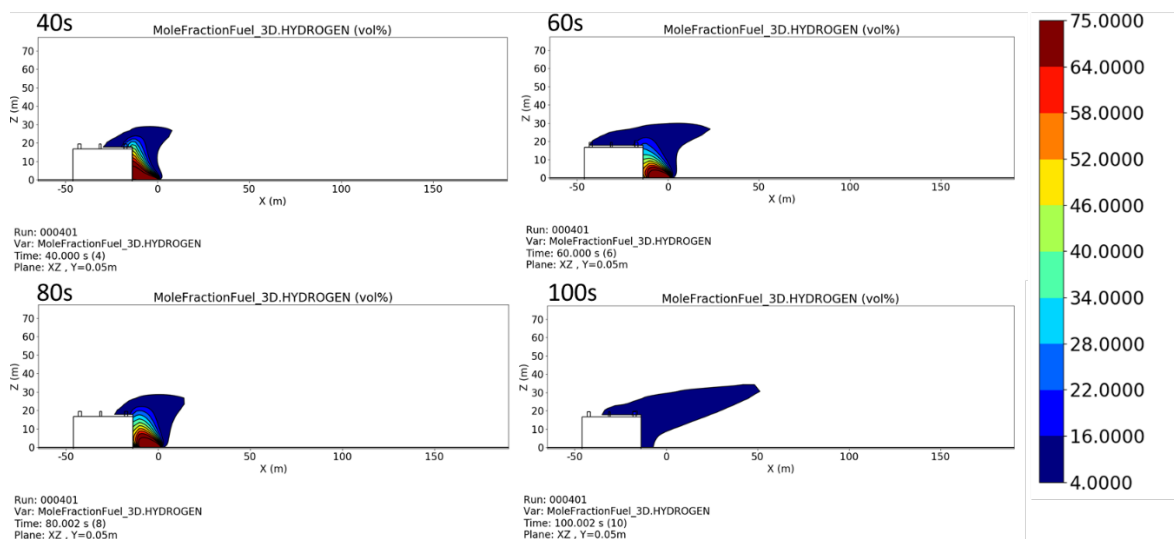


Figure 40. Vertical cross-section contour plots after LH2 pool spill at times 40 s, 80 s, 110 s, 140 s.

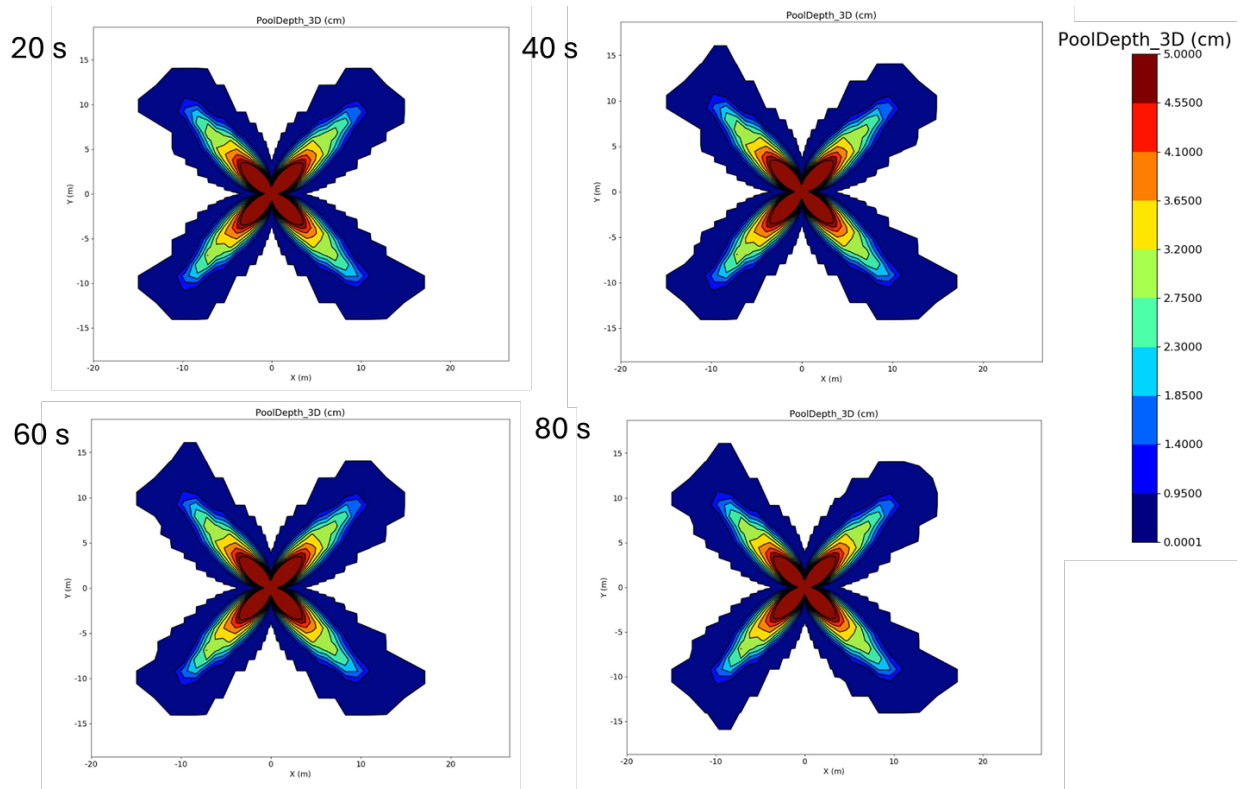


Figure 41. Top-down view of liquid hydrogen (LH_2) pool depth.

The behaviour of pool phase can also be obtained from this simulation study. Figure 41. shows a top-down view of LH_2 pool depth over time, following a spill on sea surface. The contours display the pool thickness in centimetres (cm) at four-time steps: 20 s, 40 s, 60 s, and 80 s. The LH_2 pool initially spreads rapidly within the first 10 s, maintaining an approximately symmetric radial expansion pattern. The observed four-lobed structure may be attributed to the numerical grid effects, boundary condition influences, or the specific characteristics of the release geometry. Figure 42. presents a side view (X-Z plane) of LH_2 pool depth profile over time. The plots show how the vertical cross-section of the pool evolves. The LH_2 pool stabilises quickly after the initial spill, with only slow changes between 20–80 s. Pool depth and shape suggest quasi-steady state conditions during this period. These results for the pool phase are consistent with the theoretical conclusions and experimental findings from the literature review.

