H2 Safety in Human Operations – and Safety guideline

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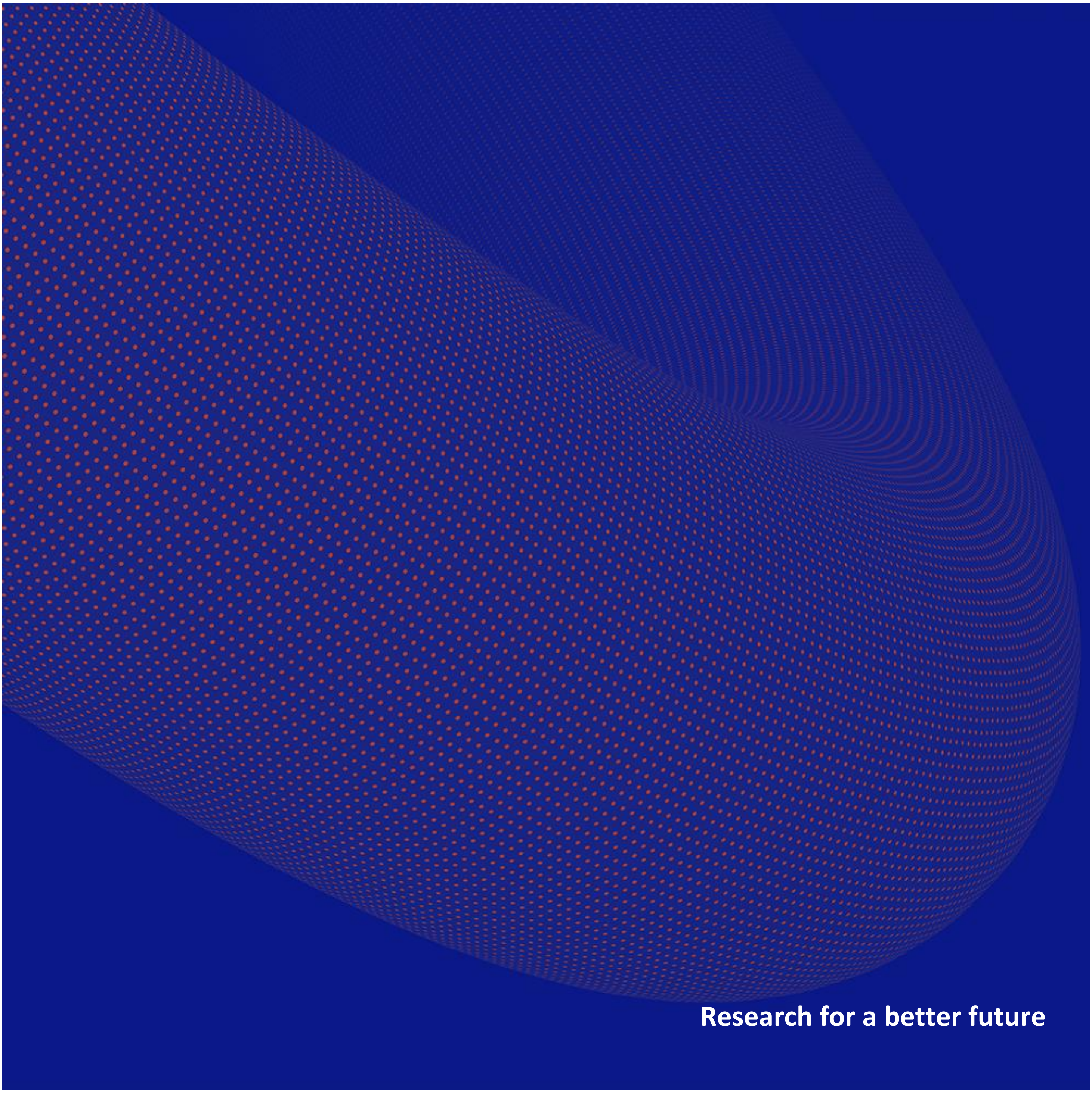

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Title:
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Summary:

This report is a part of the second work package in the research project “Hydrogen and Fuel Cells for Maritime Applications” (H2Maritime), a knowledge-building project for industry (KPN project) funded by the Research Council of Norway and 5 industry partners. A key objective of the H2Maritime-project is to aid the maritime sector in safe implementation of hydrogen as a zero-emission fuel for ships.

This report contributes to identifying the human factors aspects of safety in hydrogen refuelling and bunkering. For this purpose, a case study on a shore-based liquid hydrogen (LH2) bunkering facility for ships has been conducted using a scenario analysis. The scenario analysis method is a part of the crisis intervention and operability analysis (CRIOP) method and provides a human-centred approach to assess weak points and recommendations related to human factors. In this report the CRIOP method´s term “weak point” is renamed to “learning point”.

In the case study, the scenario analysis focused on human functions, responsibilities, roles, tasks, and teamwork during refuelling and bunkering operations in the light of potential hazards. Information that should be included in the control system´s Human System Interface (HSI) has also been identified. Several learning points related to safety in human operation of hydrogen bunkering has been found. The report includes a Safety guideline with recommendations on what to include or consider to ensure safe refuelling/bunkering of H2 and to support the human operators, i.e., the bunkering team, to succeed.

The target readers of this report are researchers, developers of H2 maritime bunkering systems and control systems, designers of control systems´ HSI, and other key stakeholders in the maritime industry (e.g., ship owners).

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Acknowledgement

The work presented in this paper is a part of the H2Maritime research project entitled “Hydrogen and Fuel Cells for Maritime Applications”, a knowledge-building project for industry (KPN project) funded by the Research Council of Norway and 5 industry partners: Equinor, ABB Marine, Havyard Design and Solutions, Umoe Advanced Composites and Lloyd's Register (RCN-project no. 294568). The authors would also like to acknowledge the useful data and information received from the owners of the liquid hydrogen bunkering facility used for the use case in the H2Maritime-project.

Keywords

Human factors, safety, liquid hydrogen, bunkering operations, maritime applications, CRIOP-method

Abbrevations

CCTV	Closed-Circuit Television (system for surveillance)
CRIOP	Crisis intervention and operability analysis
DSHA	Defined Situations of Hazards and Accidents
ESD	Emergency Shutdown System
ERT	Emergency Response Team
GH2	Gaseous hydrogen
H2	Hydrogen
HSI	Human System Interface
JRCC	Joint Rescue Coordination Centre
LEL	Lower Explosion Limit
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
OS	Operating system
UEL	Upper Explosion Limit

1 Introduction

Hydrogen fuel cells, where hydrogen is produced with zero emissions, is emerging as a promising option for several maritime applications and as an environmental-friendly alternative to traditional (fossil) fuels. Although hydrogen has been used in the industry for a century, the concept is rather new for maritime applications. There are still knowledge gaps that needs to be addressed when it comes to hydrogen systems and the use of hydrogen as a fuel for maritime vessels. These gaps include safety and safety barriers. According to Det Norske Veritas (DNV, 2021), codes and standards for hydrogen maritime applications are incomplete. Operational experience, training material, safe hydrogen bunkering, safety distances, and hazardous zones are among the knowledge gaps (DNV, 2021).

A literature search has revealed the human factors aspects of hydrogen safety has not yet been addressed properly (Lunde-Hanssen & Ulleberg, 2022). In terms of hydrogen systems, the focus is on safety in the context of the technical and physical aspects and barriers, such as performance of hydrogen technology, hydrogen behaviour, material behaviour and safety zones.

To improve safety of operations it is important to address and assess the hazards related to human factors. This report targets the human factor issues for assessing the safety barriers or measures needed to reduce the risks related to human operation during bunkering of hydrogen by using a human-centred approach. For this purpose, a case study on bunkering of liquid hydrogen (LH_2), using the crisis intervention and operability analysis (CRIOP) method, will be presented. This method involves a human-centred approach to assess weak points and recommendations related to human factors.

The purpose of this Chapter 1 is to first introduce the H2Maritime-project of which this report is a part of. Then, the scope of the report is outlined in Chapter 1.2, followed by the approach and research questions in Chapter 1.3. Lastly, there are three sub-chapters setting the context of this report, by explaining the human-centred approach and human factors perspective in Chapter 1.4, hydrogen properties and safety issues related to these properties in Chapter 1.5, and a description of the use case in Chapter 1.6.

1.1 Introduction to the H2Maritime project

The H2Maritime-project is a knowledge-building project for industry (KPN project) funded by the Research Council of Norway and 5 industry partners. The H2Maritime-project is a research collaboration coordinated by the Institute of Energy Technology (IFE). The project partners included the Norwegian University of Science and Technology (NTNU), the University of Southeast Norway (USN), the Norwegian Maritime Directorate, and the five industry partners: Equinor, ABB Marine, Havyard Design and Solutions, Umoe Advanced Composites and Lloyd's Register.

Hydrogen produced with zero emissions and fuel cells is emerging as a promising option for several maritime applications and an environmental-friendly alternative to traditional (fossil) fuel. The H2Maritime-project is expected to aid the maritime sector in the implementation of hydrogen as a safe zero-emission fuel for ships.

The overall goal of the H2Maritime-project is to research and develop new expertise in the use of hydrogen and fuel cells in the maritime sector. The main goal of the project is to establish design criteria and operating philosophies for bunkering and storage of hydrogen in ships and the use of hydrogen-powered fuel cells for propulsion. This project is organized in three research areas (work packages) of which this report is part of work package 2 (WP2). Figure 1 is a visual representation of the H2Maritime project scope and the three work packages.

- WP1: Hydrogen bunkering and storage: Develop design and operation strategies for efficient and safe refuelling and bunkering systems for maritime applications
- WP2: Hydrogen safety: How to ensure safe operation during refuelling and bunkering of hydrogen
- WP3: Integration of fuel-cells (FC) and hydrogen systems in maritime powertrains.

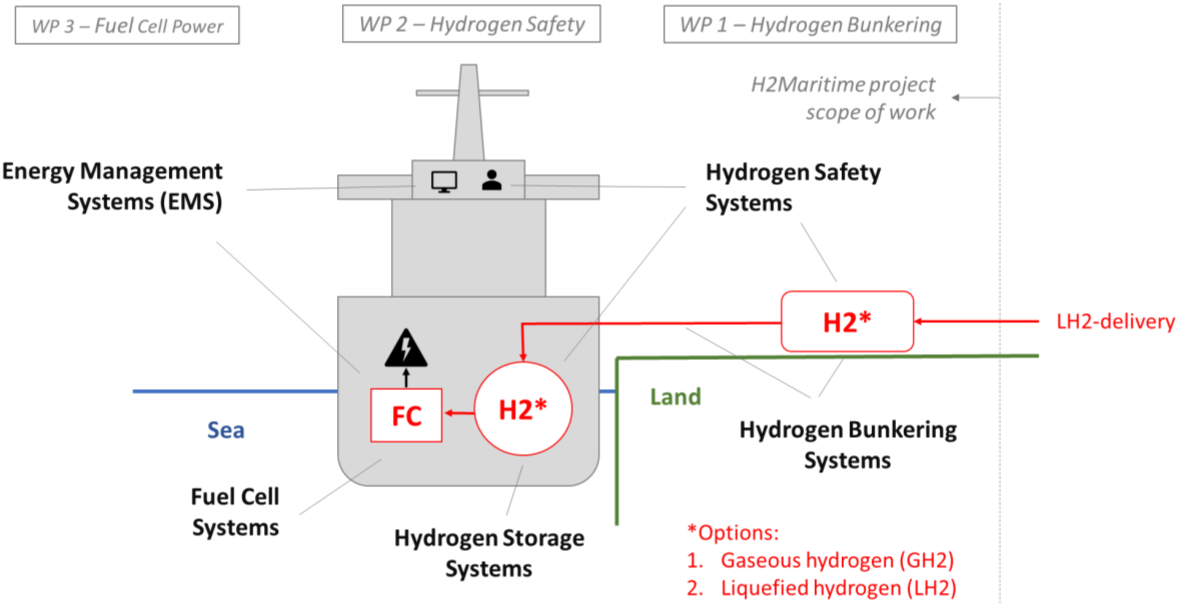


Figure 1. Illustration of H2Maritime-project´s scope of work, showing the focus areas for the three work packages

1.2 The scope of this report

This report is a part of the work package 2 (WP2), Hydrogen Safety, of the H2Maritime-project and deals with the human factors aspect of the refuelling and bunkering of hydrogen. Bunkering is in this case defined as the supply of liquid hydrogen (LH2) from a H2-storage system on land to a H2-storage system onboard a vessel. Challenges concerning hydrogen safety in the maritime, including safety related to human operation is addressed.

The primary objective of the study presented in this report is to provide recommendations on how to ensure safe human operation of refuelling/bunkering of large amounts of H2. As of this, we will approach human challenges related to maritime hydrogen refuelling/bunkering. The purpose is not to provide final answers to safety guidelines concerning human operation during hydrogen bunkering.

The H2Maritime-project poses the question of: how should the systems for the maritime hydrogen refuelling and bunkering be designed and safely operated? Based on this question, WP2 is divided into two tasks as described as follows:

T2.1: Modelling of cases and scenarios involving humans

- Identify and describe scenarios that involve hazards/risks related to bunkering, where humans are involved.

T2.2: Analyse human factors safety aspects associated with hydrogen refuelling and bunkering

- Provide input to allocation of functions between humans and technology (human/automation functions, human-technology interaction, teamwork) to maximize safety and efficiency.
- Analyse human functions, tasks, roles, work processes, and teamwork in the light of potential hazards.
- Identify information requirements related to key parameters to ensure safe H2-supply from land to ship

Different ships, H2-systems, and bunkering methods require different assessments concerning hazards and risks in human operation of H2. Therefore, a use-case was chosen for the study in WP2, with the focus on:

- A car ferry, short-sea crossings, built for using LH_2 as a fuel
- Onboard LH_2 storage system located above deck

The target audience of this report include researchers, developers of H2 maritime bunkering systems and control systems, designers of control systems´ HSI and other key stakeholders in the maritime industry (e.g., ship owners). The overall goal here is to provide knowledge to the readers that can be used to improve the safety of human operations during hydrogen bunkering.

1.3 The approach and research questions

The primary objective of the study presented in this report is to provide recommendations on how to ensure safe human operation of refuelling/bunkering of large amounts of LH_2. To meet this objective, this report takes a human-centred approach, exploring human challenges related to maritime hydrogen bunkering. This approach includes looking into challenges related to the interaction between human factors, technology, and organization, in which also the environmental context is important. Based on this, we therefore ask the following two main questions and related questions to the second question:

Research question 1:
Which scenarios involve hazards/risks related to bunkering, where humans are involved?

Research question 2:
How to ensure safe human operation of filling and bunkering of H_2 maritime applications?

1. What are the operator responsibilities and tasks during refuelling and bunkering operations?
2. What are the human functions, tasks, roles, and teamwork in the light of potential hazards?
3. What are the information requirements to human actors, including key parameters, to ensure safe H2-supply from land to ship?
4. Which safety barriers or measures are needed to reduce the risks related to human operation during bunkering of hydrogen?

The answer to the first research questions is addressed by examining relevant scientific publications and reports. This is used as a basis for approaching our work with the second research question. Scenarios involving hazards/risks related to bunkering, where humans are involved, is presented in Chapter 3.

Research question 2 is answered through a real-world case study on the filling and bunkering of liquid hydrogen (LH_2). The case study has been conducted using the crisis intervention and operability analysis (CRIOP) method. This is a human-centred approach to assess weak points and recommendations related to human factors by looking at how well people involved in H_2 bunkering operations are supported in performing their tasks and making decisions. How well these people are supported are key elements for safe and efficient operation. The case study is described in Chapter 1.6 and the CRIOP method is described in Chapter 2. The findings from the case study are discussed in Chapter 4 and 5. Recommendations for work on H_2 safety in human operations are described in Chapter 5.

1.4 Human-centred approach / Human factors

A traditional approach in case of accidents is to classify the event as "human error" and stating that the accident could be prevented if the human executer had acted correctly. The human factors perspective has a different approach, acknowledging that in most cases an accident is not caused by one single factor, such as the human, but rather a more complex issue. Norman (2013) elucidates this point:

> *Most industrial accidents are caused by human error: estimates range between 75 and 95 percent. How is it that so many people are so incompetent? Answer: They aren't. It's a design problem. If the number of accidents blamed upon human error were 1 to 5 percent, I might believe that people were at fault. But when the percentage is so high, then clearly other factors must be involved*." (Norman, 2013)

Four interrelated aspects must be considered in assessing human factors in correlation to safety incidents: the human, the technology, the organisation, and the environment in which the human tasks are to be performed. The human error triggering the accident can be a result of latent failures such as poor design or challenging framework conditions, as described by Woods et al. (1994). Two examples of latent failures related to design are: (1) The design does not match human capabilities or limitations, and (2) The design does not consider different situations or worst-case scenarios. Humans do fail; however, they are in most cases accompanied by latent errors, and as such, it is not constructive to look at human errors in isolation.

The human-centred approach and the knowledge of the human aspect in interaction with a system in the work environment can be used to optimise the match between people and the systems in which they work. The purpose of applying a human-centred approach is to improve human working conditions, safety, and performance, and to eliminate or minimize the potential for negative effects on these (International Organisation for Standardization [ISO] 9241-210, 2019). Risk reduction is achieved by optimizing the interaction between people, technology/products, the environment, and organisations. Figure 2 illustrates these interdependent aspects.

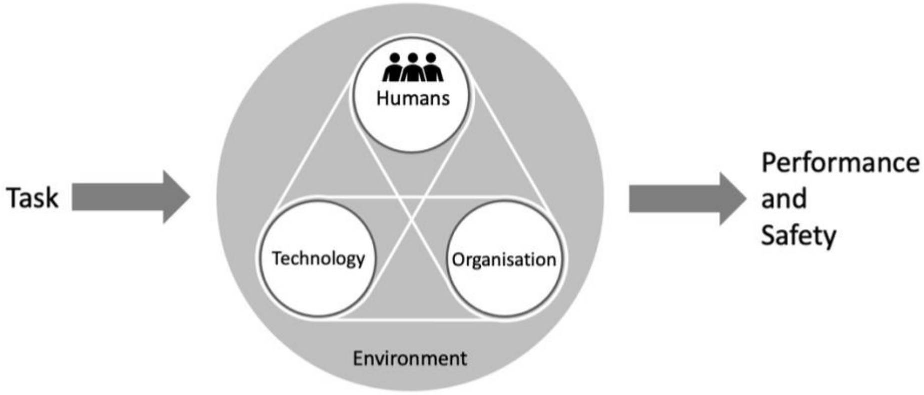


Figure 2. An illustration of the dependence between humans, technology, organisation, and environment, for the result of total performance and safety.