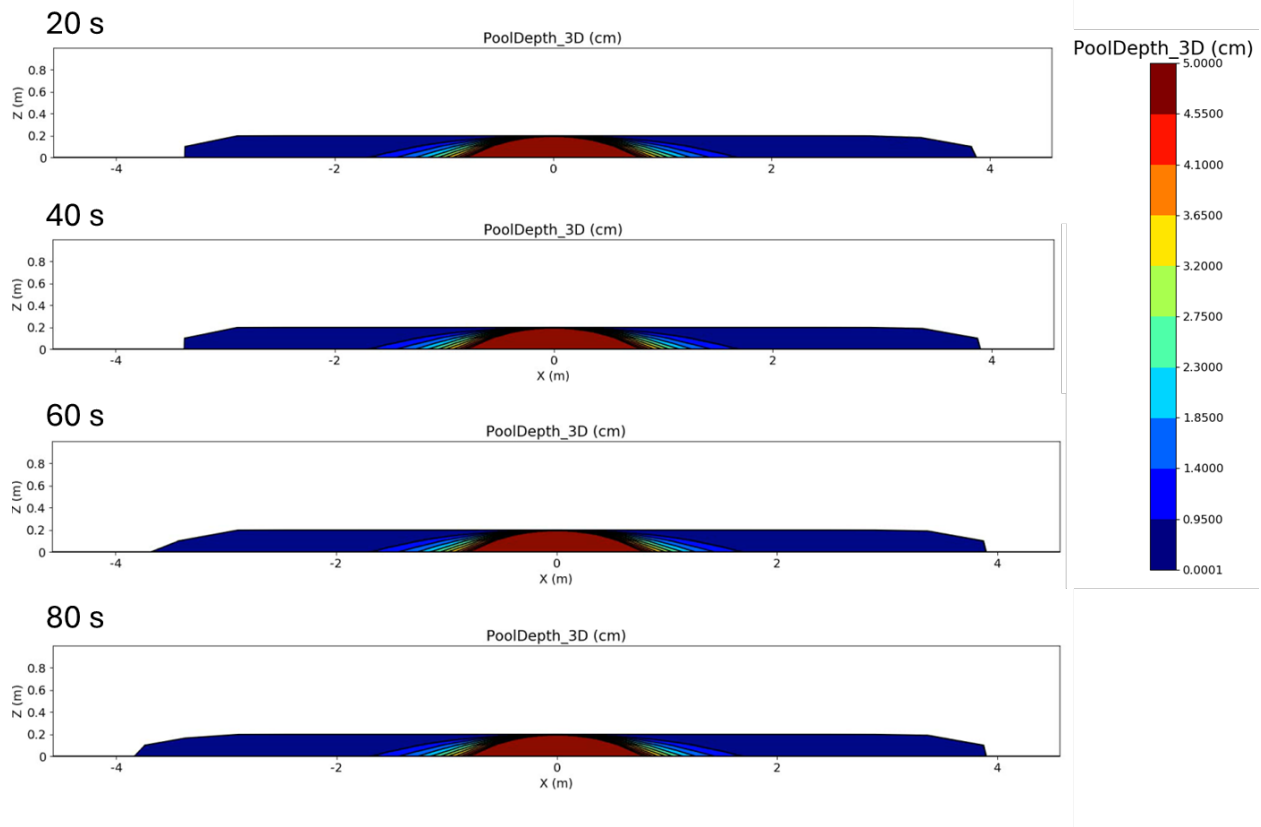


Figure 42. Side view (X-Z plane) of the LH₂ pool depth.

This simulation study helps clarify the phenomenon of LH₂ pool spill on the sea surface, which shows a quite different conditions from other liquid fuels like LNG and LN₂. Besides, these results help define hazard zones, safety standoff distances, and critical timescales for emergency response.

The effect of leak radius and wind conditions are also studied in this scenario. Figure 43. shows how hydrogen concentration changes over time at a single monitoring point for wind speeds of 1, 5, 10, and 15 m/s. At low wind speeds, the gravitational spreading and weak mixing cause the accumulation of a hydrogen gas cloud. At higher wind speeds, turbulent entrainment increases, resulting in faster dilution and transport away. Figure 43. presents contour plots of hydrogen concentration in the X-Z plane for different wind speeds at roughly the same time. With increasing wind speed, vertical mixing accelerates, reducing near-ground accumulation. Under low wind conditions, buoyancy governs the dispersion behaviour of the hydrogen cloud, promoting vertical rise. In contrast, at higher wind speeds, momentum-driven advection enhances horizontal dispersion.

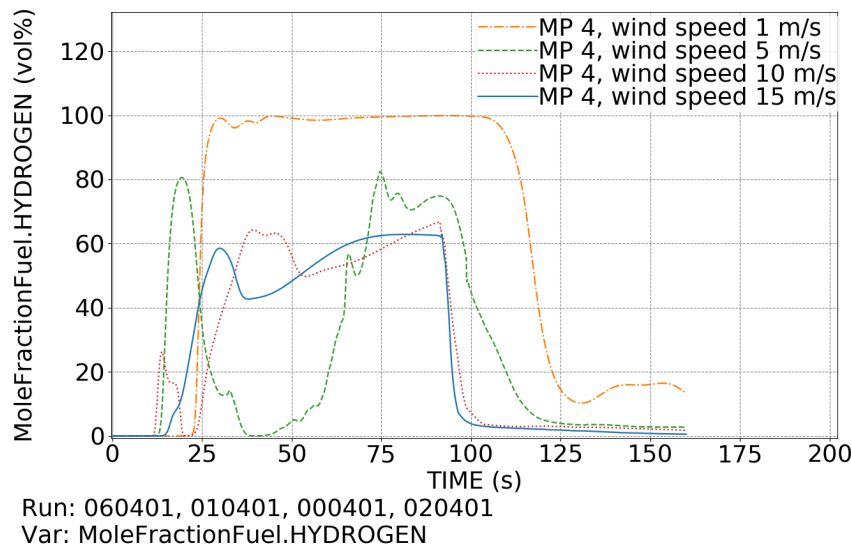


Figure 43. Temporal evolution of hydrogen mole fraction at MP4 under varying wind speeds

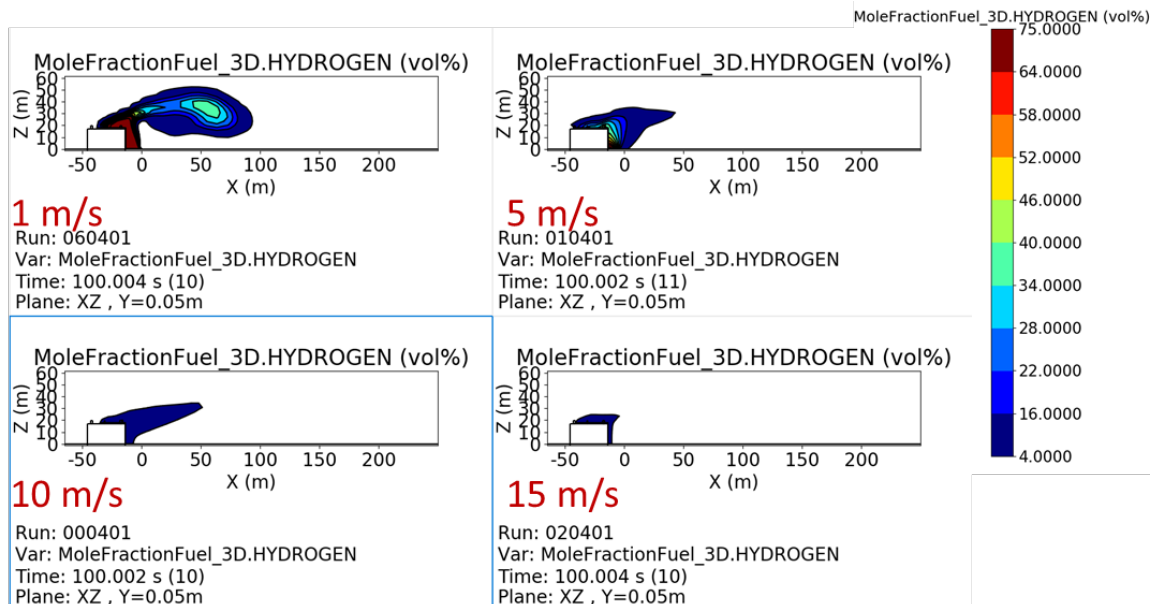


Figure 44. Distribution of hydrogen vapour cloud in the X-Z plane at 100 s for different wind speeds

Figure 43. shows how different pool radii ($r = 0.2, 0.4, 0.6, 0.8$ m), representing increasing mass flow rates, influence hydrogen concentration over time at MP5. A larger mass flow rate leads to stronger plume momentum, slower dilution relative to the supply, which results in higher concentration and longer persistence. Figure 43. presents contour plots of hydrogen concentration in the X-Z plane for different pool radii at roughly the same time. The 2D results provide a more intuitive demonstration that an increase in pool radius corresponds to a higher LH2 release rate, which leads to a larger hydrogen cloud with greater spatial extent and longer persistence in the environment.

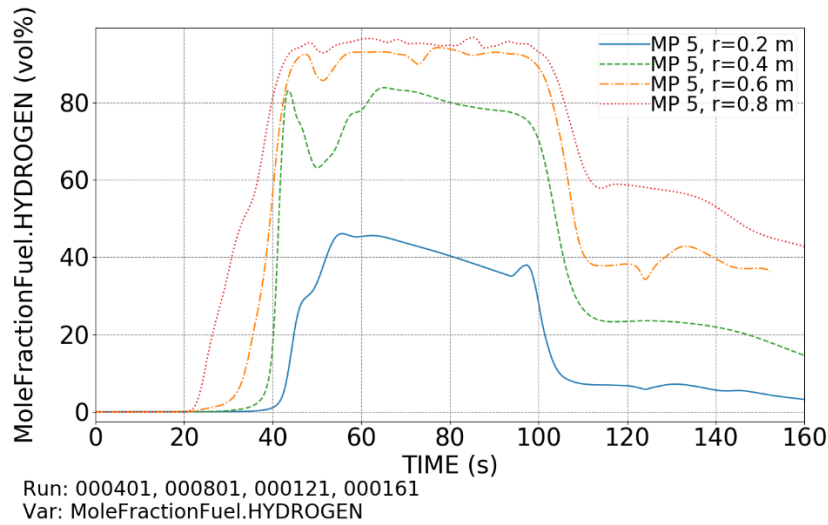


Figure 45. Temporal evolution of hydrogen mole fraction at MP5 under varying pool radius (mass flow rate)

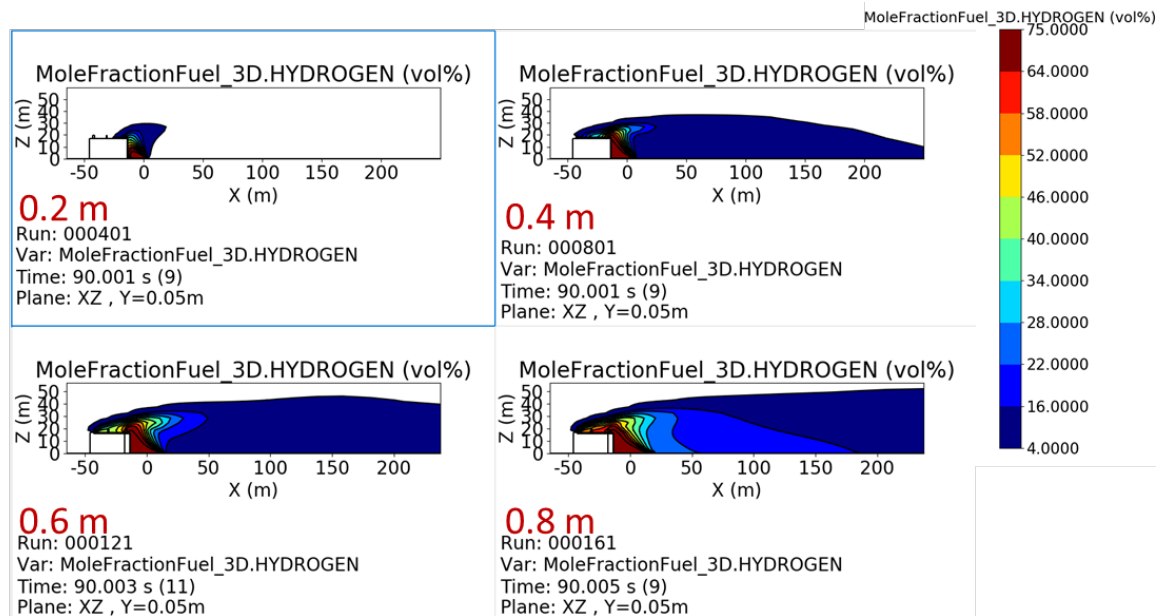


Figure 46. Distribution of hydrogen vapour cloud in the X-Z plane at 90 s for different pool radius (mass flow rate)

6.3.5 SCENARIO #5 – DISPERSION ANALYSIS AT VENT MAST No.3 & 4

This study addresses a scenario involving the simultaneous release of hydrogen gas from No.3 & No.4 vent masts on an LH₂ carrier. The primary objective is to evaluate whether the combined release could lead to the formation of a flammable or asphyxiant atmosphere in the vicinity of the accommodation area.

A key concern is that elevated hydrogen concentrations near crew living quarters may compromise designated escape routes or hinder safe evacuation during an emergency. Using CFD simulation, the dispersion behaviour of hydrogen is analysed under this dual-release condition to:

- Identify hazardous zones around the accommodation block.
- Determine the horizontal and vertical extent of the hydrogen cloud.
- Support the safe placement of vent masts to minimise risk to personnel.

The findings will contribute directly to design validation and inform potential mitigation strategies during the vessel's development phase.

Results and Recommendations

Figure 47. and Table 31 illustrate the hydrogen dispersion characteristics from vent masts No.3 and No.4 on a LH₂ carrier under two environmental conditions, both with a constant leak rate of 2.72 kg/s but differing wind speeds of 1 m/s and 6 m/s. The primary aim of this analysis is to assess whether the released hydrogen cloud poses any risk to the accommodation block, particularly in terms of blocking escape routes or creating flammable atmosphere near crew-occupied areas.

These simulations were conducted to examine the extent of the hydrogen plume using three spatial indicators: A, representing the horizontal dispersion distance; B, the vertical distance between the cloud and the accommodation structure; and C, the vertical distance between the cloud and the funnel.

As the wind speed increases from 1 m/s (Case 1) to 6 m/s (Case 2), the hydrogen cloud shows a significant reduction in dispersion range across all parameters. The horizontal dispersion length (A) decreases from 371 meters to 146 meters, while the vertical distance to the accommodation block (B) is reduced from 13.5 meters to 9 meters. Similarly, the vertical proximity to the funnel (C) decreases from 8 meters to 5 meters. This trend indicates that higher wind speeds enhance advection and promote quicker lateral dispersion, while also suppressing the upward buoyant lift of the hydrogen cloud.