The human operator is an important part of the safety barriers. In many technological applications, humans contribute in an essential way to maintain safety by controlling, supervising, monitoring, and/or intervening with the processes. Even automated systems might require support from an operator, either because of regulations, mistrust in automation or automation capabilities. To improve safety of operations, it is important to address and assess the hazards related to human factors

1.5 Hydrogen properties

The purpose of this chapter is to provide a brief introduction to hydrogen as a fuel, the hydrogen properties, and the challenges related to the properties. The use case of the study described in this report is a ferry that will utilize liquid hydrogen (LH_2) as the main source of fuel (more details in Chapter 1.6). Therefore, the properties of liquid hydrogen are the focus in this chapter.

There are several different configurations for using hydrogen fuel cells in marine applications. Hydrogen can be stored and used as a fuel at both liquified (LH_2) and gaseous (GH_2) state. The hydrogen bunkering/refuelling system can supply either LH2 or GH2 to and the onboard hydrogen storage systems. Furthermore, the storage tank onboard can either be located below or on deck. The combination of hydrogen will affect the system solutions, and thus also the human operations and safety- and risk assessments.

Even though hydrogen is not more dangerous or safe than other fuels (Saffers & Molkov, 2014), the properties of hydrogen, both in gaseous (GH_2) and liquid (LH_2) form, pose some challenges that differ from other fuels.

Hydrogen is a small molecule and can easy leak even through intact materials and components. This property of hydrogen along with the fact that it ignites easily, is one of the risks associated with hydrogen. When hydrogen is mixed with air, there is a high risk of fire and the flames are almost invisible (Yang et al., 2021). The hydrogen gas is both odourless and invisible (Van Hoecke et al., 2021). Therefore, using human senses alone to assess the severity of leakages and hydrogen fires is not a reliable technique. Furthermore, leakages in an enclosed or semi-open space can result in a hydrogen explosion (DNV, 2021). Thus, hydrogen leakages can result in serious consequences.

One challenge with LH_2 is that it needs to be cooled to cryogenic temperatures of -253 ^{o}C to ensure the hydrogen remains in liquid state (DNV, 2021). When exposed to humans, this cryogenic temperature can result in severe frostbite. The LH_2 can also cause damage to constructions, such as the ship hull, in case of leakages (Van Hoecke et al., 2021).

Because of the very low temperature of liquid hydrogen, bunkering procedures are expected to be complex. *“Safety zones, bunkering line inerting and purging, boil off handling, pre-cooling of piping and air condensation on bunkering equipment are some of the challenges that must be handled.”* (Valland, 2020, p.12). In general, the main challenges related to technical solutions and human operation of a LH2-bunkering or GH2-fueling process are related to: (1) Preparation of H2-supply system and connection of H2-hose, (2) Monitoring and controls of hydrogen flow, pressure, and temperature during H2-supply (3) Shut-down of H2-supply system and disconnection of H2-hose.

1.6 Use case

The specific use case studied in the H2Maritime-project is a hydrogen fuel cell and battery electric driven ferry that will utilize liquid hydrogen (LH_2) as the main source of fuel. The use case facility, LH2-bunkering systems, procedures, and Human System Interface (HSI) of the control system were still under development during the study.

The LH_2-bunkering will take place approximately every three weeks on a municipal quay that is used by various actors for loading and unloading between ships and the quay. The quay will be closed for traffic during the bunkering operations. Passengers will not be allowed onboard during bunkering.

The method for hydrogen bunkering will be to fill LH_2 from a truck to the ship via a mobile bunkering tower with a crane for handling the bunkering hose. The bunkering tower includes a ventilation mast for hydrogen releases of residues in the bunkering hose. Hydrogen in the bunkering hose will be automatically ejected in the event of an emergency, i.e., when the Emergency Shutdown System (ESD) is activated. The LH_2-bunkering can be monitored and controlled from four places: The bridge, the ship office, the bunkering station (on the ground next to the bunkering tower), and from the truck.

During LH_2-bunkering, personnel will be involved both from the ferry bridge and the quay. Under normal operating conditions, there will be no need for manual operations during the hydrogen bunkering process, i.e., all operations on the truck, bunkering tower, and LH_2-storage tank onboard the ship are automated and handled by an overall control system. When the bunkering is complete, the bunker hoses and grounding must be manually disconnected from the LH_2-systems on the ferry and truck. The ferry can only leave the quay after the bunkering hose, grounding cable, and mooring have been disconnected. The LH_2-tank on the truck must be depressurized through the tower mast before the hose on the truck side can be disconnected. Finally, the LH_2 in the hose in the bunkering tower will be made liquid-free, depressurized, and then rolled back to its storage position.

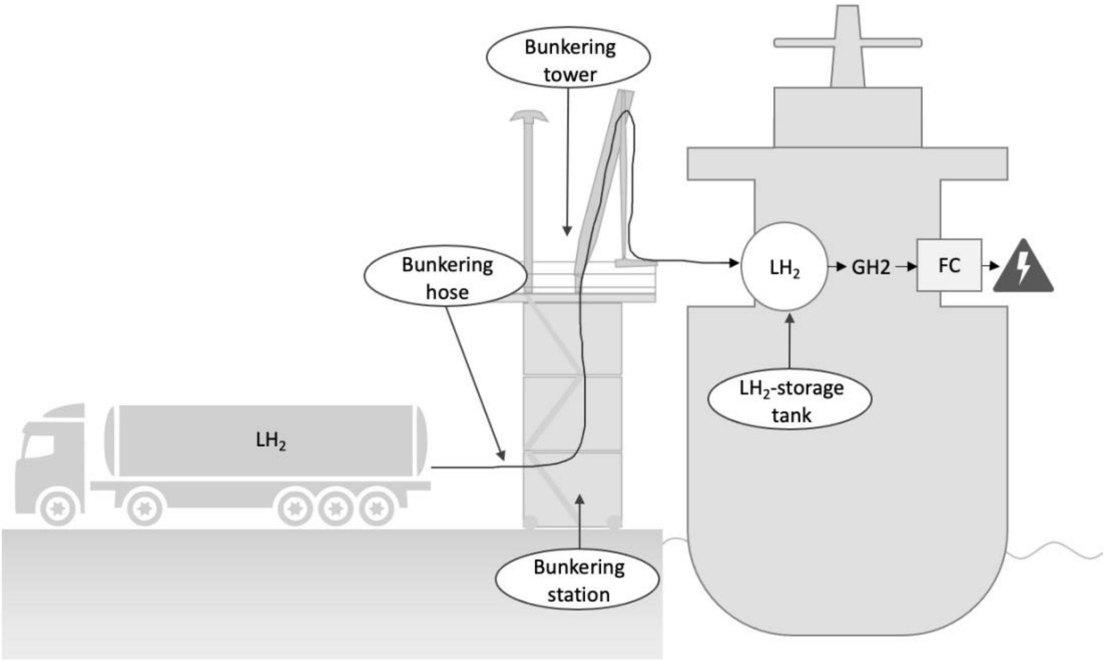


Figure 3. Illustration of the use case: Bunkering of LH_2 from truck to ship.

2 Method: CRIOP scenario analysis

The CRIOP method includes a holistic perspective on man, technology, organisation, and environment. The focus of the CRIOP method is on the human aspects in terms of conditions for successful (safe and efficient) operation in control centres.

The method is used to verify and validate aspects of human factors concerning the ability of a control centre to handle all modes of operations safely and efficiently, including such as start-up, normal operations, maintenance, process disturbances, safety critical situations and shut down. According to Johnsen et al. (2011), the method can be applied to different types of control sites, such as a central control room, emergency control-room, bridge of a boat, driving cabin of a train, drillers' cabins, cranes, and other types of cabins, both onshore and offshore. Therefore, the method should also be applicable to the context of hydrogen refuelling and bunkering for maritime applications.

CRIOP consists of two parts: 1) A checklist covering relevant areas in design of a Control Centre, and 2) Scenario analysis of key scenarios. The method also facilitates a learning arena where the workforce with operating experience, designers, system solution providers and management can meet and evaluate the operation environment.

The purpose of using the CRIOP method is to assess the possibilities of the roles involved in LH_2-bunkering to obtain good of situational awareness, make good decisions, and take necessary actions in case of challenging events, incidents, or accidents. Based on this purpose, only CRIOP part 2, the scenario analysis has been used.

The focus of the scenario analysis has been how operators are supported in performing their tasks with respect to:

- Cognitive abilities
- Human-system interaction
- Cooperation/communication
- Other factors affecting performance

According to Johnsen et al. (2011), the performance shaping factors selected in the CRIOP-method *"represent common root causes found in incidents and accidents across various industries"* (p.131). The following performance-shaping factors has been assessed during the scenario analysis:

- Teamwork, task allocation, communication
- Human-system interface (HSI)
- Work environment
- Competence and training
- Procedures
- Emergency preparedness/response
- Prioritization, conflict of objectives
- Time of day
- Time available (including workload)
- Interventions (identify and correct wrong interventions)

Scenarios should be based on experiences, hazards or risks identified by the participants to ensure understanding and involvement from the participants. The chosen scenarios are visualized in a STEP-diagram (Sequentially Timed Events Plotting) for further analysis. The STEP-diagram provides a systematic means of organizing information about the tasks and actors in the correct temporal sequence. The aim is to convert the information into a level of detail suitable for assessing the operators´ ability to handle abnormal situations and reveal possible weaknesses and challenges that may affect the performance of tasks regarding the four categories described in Table 1.

Table 1. The four categories used as a framework for assessing weak points and challenges. The table is based on CRIOP-method (Johnsen et al., 2011).