In evaluating overall safety, parameter B is an important consideration, as it indicates the closest vertical distance between the hydrogen plume and the accommodation block. This distance influences the potential exposure of crew members and the accessibility of evacuation routes. Although B decreases slightly under stronger wind conditions, it remains at a safe margin in both cases. This demonstrates that the current vent arrangement prevents hazardous proximity to the accommodation area, even under low wind conditions.

Parameter C, which measures the vertical distance between the hydrogen cloud and the funnel, is also of high relevance in safety assessments. The funnel is a potential ignition source due to its high-temperature exhaust gases. In low wind conditions, the hydrogen cloud rises higher due to buoyant forces and reaches up to 8 meters from the funnel. In higher wind conditions, vertical lift is constrained and the distance is reduced to 5 meters.

In conclusion, the results confirm that the current exhaust layout provides a sufficient safety buffer between the hydrogen plume and both the accommodation block and the funnel structure under the studied conditions. Nonetheless, these findings reinforce the importance of incorporating wind direction variability, exhaust elevation, and potential ignition sources into future design optimizations. A clear understanding of environmental dispersion mechanisms is essential to ensure safe hydrogen handling and protect onboard personnel.

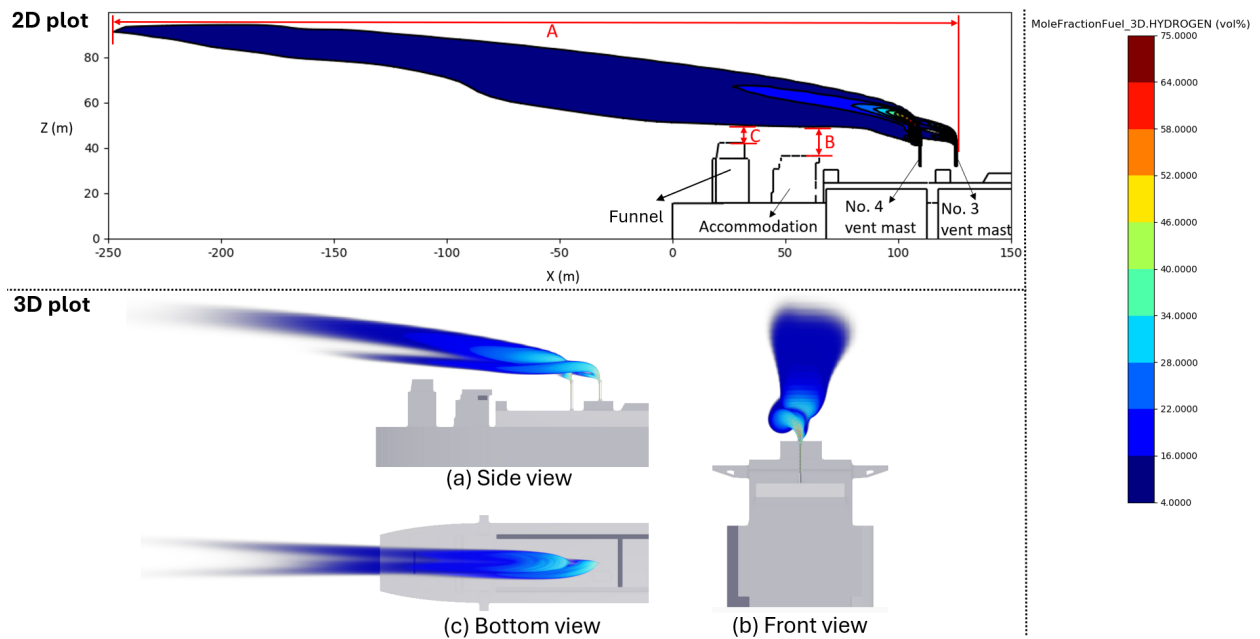


Figure 47. 2D and 3D Dispersion Profiles of Hydrogen Gas Released from No.3 and No.4 Vent Masts: (A) Horizontal dispersion length, (B) Vertical distance between the cloud and the accommodation structure, and (C) Vertical distance between the cloud and the funnel.

Table 31. Summary of Hydrogen Dispersion Distances under Different Leak and Wind Conditions.

Case no.	Leak rate [kg/s]	Wind speed [m/s]	A [m]	B [m]	C [m]
Case 1	2.72	1	371	13.5	8
Case 2	2.72	6	146	9	5

6.3.6 SCENARIO #6 – DISPERSION ANALYSIS AT VENT MAST No.4

The analysis focuses on whether hydrogen gas released from either No. 3 or No. 4 vent mast can propagate toward and enter the ventilation system inlets that serve the accommodation, machinery, and service spaces. The potential ingress of hydrogen into these systems poses a severe risk, including the formation of flammable mixtures in confined spaces and the possibility of internal ignition.

This scenario highlights the importance of:

- Verifying the placement of ventilation inlets during detailed risk assessment phases.
- Ensuring that released hydrogen does not lead to hazardous conditions inside the vessel.
- Supporting future mitigation strategies or layout modifications to ensure internal safety.

Through these two scenarios, the CFD-based hydrogen dispersion analysis contributes directly to the risk-informed design of the LH₂ carrier, ensuring compliance with safety standards and enhancing crew protection in line with the vessel's operational profile.

Results and Recommendations

FIGURE 48. and *Table 32* summarise the hydrogen dispersion characteristics resulting from a simultaneous release at the No. 4 vent mast on an LH₂ carrier, under two distinct wind conditions. The primary objective is to assess whether the hydrogen cloud poses a risk to the accommodation block, particularly regarding potential obstruction of escape routes or the formation of flammable or asphyxiant atmospheres near crew-occupied zones.

These simulations were conducted at a fixed leak rate of 2.72 kg/s, with wind speeds of 1 m/s (Case 1) and 6 m/s (Case 2). The dispersion results were evaluated using three key spatial indicators: A (horizontal dispersion distance), B (distance to the accommodation block), and C (distance to the funnel).

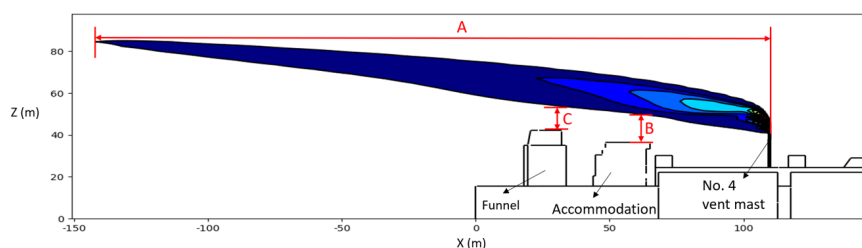
Under low wind conditions (Case 1), the hydrogen cloud spreads horizontally up to 252 meters, with 12 meters of clearance from both the accommodation block and the funnel. When wind speed increases to 6 m/s (Case 2), the extent of the cloud decreases significantly—A reduces to 76 meters, while both B and C shrink to 8 meters. This pattern demonstrates that stronger wind speeds limit both the horizontal reach and vertical rise of the hydrogen plume due to enhanced advection and reduced buoyancy-driven uplift.