Categories	▲ Examples of Risks	Possible factors affecting performance
1. Observation/ identification	Fail to notice information, lacking information	The type of information (e.g., sound, light, text) Quality of the information provided (visible, readable, audible) Type of and the existence of feedback on execution
2. Assessment/ interpretation	Misinterpret situation/information	What the information looks like, how understandable it is, in what order it is given, and how reliable it is
3. Planning/decision	Make the wrong decision	
4. Execution/action	Executing on the wrong equipment, executing incorrectly on the right equipment, too late, too fast	Time available, motivation and the possibility to make short-cuts

The CRIOP method uses the term “weak point”. However, since the use case were still under development during this study, the term “learning point” is used in this report. This is to underline that there were still details that were not known by our use case participants, and that the findings can be regarded as learning points (input) to what needs to be assessed during construction and development of shore-based LH2-bunkering facilities for ships.

Two scenarios were selected and described in advance of a workshop. Results from the literature review concerning scenarios involving humans (Chapter 3) were used as an initial input to the process of selecting the scenarios for the CRIOP scenario analysis. Further inputs were given by the H2Maritime researchers and industry partners and finally, the owner and operator of the use case (an actual installation).

The process that led to the selection of scenarios and descriptions was iterative. First, the use case owner received a presentation of the CRIOP-method and a description of what should be included in a scenario description. The use case owner also received examples of scenarios, both defined situation of hazard and accidents (DSHA) from the Oil & Gas industry and examples from the hydrogen industry, as mentioned in Chapter 3. Based on this, it was agreed to include scenarios for a small and large hydrogen leakage from the bunkering hose. The use case owner created the initial descriptions, which was commented, and questions were asked by the research partner (authors of this report). Thereafter, the use case owner refined and made the descriptions more specific. At a certain point the iterations were stopped, and further clarifications and questions were reviewed during the scenario analysis workshop.

The scenario analysis was conducted as a group discussion between key representatives from the use case owner. These representatives included a Captain, a Chief (in charge of the machinery onboard), a Project Manager and a Project Engineer. A H2Maritime-project representative with hydrogen systems expertise (the second author of this report) also participated in the workshop. The group discussions were facilitated by another H2Maritime-project representative with a human factors and human-centred design expertise (the first author of this report). The scenario analyses were performed in the following way:

1. The selected scenarios were described using STEP-diagrams showing main tasks/events and actors during the bunkering process.

2. Critical tasks were selected for further analysis. Some tasks were equally critical as the ones chosen; however, they were not analysed further as they were nearly duplicates of other operators' tasks. Only the tasks of the main responsible operator were chosen for the further analysis.
3. Each of the critical tasks were assessed in terms of which of the four categories, as described in Table 1, applied to the task.
4. Problems and challenges related to the operators' ability to handle the scenarios were discussed using the scenario checklist from the CRIOP method (Johnsen et al., 2011). This is a structured interview guide with questions related to each of the four categories (Table 1). The questions facilitated discussion of factors that may (positively or negatively) affect performance and the outcome of the scenario. The checklist also addresses questions that shed light on performance-shaping factors. These were first discussed per critical task, and finally for the entire scenario.

In addition to the STEP-diagram, illustrations, pictures, drawings, and process diagrams of the LH_2-bunkering facility were used in the workshop to assess how well people involved in bunkering operations are supported in performing their tasks.

STEP-diagrams were made for both scenarios, but only the small hydrogen leakage scenario was analysed in detail, using the scenario checklist. During the work with the STEP-diagram it turned out that the two scenarios (small and large hydrogen leakage), including the critical tasks, were quite similar. Hence, the scenario analyses could be simplified.

The use case facility, LH2-bunkering systems, procedures, and Human System Interface (HSI) of the control system were still under development during the data collection. Hence, no end users had operated nor been trained in the operating of the LH_2-bunkering system at the time of this study. This means that there were no experienced end-users involved in the discussions. This is a normal situation when taking a human-centred approach to design and is not a limitation for using the CRIOP-method.

The CRIOP-method can be applied in different stages of a project, from preliminary work on different system concepts to more detailed design, final verification, and even after a period of system operation. The potential for improvements is largest during the early phases of a development process and decreases as it matures (Johnsen et al., 2011). The more mature the solution (systems, facilities, etc.), the more difficult it is to make changes due to costs and time. When the aspects of human factors are not considered from early design phases, the result can be that humans have to adapt to the solution, which is not optimal in terms of reducing human errors, or in terms of supporting the human operator in succeeding. The CRIOP method should therefore be used from early design phases and iteratively throughout the design process, according to a human-centred process as outlined by ISO 11064-1 (2000).

3 Scenarios involving humans

According to Tofalos et al. (2020), the bunkering operation is the riskiest process related to LH_2 and the fuel leak accident is the main risk that can occur during the bunkering operation. The high risk relates to the LH_2 properties.

In this chapter, we will identify some scenarios that involve hazards or risks related to bunkering, where humans are involved. This answers to the first research question of this report:

Research question 1: Which scenarios involve hazards/risks related to bunkering, where humans are involved

Relevant literatures are visited to sum up some relevant scenarios, including the potential for major accidents. Scenarios from literature concerning liquified natural gas (LNG) bunkering that are applicable to LH_2 bunkering are included. In Table 2 the undesirable events (scenarios) and the related risks, possible cause and barriers/risk reducing measures are listed. However, the reviewed literature did not discuss related risks, possible cause, and barriers for all listed scenarios. Furthermore, the listed related risks, possible causes and barriers per hazardous scenario are examples found in the literature and should not be regarded as a complete list. The information in this table is collected information from Fagerland (2017), Safety4Sea (2019), EMSA (2018), Feng et al. (2021), Balestra & Utne (2019), Pacific Northwest National Laboratory (n.d.-c). and Hyde & Ellis (2019).

Table 2. Scenarios that involve hazards or risks related to bunkering

Undesirable events	Risk	Possible cause	Barriers, risk reducing measures
Leakage from hoses, defect in hoses, hose failure, hose rupture	Hydrogen leakage and diffusion, fire and explosion in case of ignition source	• The ship/shore relative motion is too large • The bending radius is too small • Aging corrosion • Fatigue failure • Improper storage • The hose is not properly supported • Hose type and condition • Connection problems • Seal failure • Maintenance problems	• Refuelling inspection check list • Active monitoring of cryo-coupling during the refuelling procedure • Hydrogen sensors • ESD cut off the bunkering pipeline on board • Onshore ESD cut off the hydrogen supply • Firefighting system • No bunkering operations in windy weather • Firm attachment of hose before bunkering • Leak detection before bunkering operation • Establishment of restricted area (including zones) and control of ignition sources in the restricted area • Use of hydrogen bunkering arm and hose to reduce the length of hose
Rupture of hard pipe	Hydrogen leakage and diffusion, fire and explosion in case of ignition source	• Falling objects • Collision	• ESD cut off the bunkering pipeline on board • Onshore ESD cut off the hydrogen supply • Firefighting system • Set up proper protection against mechanical damage • Establishment of restricted area and control of the ignition sources in the restricted area
Unplanned disconnection of hoses or loading arm	Leakage Fires if ignition is present Risk to people and/or facility Operation delay	• Weather conditions, • Inadequate connection • Human related error • Excessive ship motions due to failure in engine control system on ship. • Failure in mooring • Passing ships • Extreme weather conditions	• Birthing and engine control of the ship • Quick release coupling that will minimize damages to the loading arm

Undesirable events	Risk	Possible cause	Barriers, risk reducing measures
Valve leakage, valve failure	Hydrogen leakage and diffusion, fire, and explosion in case of ignition source	• Seal failure • Fatigue failure • Strength failure • Improper operation	• Equipped with ESD system • Combustible gas leakage detection alarm • Firefighting system • The material selection of valves is reasonable • Adopt approved valve parts • Replace flange gasket regularly • Leak detection before operation • Regular maintenance and replacement of valves • Establishment of restricted area and control of the ignition sources in the restricted area
Tank overfilling (from truck)	Leakage/overfilling	• Inadequate monitoring, incorrect level readings • Delay in flow stoppage	• Overflow control by implementing a high liquid level alarm giving an audible and visual warning when activated, and a sensor activating an automatic shut-off valve. • ESD
Joints leakages			
Incompatible flange types			
Drive away (truck)	Leakage Property/facility damage	• Failure to follow standard operating procedure • Lack of site-specific delivery procedures and checklist as a reminder of key safety items prior to departure • Lack of technical barriers	• Train personnel on delivery procedures • Emphasize the safety aspects of hydrogen connections and disconnections • Provide site-specific delivery procedures • Provide checklist as a reminder of key safety items prior to departure • Verify clearance for trailer movement prior to departure • Air supply to connect to a pneumatic isolation valve on the trailer. The supply of air to this valve should be controllable, allowing hydrogen to be isolated at the tube trailer rather than at the gas panel. The air line must be shorter than the hydrogen line, so if the trailer rolls away, the airline will fail first, isolating the trailer.
Ship away			
Overpressure of piping by trailer pump	• Pipe rupture • Failure of safety valves	• Temperature build-up in pipe • Malfunctioning valves in pipe	• Pressure, temperature, and flow monitoring • Safety valves (several redundant valves) that go off in case of overpressure

Undesirable events	Risk	Possible cause	Barriers, risk reducing measures
	• Small H2 leakage and dispersion, possible self-ignition of H2		
Overpressure of tank by trailer pump without overfilling (bottom loading)	• Tank rupture • Failure of safety valves • Large LH2 leakage and dispersion, possible self-ignition and explosion of H2	• Temperature build-up in tank • Malfunctioning valves in tank	• Pressure and temperature monitoring • Safety valves that go off in case of overpressure
Unintended opening of truck transfer/tank vent (vent used for hose purging)	• LH2 spill on ground • Large LH2 leakage and dispersion, possible self-ignition and explosion of H2	• Technical failure in purge activator • Human error	• Double-check all connections before starting the transfer process • Regular testing of activator for purging
Overpressure of tank by Pressure build up coil (PBU)			
Simultaneous operations		• Simultaneous operation of operations that can affect each other negatively	• The operation system prevents the possibility of simultaneous operation of operations that can affect each other negatively

4 The two scenarios

This chapter first presents the descriptions of the two scenarios from the real-world use case and each of the resulting STEP-diagrams. These are used for the CRIOP scenario analysis. This is a human-centred approach to assess weak points and recommendations related to human factors by looking at how well people involved in H_2 bunkering operations are supported in performing their tasks and making decisions.

Two hydrogen incidents were selected as scenarios for the CRIOP scenario analysis. One involving a small hydrogen leakage and the other a large leakage, both concern a leakage in a hose connection:

Scenario 1 – A small leakage that develops and spreads: During bunkering a small leakage of LH_2 takes place in a hose connection at the tower side, for the hose connecting the tower and the ferry. The leak is not detected until it has spread

Scenario 2 – A sudden/acute leakage: During bunkering a large LH_2 leakage takes place due to a hose rupture in the hose connecting the bunkering tower and the ferry

The collective work with the STEP-diagram and discussions of topics in the scenario checklist resulted in more details and changes to the descriptions of the scenarios. The versions used when initiating the scenario analysis and discussions are included in Chapter 4.1 and 4.2. Changes and comments to the scenario descriptions are described in Chapter 5.1 and relates to roles, responsibilities and, tasks. Both scenarios include some common terms and assumptions. These are explained in the following paragraphs:

Terms/Abbreviations

Captain	The vessel's Master of command
Chief	In charge of the machinery on board
ESD	Emergency Shutdown System
H2	Hydrogen
JRCC	Joint Rescue Coordination Centre
LEL	Lower Explosion Limit
LH_2	Liquid Hydrogen
OS	Operating System
UEL	Upper Explosion Limit

Assumptions for the surroundings and scenario

The bunkering is to take place during the night. This means that the surroundings will be quite dark, except for light from spotlights around the quay. The scene has been prepared for bunkering. The LH_2-truck is in correct position, the tower has been prepared and found ready for bunkering. The ferry is moored and prepared for bunkering.

The bunkering can be monitored and controlled from four places: (1) The bridge, (2) The ship office (secondary station, often down a staircase from the bridge), (3) The bunkering station (on the ground next to the bunkering tower), and (4) The truck. The vessel's Chief will have command over the bunkering.

The bunkering takes place at a municipal quay, which has been sealed off for any outsiders on the land side. On the bridge, the Captain´s task is to avoid boats going too near the ferry. There are no passengers on board, only the crew of 7 where some are off duty, and some are on duty.

The crew on duty are fully dedicated to the bunkering operation:

- The Navigator (or Captain) is in the wheelhouse overlooking surroundings for ships and people or other threats
- The Chief is in the ship office overlooking the bunkering and in charge of the filling process.
- The Seaman is to be near the tower bunkering station (on shore) and be able to push the ESD button to stop the bunkering.
- On the ground the truck driver is monitoring and operating the truck.

No person should be in the tower during bunkering

Weather limitations will apply. No bunkering if the wind exceeds 12 m/s. Wind direction can affect a failure scenario.

Bunkering process

The bunkering is driven by higher pressure in the truck than in the onboard tank. The process is controlled by valves and an operating system (OS), monitored from both the truck, the tower bunkering station, the bridge, and the ship office.

After all preparations are done and all items are checked, the valve at the ferry side will open and the hydrogen transfer will take place. The hydrogen is transferred until the level in the ferry tank has reached the desired level.

The normal time of hydrogen transfer be approximately one hour.

4.1 Scenario 1 – A small leakage that develops and spreads

The bunkering is ongoing as per procedure. At some point a small leakage takes place in a hose connection at the tower side, for the hose connecting the tower and the ferry.

The leak is not detected until it has spread. The leak is detected by the Seaman after seeing and hearing the gas leaking before the gas has ignited. Preventive actions and evacuation are initiated.

If the leakage is determined: Alert the truck driver and ask him/her to immediately stop the transfer. Activate the ESD if this has not happened automatically.

All personnel to evacuate to safe zone.

Alarm 110-central about hydrogen release.

After 10 minutes, if the bunkering has been stopped, measurements can be carried out to check whether the release is diluted to a non-ignitable solution (less than 4% H_2).

If the leakage is of a given size the mixture of hydrogen in air can reach 4% or higher (4% = Lower Explosion Limit, LEL). This is an explosive level up to 75% (75% = Upper Explosion Limit, UEL). If the hydrogen hits any items as it leaks this will increase the likelihood of ignition (can self-ignite).

Information available to the people present

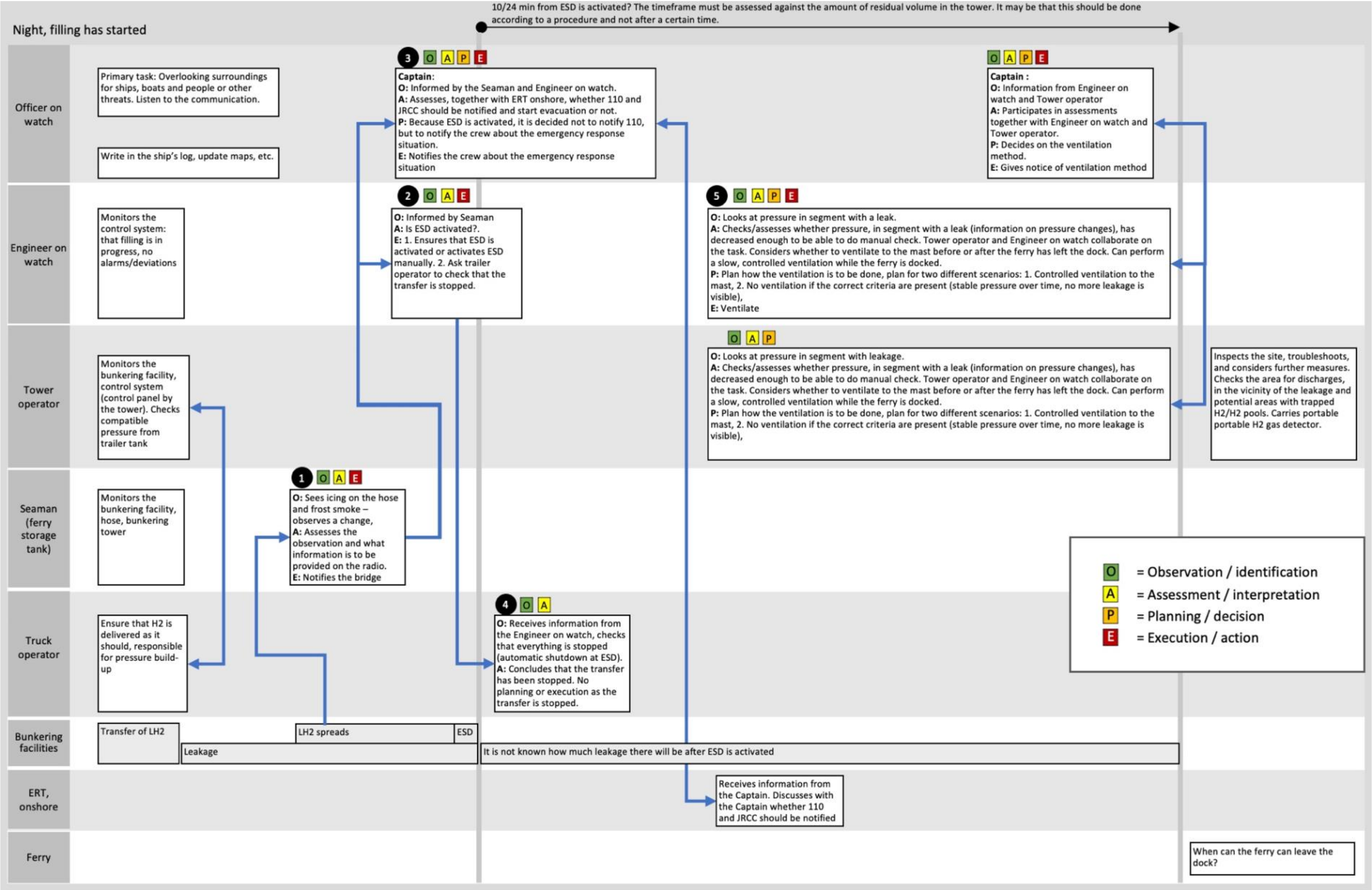
If the leakage is very small, it will not be seen nor detected. Little harm will be caused by very small leakages.

At a larger leak rate, the leakage may be visible (very cold gas, though invisible in itself), audible, or a fire is seen.

STEP-diagram scenario 1

The final STEP-diagram for the small leakage scenario, including the categorisation of five critical tasks is shown in Figure 4 (see next page).

When working with the STEP-diagrams in the workshop some learning points in the scenario descriptions were revealed. Therefore, the STEP-diagrams do not match the descriptions as specified earlier in this chapter. The learning points and the reasons for the changes are discussed in Chapter 5.



10/24 min from ESD is activated? The timeframe must be assessed against the amount of residual volume in the tower. It may be that this should be done according to a procedure and not after a certain time.