Among the spatial indicators, parameter B is a key safety consideration, as it represents the minimum distance between the cloud and the accommodation area. While both cases remain within acceptable margins, the reduced clearance in Case 2 underlines the need for continuous monitoring and risk-informed layout design.

Similarly, the shorter C distance under high wind conditions suggests the plume's proximity to the funnel increases, underscoring the need to assess potential ignition risks during design validation.

In conclusion, the current vent configuration maintains a conservative buffer zone between the hydrogen cloud and sensitive structures, effectively minimising hazard even under varying environmental conditions. These results provide critical design input and highlight the need to consider wind speed, direction, and vent height in optimising hydrogen vent safety on LH₂ carriers.

2D plot



3D plot

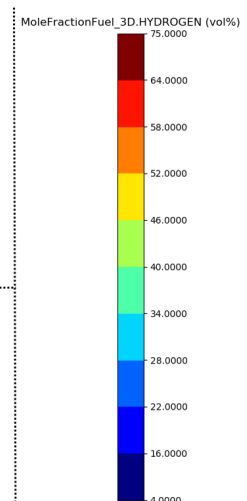
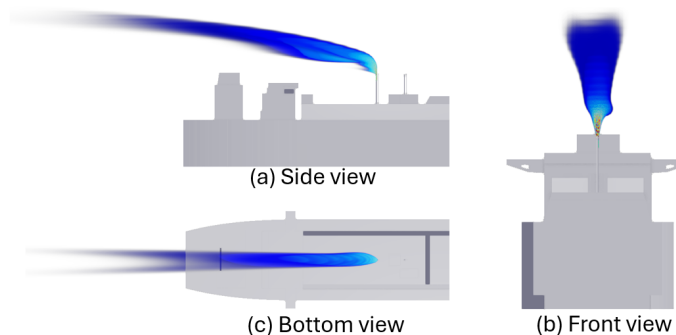


Figure 48. 2D and 3D Dispersion Profiles of Hydrogen Gas Released from No.4 Vent Masts: (A) Horizontal dispersion length, (B) Distance between the cloud and the accommodation structure, and (C) Distance between the cloud and the funnel.

Table 32. Summary of Hydrogen Dispersion Distances under Different Leak and Wind Conditions.

Case no.	Leak rate [kg/s]	Wind speed [m/s]	A [m]	B [m]	C [m]
Case 1	2.72	1	252	12	12
Case 2	2.72	6	76	8	8

6.3.7 SCENARIO #7 – DISPERSION ANALYSIS FROM CARGO COMPRESSOR ROOM

This study addresses a scenario involving the unintended release of hydrogen gas on the weather deck, potentially originating from the cargo handling system. Specifically, concern is raised about leakage within the cargo compressor room, which may result in hydrogen being emitted through the ventilation fan. The primary objective is to evaluate whether such a release could pose a flammability hazard or result in unsafe gas concentrations in operational areas.

A key concern is that hydrogen dispersion in this region may create ignition risks on exposed upper decks or impair localised ventilation efficiency. Using CFD simulation, the release behaviour is analysed to:

- Identify the hydrogen concentration profile at the ventilation fan outlet.
- Quantify the gas cloud's spread from the cargo compressor room to nearby zones.
- Support risk-informed decision-making regarding ventilation design and leak detection measures.

The findings will serve as a basis for scenario inclusion in the QRA and help validate the integrity of hydrogen management systems on the vessel.

Results and Recommendations

FIGURE 48. As depicted in Figure 49. , Case 1 models hydrogen dispersion under low-wind conditions with a wind speed of 1 m/s. Under this scenario, the released hydrogen plume remains relatively concentrated and rises upward due to buoyancy, with minimal horizontal deflection. The maximum horizontal dispersion from the vent outlet was approximately 6.4 metres. The plume geometry indicates localized accumulation near the weather deck exhaust area, posing potential risks to nearby elevated structures or confined spaces. The dominant vertical trajectory reflects the weak wind influence and underscores the importance of implementing vertical gas detection strategies under calm conditions.

Case 2 assesses hydrogen dispersion under high-wind conditions with a wind speed of 6 m/s, assuming the same hydrogen release rate. Unlike the low-wind case, the plume exhibits a markedly different behaviour, becoming horizontally elongated due to strong wind advection. Hydrogen disperses approximately 16 meters downwind from the vent outlet, with reduced vertical rise. This indicates that stronger winds enhance horizontal transport, enlarging the affected area and shifting the flammable zone farther away

from the release point. These results highlight the critical need to account for wind conditions in safety assessments and gas detection system designs, particularly in exposed weather deck environments.

Both cases clearly demonstrate how ambient wind conditions influence hydrogen behaviour during a release event. Low wind conditions favour vertical accumulation near the source, while higher wind speeds lead to wider horizontal dispersion and broader hazard zones. These effects must be considered in the design of ventilation systems and risk mitigation strategies. As shown in the simulations, the size and shape of the hydrogen plume vary significantly with wind speed. Specifically, in Case 2, where the plume extends up to 16 metres, it is essential to ensure that within a 16 metre radius around the ventilation fan of the cargo compressor room, explosion-proof equipment is installed and no potential ignition sources are present.

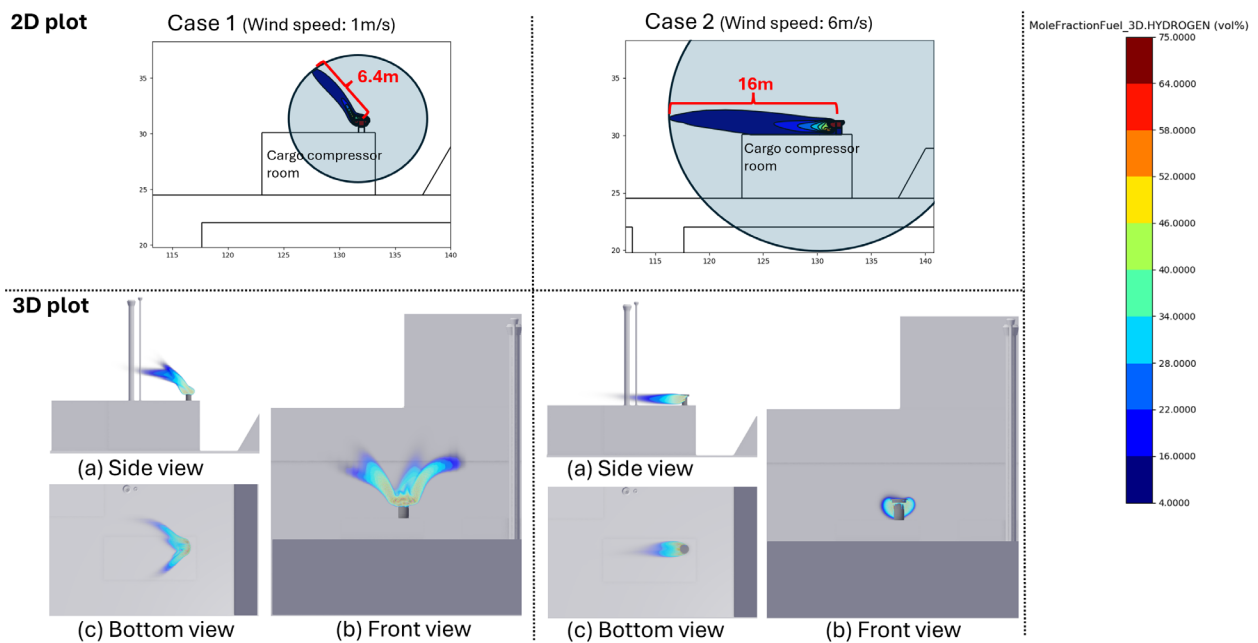


Figure 49. 2D and 3D Dispersion Profiles of Hydrogen Gas Released from ventilation fan.