Primary task: Overlooking surroundings for ships, boats and people or other threats. Listen to the communication.

Write in the ship's log, update maps, etc.

Captain:
O: Informed by the Seaman and Engineer on watch.
A: Assesses, together with ERT onshore, whether 110 and JRCC should be notified and start evacuation or not.
P: Because ESD is activated, it is decided not to notify 110, but to notify the crew about the emergency response situation.
E: Notifies the crew about the emergency response situation

Captain :
O: Information from Engineer on watch and Tower operator
A: Participates in assessments together with Engineer on watch and Tower operator.
P: Decides on the ventilation method.
E: Gives notice of ventilation method

Monitors the control system: that filling is in progress, no alarms/deviations

O: Informed by Seaman
A: Is ESD activated?.
E: 1. Ensures that ESD is activated or activates ESD manually. 2. Ask trailer operator to check that the transfer is stopped.

O: Looks at pressure in segment with a leak.
A: Checks/assesses whether pressure, in segment with a leak (information on pressure changes), has decreased enough to be able to do manual check. Tower operator and Engineer on watch collaborate on the task. Considers whether to ventilate to the mast before or after the ferry has left the dock. Can perform a slow, controlled ventilation while the ferry is docked.
P: Plan how the ventilation is to be done, plan for two different scenarios: 1. Controlled ventilation to the mast, 2. No ventilation if the correct criteria are present (stable pressure over time, no more leakage is visible),
E: Ventilate

Monitors the bunkering facility, control system (control panel by the tower). Checks compatible pressure from trailer tank

O: Looks at pressure in segment with leakage.
A: Checks/assesses whether pressure, in segment with a leak (information on pressure changes), has decreased enough to be able to do manual check. Tower operator and Engineer on watch collaborate on the task. Considers whether to ventilate to the mast before or after the ferry has left the dock. Can perform a slow, controlled ventilation while the ferry is docked.
P: Plan how the ventilation is to be done, plan for two different scenarios: 1. Controlled ventilation to the mast, 2. No ventilation if the correct criteria are present (stable pressure over time, no more leakage is visible),

Inspects the site, troubleshoots, and considers further measures. Checks the area for discharges, in the vicinity of the leakage and potential areas with trapped H2/H2 pools. Carries portable portable H2 gas detector.

Monitors the bunkering facility, hose, bunkering tower

O: Sees icing on the hose and frost smoke – observes a change,
A: Assesses the observation and what information is to be provided on the radio.
E: Notifies the bridge

Ensure that H2 is delivered as it should, responsible for pressure build-up

O: Receives information from the Engineer on watch, checks that everything is stopped (automatic shutdown at ESD).
A: Concludes that the transfer has been stopped. No planning or execution as the transfer is stopped.

It is not known how much leakage there will be after ESD is activated

Receives information from the Captain. Discusses with the Captain whether 110 and JRCC should be notified

When can the ferry can leave the dock?

Figure 4. STEP diagram for scenario 1 with a small leakage, including categorisation of five critical tasks (numbered from 1 to 5)

4.2 Scenario 2 – Sudden/acute leakage

The bunkering is ongoing as per procedure. At some point a large leakage takes place due to a hose rupture in the hose connecting the tower and the ferry. The leakage is spotted by the Seaman.

When the leakage is determined: Alert the truck driver and ask him/her to immediately stop the transfer. Activate the ESD if this has not happened automatically.

All personnel to evacuate to safe zone.

Alarm 110-central about release

After 10 minutes it can, if the bunkering is stopped, be made measuring to control if the release is diluted to a non-ignitable solution (less than 4% H2).

If the leakage is of a given size the mixture of hydrogen in air can reach 4% or higher. This is an explosive level. If the hydrogen hits any items as it leaks this will increase the likelihood of ignition (can self-ignite).

Information available to the people present

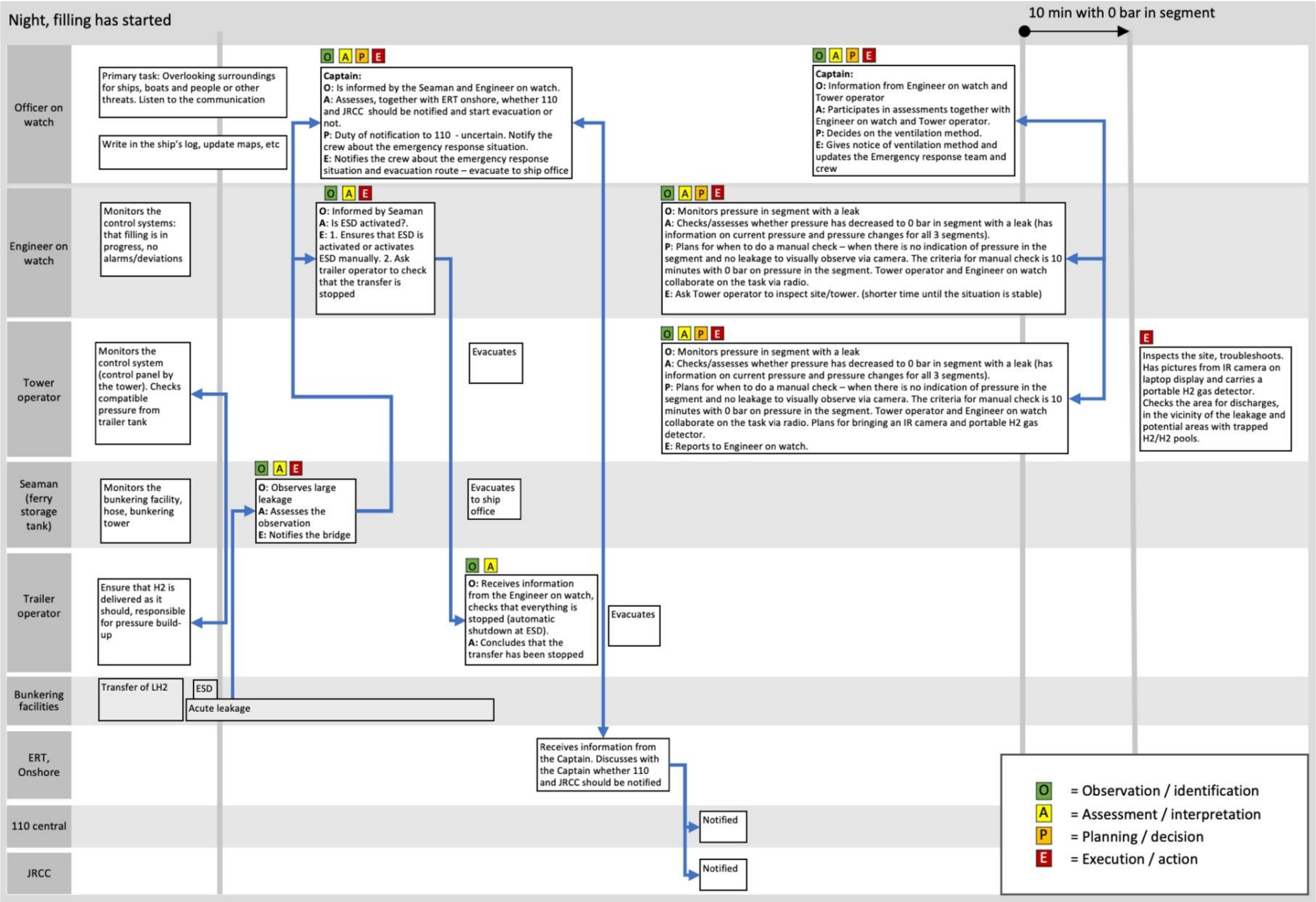
At a larger leak rate: the leakage could be visible (very cold gas, though invisible in itself), audible, or a fire is seen. Explosions may occur.

Monitoring equipment might be broken because of the leak.

STEP-diagram scenario 2

The final STEP-diagram for the sudden/acute leakage scenario is shown in Figure 5 (see next page).

When working with the STEP-diagrams in the workshop, some learning points in the scenario descriptions were revealed. Therefore, the STEP-diagrams do not match the descriptions as specified earlier in this chapter. The reasons for the changes are discussed in Chapter 5.



Primary task: Overlooking surroundings for ships, boats and people or other threats. Listen to the communication

Write in the ship's log, update maps, etc

Captain:
O: Is informed by the Seaman and Engineer on watch.
A: Assesses, together with ERT onshore, whether 110 and JRCC should be notified and start evacuation or not.
P: Duty of notification to 110 - uncertain. Notify the crew about the emergency response situation.
E: Notifies the crew about the emergency response situation and evacuation route – evacuate to ship office

Captain:
O: Information from Engineer on watch and Tower operator
A: Participates in assessments together with Engineer on watch and Tower operator.
P: Decides on the ventilation method.
E: Gives notice of ventilation method and updates the Emergency response team and crew

Monitors the control systems: that filling is in progress, no alarms/deviations

O: Informed by Seaman
A: Is ESD activated?.
E: 1. Ensures that ESD is activated or activates ESD manually. 2. Ask trailer operator to check that the transfer is stopped

O: Monitors pressure in segment with a leak
A: Checks/assesses whether pressure has decreased to 0 bar in segment with a leak (has information on current pressure and pressure changes for all 3 segments).
P: Plans for when to do a manual check – when there is no indication of pressure in the segment and no leakage to visually observe via camera. The criteria for manual check is 10 minutes with 0 bar on pressure in the segment. Tower operator and Engineer on watch collaborate on the task via radio.
E: Ask Tower operator to inspect site/tower. (shorter time until the situation is stable)

Monitors the control system (control panel by the tower). Checks compatible pressure from trailer tank

Evacuates

O: Monitors pressure in segment with a leak
A: Checks/assesses whether pressure has decreased to 0 bar in segment with a leak (has information on current pressure and pressure changes for all 3 segments).
P: Plans for when to do a manual check – when there is no indication of pressure in the segment and no leakage to visually observe via camera. The criteria for manual check is 10 minutes with 0 bar on pressure in the segment. Tower operator and Engineer on watch collaborate on the task via radio. Plans for bringing an IR camera and portable H2 gas detector.
E: Reports to Engineer on watch.