6.3.8 SCENARIO #8 – SAFETY ZONES FOR CARGO OPERATION

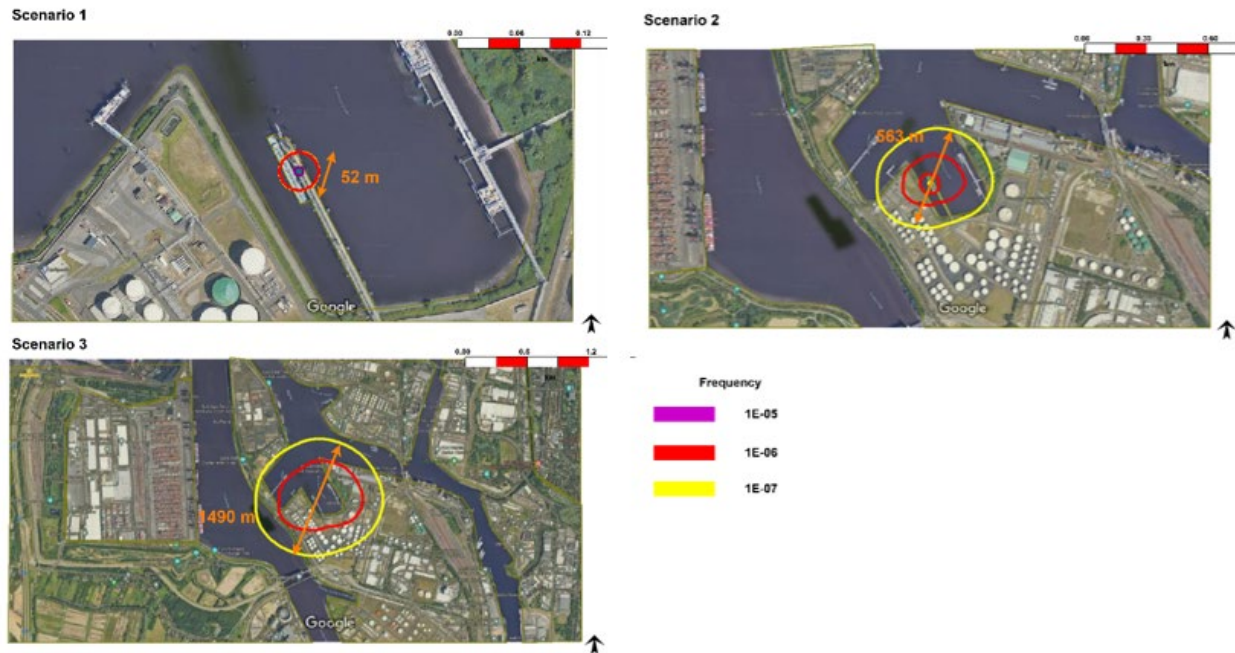


Figure 50. Overview of scenario #8.

The objective of this scenario is to perform a liquified hydrogen dispersion analysis, including fire and explosion events, during the cargo operation and the resulting impact on the port area. The case studies identified from the qualitative risk assessment (HAZID), are as follows:

- i.) 'Evaluate the impact of liquid hydrogen cargo leaked and dispersed to the port area and define the cargo operation safety zone'
- ii.) 'Evaluate the fatalities within the defined cargo operation safety zone and provide mitigations according to the results.'

In other words, this study aims to define the boundaries that may lead to fatalities caused by leaked liquid hydrogen during cargo operations.

Results and Recommendations

FIGURE 48. DNV's Safeti software was utilised to model and calculate the impact range, producing detailed results overlaid on a geographical map that integrates both frequency and consequence analyses. The consequence analysis defines accident boundaries on the map, indicating areas where fatalities are likely to occur due to fires or explosions resulting from hydrogen leaks. Each accident scenario is represented by a distinct boundary line, with different colours indicating varying cases. The accident frequencies are categorised by occurrence rates during specific time periods. In this study, the analysis focuses on three frequency thresholds—1E-05, 1E-06, and 1E-07—as outlined in **Error! Reference source not found..**

LOADING OPERATION

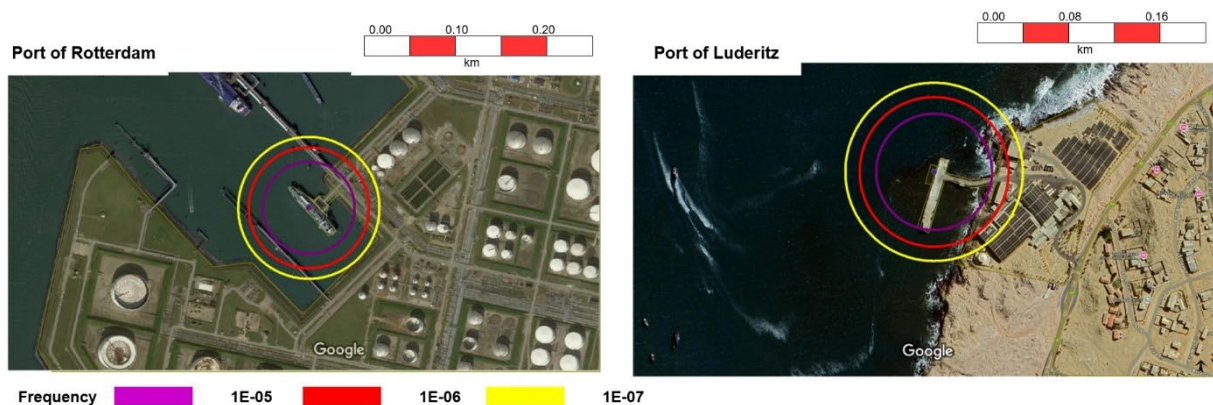


Figure 51. Overview of scenario

Error! Reference source not found. summarises the zonal distribution derived from the results presented in **Figure 51**. Overall, the two sets of results show similar patterns both in the Port of Rotterdam and the Port of Luderitz. A large-scale hydrogen leak poses a significant risk of fire and explosion when released into the atmosphere. The inner zone extends to approximately 170 metres from the source, the middle zone reaches up to 220 metres, and the outer zone extends beyond 260 metres at both potential locations.

Table 33. Detailed range for simulation results (loading operation)

Location	Zone	Range (m)	Location	Zone	Range (m)
Port of Rotterdam	Inner zone	171.6	Port of Luderitz	Inner zone	170
	Middle zone	224.82		Middle zone	218.76
	Outer zone	263.77		Outer zone	262.73

Additionally, an FN curve for each port is presented in **Error! Reference source not found.**. An FN diagram, also known as a Farmer diagram, is a graphical tool used to represent societal risk associated with a specific technology, activity, or project. The vertical axis (F) indicates the frequency of events, while the horizontal axis (N) shows the number of fatalities. Each point (F, N) on the curve represents the cumulative frequency of incidents resulting in N or more fatalities.

In the diagram, the green line represents the calculated number of fatalities, while the yellow line indicates the minimum acceptable risk threshold. The red line marks the maximum tolerable risk level, beyond which additional safety measures or barriers are required. The FN curve provides a more practical evaluation of risk acceptability than safety zone boundaries alone.

For both the Port of Rotterdam and the Port of Luderitz, the FN curves for loading operations exceed the maximum criterion line, indicating an unacceptable level of risk. Although Rotterdam has a population density roughly three times higher than Luderitz, the proximity of the cargo operation site to residential areas in Luderitz results in a comparable severity level.

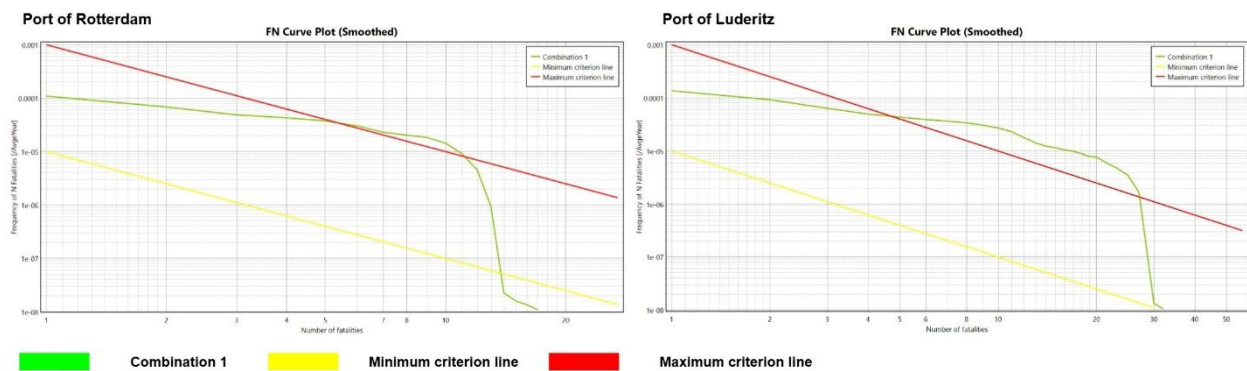


Figure 52. FN Curve result for loading operation.

UNLOADING OPERATION

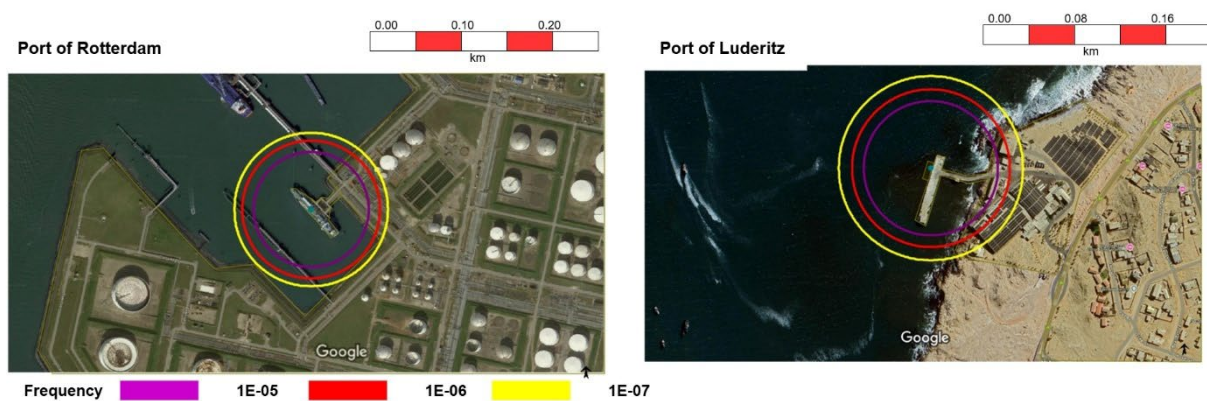


Figure 53. Simulation results for unloading operation.

Table 34 provides a summary of the zonal distribution based on the results shown in Figure 53. . In both the Port of Rotterdam and the Port of Luderitz, the results for unloading operations are notably more extensive than those for loading operations. This is primarily due to the unloading operation time being approximately five times longer, which leads to more severe consequences. The inner zone extends up to 210 metres—an increase of 40 metres compared to the loading scenario. For the middle zone, the expansion is around 30 metres, reaching up to 253.05 metres in the case of the Port of Rotterdam. In contrast, the outer zone shows a relatively smaller increase of 20 metres, exceeding 280 metres in total.

Table 34. Detailed range for simulation results (unloading operation)

Location	Zone	Range (m)	Location	Zone	Range (m)
Port of Rotterdam	Inner zone	210.13	Port of Luderitz	Inner zone	208.75
	Middle zone	253.05		Middle zone	243.21
	Outer zone	284.48		Outer zone	287.31

At both the Port of Rotterdam and the Port of Luderitz, as shown in Figure 54, the FN curves for loading operations surpass the maximum criterion line, signifying a critical and unacceptable level of societal risk. Moreover, unloading operations clearly present broader accident impact zones than loading operations. These findings highlight the necessity for enhanced safety measures, particularly during extended unloading operations, to ensure risk remains within acceptable thresholds.

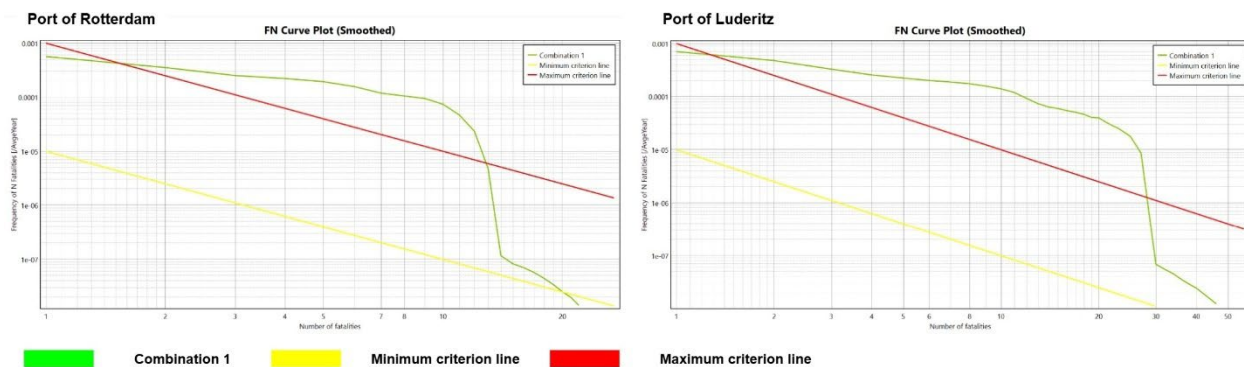


Figure 54. FN Curve result for unloading operation

7 CONCLUSIONS

This deliverable presented the comprehensive concept, basic, and detailed engineering design of the Hydrogen Distribution and Management System (HDMSS), together with the associated operational, safety, and risk assessment activities required to support the safe and efficient handling of liquid hydrogen (LH2) in maritime applications. The work contributes directly to the advancement of hydrogen-enabled maritime transport solutions and supports the broader objectives of decarbonisation within the European shipping sector.