Inspects the site, troubleshoots. Has pictures from IR camera on laptop display and carries a portable H2 gas detector. Checks the area for discharges, in the vicinity of the leakage and potential areas with trapped H2/H2 pools.

Monitors the bunkering facility, hose, bunkering tower

O: Observes large leakage
A: Assesses the observation
E: Notifies the bridge

Evacuates to ship office

Ensure that H2 is delivered as it should, responsible for pressure build-up

O: Receives information from the Engineer on watch, checks that everything is stopped (automatic shutdown at ESD).
A: Concludes that the transfer has been stopped

Evacuates

Transfer of LH2

ESD

Acute leakage

Receives information from the Captain. Discusses with the Captain whether 110 and JRCC should be notified

Notified

Notified

Figure 5. STEP diagram for scenario 2 with a large, acute leakage.

5 Results from the scenario analysis

The results from this analysis are used to answering research question 2:

Research question 2: How to ensure safe human operation of filling and bunkering of H_2 maritime applications?

1. What are the operator responsibilities and tasks during refuelling and bunkering operations?
2. What are the human functions, tasks, roles, and teamwork in the light of potential hazards?
3. What are the information requirements, including key parameters, to ensure safe H2-supply from land to ship
4. Which safety barriers or measures are needed to reduce the risks related to human operation during bunkering of hydrogen

Some of the findings are discussed in Chapter 5.1-5.4. All findings related to learning points, including the topics discussed in Chapter 5.1-5.4, are gathered in Chapter 5.5, which also includes recommendations to barriers.

5.1 Roles, responsibilities, and tasks

During the scenario analysis workshop, some of the descriptions of the scenarios were changed and more details were discussed. Some of these changes and details will be referred to in Chapter 5.5. This means that the conclusions on responsibilities, tasks and roles should be considered in the light of the learning points.

There were some changes in roles, responsibilities, and tasks per role. The changes in roles are illustrated in Figure 6, and after this figure are explanations to the changes. The new description of tasks and responsibilities per role is in Table 3.

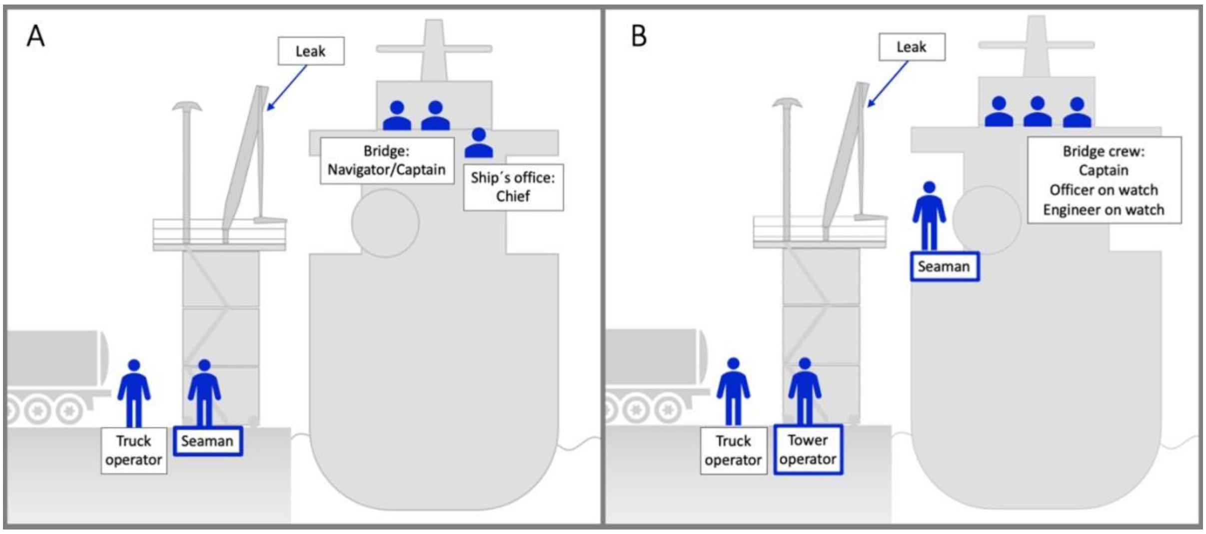


Figure 6. Roles involved in bunkering. (A) As defined in the scenario description (Chapter 4.1 and 4.2). (B) As defined after the work with the STEP-diagram and discussions related to the scenario checklist

Before working with the STEP-diagram, the descriptions did not include a Tower operator. The Seaman was to stay on deck until everything is ready for bunkering, and then move onshore to monitor the control system and bunkering facility from the bunkering station. Detailed discussion of the scenarios by using the scenario checklist and pictures of the facility revealed that an operator placed onshore, by the bunkering station, would not be able to see a leakage in the hose connection at the tower side (see illustration B in Figure 6). There are obstacles in the line of sight and the operator would not be able to notice the hydrogen leakage. Therefore, the representatives from the use case concluded that the Seaman should remain on deck during bunkering to observe the ferry LH_2-storage tank and bunkering facility. The onshore tasks, concerning monitoring the control system and observing the bunkering facility from the bunkering station, should be allocated to a Tower operator.

The scenario descriptions and the initial talks about tasks per role did not define main responsible roles per tasks, such as the team communication (via open radio communication), monitoring the operating system (OS) and who to press the ESD (Emergency Shutdown System) button if ESD has not been activated by automation. The results of the scenario discussions were to centralise the team communication responsibility and the main responsibility for the ESD button and monitoring/controlling the operating system to the Engineer on watch. This is a reasonable solution, since this role is stationary in front of the OS screens, while other operators will need to move around more, such as the Truck operator, Tower operator and Seaman.

The responsibilities and tasks per role in Table 3 is related to the tasks and situation in the two scenarios. The order of tasks in each scenario is visualised in STEP-diagrams (see Figure 4 and Figure 5). The communication links (dialogue) between the roles are illustrated in Figure 7.

Table 3. Roles, tasks and responsibilities during normal operating conditions and leakage of LH_2 (related to the scenarios)

Role/Actor	Normal operating conditions	Leakage of LH_2 (small and large leakage)
Captain	Is in command on the ship Has the overall responsibility for the bunkering operations	Emergency manager Responsible for the communication with Emergency response team (ERT) onshore. Assesses, together with ERT, whether 110 central (The fire and rescue service's emergency call centre) and Joint Rescue Coordination Centre (JRCC) should be notified and start evacuation or not Small leakage: Notifies the crew about the emergency response situation Large leakage: Notify the crew of the emergency response situation and evacuation route Assess whether ventilation is needed and how it is to be done Decide on the hydrogen ventilation method
Officer on watch (Captain or Navigator)	Is on the bridge overlooking surroundings for ships and people or other threats.	Navigator is the Deputy of the Captain, if the Captain is absent.
Engineer on watch (Chief engineer or Engineer)	Is on the bridge monitoring the operating system and in charge of the bunkering process, including start and stop of the LH_2 transfer and team communication	Is responsible for ensuring that ESD is activated (and active ESD manually if it is not automatically activated) Get a verification from the truck operator that the hydrogen transfer has stopped Assess whether ventilation is needed and plan how it is to be done Initiate ventilation

Role/Actor	Normal operating conditions	Leakage of LH_2 (small and large leakage)
		Assess when it is safe for a visual inspection and plan for it to be conducted
Tower operator	Is to be near the tower bunkering station (on shore) during the bunkering Is trained personnel rotating between being a Seaman on the ship and Tower operator onshore	Push the ESD button if needed Assess whether ventilation is needed and how it is to be done Assess when it is safe for a visual inspection and plan for it to be conducted Conduct a visual inspection at the site and troubleshoot. When needed: evacuate
Seaman	Is on the ship and on watch close to the ship storage tank Monitor the LH_2-storage tank onboard the ferry and the LH_2-bunkering system onshore from the ferry side	Notify the bridge (Engineer on watch) of any deviations Large leakage: Evacuate to ship´s office after notifying the bridge that a large leakage has been observed.
Truck operator (truck driver)	Monitor the truck LH_2-control system Operate the truck Ensure that LH_2 is delivered as it should Responsible for pressure build-up	Ensure that the hydrogen transfer is stopped Notify the bridge (Engineer on watch) of any deviations. Large leakage: Evacuate after notifying to the bridge (Engineer on watch)
Control system	Handle all operations on the truck, bunkering tower, and LH_2-storage tank onboard the ship during the hydrogen bunkering process	Activate ESD in the event of an emergency (leakage): The bunkering hose will be automatically ejected
ERT (Emergency Response Team)		In communication with the Captain during emergency response situation. Responsible for notifying 110-central and JRCC when needed, e.g., large leakages

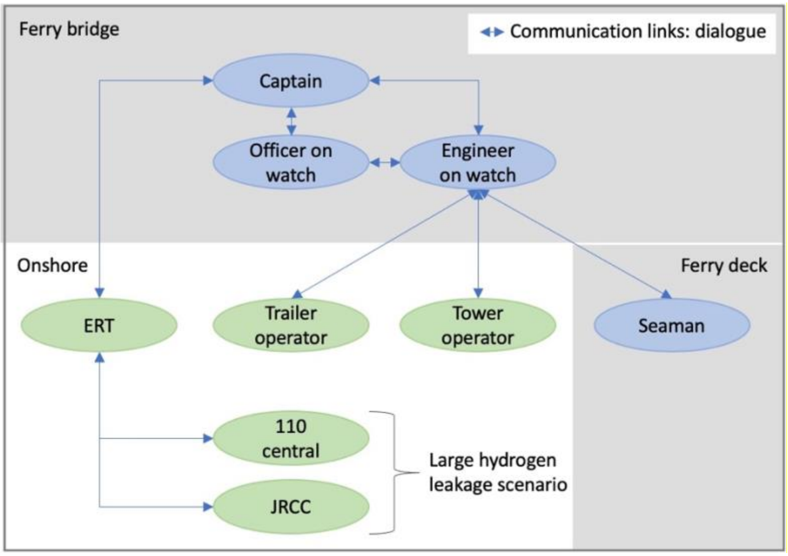


Figure 7. Roles and communication links, dialogues. The result of the scenario analysis.