The assessment of existing port bunkering infrastructures and operational practices, including the examined case studies, enabled the identification of key operational requirements and infrastructure considerations for LH2 transfer and handling. These findings provided the foundation for the development of the HDMSS architecture and operational philosophy.

The deliverable further established the engineering basis for the system through the evaluation of applicable regulations, classification society requirements, standards, and safety frameworks relevant to LH2 maritime operations. Particular emphasis was placed on the unique physical properties and hazards associated with liquid hydrogen, ensuring that safety considerations were integrated from the earliest stages of the design process.

A complete operational framework for cargo handling was developed, covering all major operational modes including inerting, cooling-down, loading, unloading, stripping, gas freeing, ballast and laden voyage conditions, and emergency operations. The proposed process and instrumentation architecture, together with the associated cargo handling, monitoring, control, and emergency shutdown systems, demonstrate the technical feasibility of safe LH2 transfer and storage operations onboard.

The detailed engineering activities addressed critical aspects of piping design, material selection, insulation systems, thermal protection, vacuum arrangements, and stress analysis, while simulation activities supported the optimisation of system performance and operational efficiency. The resulting design approach reflects current best practices and aligns with the emerging requirements for hydrogen-based maritime systems.

Extensive safety and risk assessment activities, including HAZOP, FMEA, and quantitative risk evaluations, enabled the systematic identification and mitigation of potential hazards associated with LH2 operations. The analysed fire, explosion, dispersion, and spill scenarios confirmed the importance of robust safety barriers, monitoring systems, and operational procedures. The outcomes of these analyses contributed directly to design refinements and the definition of safety zones and operational safeguards.

Overall, the work performed within this deliverable demonstrates the technical viability of the proposed HDMSS concept and provides a strong engineering and safety foundation for subsequent development, validation, and demonstration activities within the project. The results contribute to reducing technological barriers for hydrogen adoption in maritime transport and support the development of future regulatory and industrial frameworks for safe LH2 bunkering and distribution operations.

The knowledge generated through this work is expected to support future research, industrial deployment, and standardisation efforts, thereby contributing to the transition towards a more sustainable, resilient, and climate-neutral European maritime sector.

The engineering design process has been reviewed and approved by ABS Classification Society within the concept of T9.2. The final list of documents/drawings that have been submitted, and reviewed are included in the respective annex section.

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ANNEX I – LIST OF DRAWINGS SUBMITTED TO ABS FOR THE AIP REVIEW AND APPROVAL PROCESS

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Reference WO0359349, dated 12-Dec-2025



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Work Order – WO0359349
Engineering Design Process for the LH2CRAFT
HDMSS Auxiliary Systems
Approval in Principle for LH2CRAFT Project

Attention: Mr. Astrinos Papadakis, Hydrus Engineering (WCN: 402013)

The documents shown in the attached list are reviewed in accordance with the applicable requirements of the following:

- ABS Rules for Alternative Arrangements, Novel Concepts and New Technologies, 2024
- ABS Rules for Building and Classing Marine Vessel Rules, 2023
- ABS Requirements for Liquefied Hydrogen Carriers, 2023
- ABS Requirements for Hydrogen Fueled Vessels, 2023
- IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)
- IMO Resolution MSC.565(108) – Revised Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk
- IMO CCC 11/WP.9, Annex 1, Draft Amendments to Revised Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk

Please note our review is based on the following conditions:

1. Our review of the drawings in the attached list is for "Approval in Principle". The purpose of the review for "Approval in Principle" is to investigate the feasibility of the conceptual design and identify any major deficiencies that would prove problematic in a full ABS review of the design for classification. The proposed design concept is acceptable in principle.
2. Please be advised that our review is based on a general overview of the concept design rather than a detailed analysis and note that the final detailed design will need to be verified against the Rules, Guides and Statutory Guidelines or Regulations at the time of construction.
3. It should also be noted that our review at this time in no way precludes any further amendments and comments which may be deemed necessary during the review for final approval.
4. Please note that in this instance, ABS is not acting on behalf of any Flag State or Coastal State Authority since there is no specific agreement or delegation in place.

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5. It is noted that the submitted electrical drawings (i.e., one-line diagrams and alarm and monitoring connection diagrams) are preliminary (i.e., details of electric cables, protective devices are not included, certification of equipment, etc.) and accordingly, review of these drawings is not covered by this assessment. Vessel's specific details are to be submitted during the review of the final approval.
6. The vessel's specific details (e.g., fire safety plan, general arrangement plan, interconnection of the systems associated with LH₂ piping systems with the vessel's systems, etc.) are not covered by this assessment. Vessel's specific details are to be submitted during the review of the final approval.

Based on our review, a list of comments generated during the review has been compiled and is enclosed herewith as Appendix 2 for your information. This document suggests areas of further engineering that we would expect to be addressed during the next design stage and do not require a response in this stage.

For any clarifications, contact Mr. Konstantinos Tsoukas at +30-2109441136 or ktsoukas@eagle.org, or Mr. Evangelos Kourtis at +30 210 9441142 or EKourtis@eagle.org.

Very truly yours,

Pier Carazzai
Vice President of Engineering

Electronically Signed by: Anastasios Dionysatos

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Appendix 1: Drawing List

Drawing No.	Rev. No.	Title	Status
LH2CRAFT-GD-02	00	Hazardous Area Plan (*)	Reviewed
LH2CRAFT-GD-03	00	Preliminary Fire Plan (*)	Reviewed
LH2CRAFT-HDMSS-04	00	Piping and Instrumentation Diagrams	Reviewed
LH2CRAFT-HDMSS-13	00	Fire and Gas Detection System	Reviewed
LH2CRAFT-GD-01	-	General Arrangement (*)	Reviewed
LH2CRAFT-HDMSS-01	00	Process Flow Diagrams (PFD)	Reviewed
LH2CRAFT-HDMSS-02	00	System Schematics	Reviewed
LH2CRAFT-HDMSS-03	0.1	Preliminary Material Specification for the HDMSS	Reviewed
LH2CRAFT-HDMSS-05	02	Cargo Operation Modes	Filed by ABS for Reference Only
LH2CRAFT-HDMSS-12	00	Preliminary ESD and Safety Systems	Reviewed
LH2CRAFT-HO-01	1.0	Preliminary Operation Manual	Filed by ABS for Reference Only
LH2CRAFT-RA-01	1.0	LH2CRAFT Risk Assessment Plan	Filed by ABS for Reference Only
LH2CRAFT-HDMSS-11	00	Wiring Diagram of Alarm and Monitoring Connection Diagram	Filed by ABS for Reference Only
LH2CRAFT-HDMSS-10	00	Preliminary Electric One-Line Diagrams	Filed by ABS for Reference Only
-	-	Appendix – List of Drawings/ Documentation Index for the HDMSS	Filed by ABS for Reference Only

Electronic copies of the documents, appropriately stamped, are available in the ABS MyFreedom™ Client Portal.

(*): Our review of these drawings is limited only to the specific parts associated / affected by the installation of LH₂ systems.

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