5.2 Emergency response, visual inspections

The two scenarios, including the critical tasks, turned out to be quite similar when working with the STEP-diagrams. Therefore, only the small hydrogen leakage scenario was analysed in detail, using the scenario checklist. However, there are a few differences in the scenarios requiring different actions and safety assessments. Some of the differences, concerning roles, tasks and responsibilities are defined in Table 3 (Chapter 5.1).

In both the initial scenario descriptions (large and small hydrogen leakage), it was assumed that detection of hydrogen in air could be done (by manual inspection) after 10 minutes if the bunkering (transfer) is stopped. This was discussed during the scenario analysis. The system designers have determined the criterion for conducting a visual inspection to be 10 minutes at 1 bar (atmospheric pressure) after a large hydrogen leakage. The ESD is activated much earlier in the event of a large than a small leakage. After a small leakage it is more uncertain when it is safe to perform a visual inspection after ESD as this depends on the specific conditions (size and location of leakage, ambient weather conditions etc.). Also, the information on pressure in the case of a small leakage is probably not reliable enough for deciding whether it is safe or not to conduct visual inspections. It was therefore concluded in the workshop that the safest approach probably would be to act according to a strict and predefined procedure (based on calculations for different hydrogen release rates and ambient conditions). This means that the type of incident (i.e., scenario) leading to the activation of the ESD will influence how to decide when it is safe to perform the inspection of the facility after the incident.

The required emergency response, including the evacuation of people from the ferry, depends on the incident and conditions. In a small leakage scenario where the pressure is stable after the activation of ESD, it might not be necessary for personnel to evacuate. The Captain must assess the situation before deciding whether to evacuate the crew or not. In situations with a large hydrogen leakage, the Captain should instruct everyone onboard to evacuate. However, it is not easy to determine who to evacuate or when to evacuate in all situations. This depends on required tasks to be executed and the expected severity of the situation. The reason for this uncertainty is that there is a possibility that the ESD fails in closing some of the valves, even though there is a very low probability for this to happen. It was therefore concluded in the workshop that visual inspections are necessary to ensure that the hydrogen transfer has been stopped before the next actions can be taken (e.g., Truck operator can evacuate).

5.3 Training

The essence of the training requirements stated by the Norwegian regulation is that the company must ensure that employees have the necessary skills, both for handling normal and abnormal situations safely (Lovdata, 2009). H2Tools´ best practices (Pacific Northwest National Laboratory, n.d.-b) are more specific regarding training requirements, specifying the need for appropriate training plans both related to potential job hazards and to the introduction of new or modified equipment or information. Also, the H2Tools´ best practices state that adequate training of staff in hydrogen safety procedures is necessary. In the IMO guideline (International Maritime Organisation [IMO], 2009), there is a chapter only focusing on requirements to training of crews on gas-fuelled ships. The guideline has different training requirements depending on crew category: "*category A: Basic training for the basic safety crew; category B: Supplementary training for deck officers; and category C: Supplementary training for engineer officers»* (p.40). However, neither of these references provide any guidelines on training frequency.

In the use case discussed in this report bunkering was assumed to take place approximately every three weeks. Furthermore, it was assumed that there will be different teams responsible for the different shifts performing the bunkering tasks. Several weeks can pass between each time a person participates in bunkering operations, depending on the shift rotation. The same situation is likely to apply to other similar bunkering facilities. It is therefore necessary to find an appropriate training frequency required for personnel who are rarely involved in bunkering, both in terms of normal operation and Defined Hazards and Accidents Situations (DSHA), to maintain knowledge and thus also safety.

5.4 Personnel in the safety zone

The bunkering crew includes a Seaman by the LH2-storage tank onboard the ferry and two other operators onshore, the Tower operator and Truck operator. The advantages and disadvantages of the operators' presence in a safety zone compared to remote operation during the bunkering should be carefully considered. The disadvantages of having operators in the safety zone (close to the bunkering system) during a one-hour bunkering process is the risk of reduced alertness, their inability to detect small leakages, there might be obstructions in the line of sight to a possible leakage. Furthermore, the operators are in an area where they can be exposed to high risk in the case of large leakages.

Technology such as sensors, surveillance cameras, digital control system and automation allow for remote operation and removal of personnel from the immediate sources of risk. Taking advantage of these technologies should be considered for these operators.

5.5 Learning points, recommendations, and barriers

This chapter presents the learning points identified in the workshop with focus on the human factors related to hydrogen bunkering (i.e., human-centred scenario analysis). Many of the learning points include suggested barriers. The suggested barriers refer to standards and guidelines (ANSI/ISA 18.2, NUREG-0899, NUREG-0700, IAEA-TECDOC-1058, ISO 11064) used in such as the Oil & Gas industry and nuclear industry. Some barriers have been identified in other sources, such as Lovdata (2009) and the H2Tools Portal (Pacific Northwest National Laboratory, https://h2tools.org/). Barriers suggested by the representatives from the use case during the workshop is also included.

The learning point findings are grouped into the following categories:

- Teamwork, task allocation, and communication
- Human-system interface (HSI), information (situational awareness)
- Facility design

- System design
- Work environment/Time of day
- Work environment
- Competence and training
- Procedures
- Emergency response
- Time available

Some learning points involve a combination of more than one mitigating factor. This means that learning points related to one of the topics mentioned above might include suggested barriers or comments related to other topics. An example of this is that the need for information is often linked to the need for a technical solution, such as a sensor. All learning points are numbered (#ID). Some of the recommendations and comments are relevant to other learning points, including recommendations and comments. In these cases, the relevant learning point #ID is referred to.

5.5.1 Teamwork, task allocation and communication

#ID	Learning points	Recommendations to barriers/Comments
1.	Allocation of tasks and responsibilities is somewhat unclear (See #ID 2 and #ID 3)	According to ISO 11064-1 (2000), a work organization must be defined that groups the designed jobs into specific roles as prescribed by the overall project's organizational plan. Topics of consideration includes such as lines of authority and responsibility, team structure, regulatory requirements, and intercommunication.
2.	Allocation of tasks and responsibilities is somewhat unclear Personnel on the bridge: Who is responsible for the bunkering operations; the Captain/Officer on watch or the Chief Engineer/Engineer on watch?	Captain: Has the overall responsibility for the bunkering operations and is the emergency manager (deputy in the role of Captain and emergency manager: Officer on watch) Chief Engineer/ Engineer on watch: Responsible for the execution of the bunkering operations, monitoring/controlling and team communication. See #ID 1, #ID 3
3.	Allocation of tasks and responsibilities unclear Personnel on the bridge and on the quay: - Who is responsible for the communication with trailer operator: The Tower operator or Engineer on watch? - Who is the main responsible for checking that the ESD is triggered, and manually activate the ESD if it is not triggered: The Tower operator or Engineer on watch? - Both Tower operator and Engineer on watch monitors the process on the OS.	Centralise main responsibility of team communication and monitoring of, and interactions with, the control system during bunkering to one role to avoid confusion. In the scenario analysis workshop, this responsibility was allocated to the Engineer on watch. A more in-depth risk assessment including evaluation of team structure, allocation of responsibility and workload is needed to conclude on whether two people are needed for monitoring and control (Tower operator and Engineer on watch) in addition to the Truck operator who monitors and controls the system from the truck side. Consider what their individual responsibilities related to this should be. See #ID 1

#ID	Learning points	Recommendations to barriers/Comments
4.	Observation tasks cannot be performed by the designated role by the bunkering station/bunkering tower onshore because of obstacles in the line of sight from the work location. Lacking a role that can observe a leakage from the hose connection at the ferry side	As a result of discovering this learning point during the workshop, the Seaman was relocated from the bunkering station onshore to the ferry deck, placed by the ferry storage tank, with a view towards the bunkering hose at the ferry side. A Tower operator was placed by the bunkering station. This might solve the discovering of this specific leakage, if the leakage can be observed (see #ID 23, #ID 26). A different or additional barrier is needed. See #ID 9, #ID 22, #ID 32, #ID 36
5.	The Officer on watch (Navigator) is the deputy for the Captain and emergency manager when the Captain is absent It could be a weakness for the situation if the Captain interferes in the middle of a situation. The Captain is expected to take responsibility, but does not have full situational awareness in such a situation.	Assess whether the Officer on watch should continue being in command on the ship in such a situation. Provide a checklist that includes the most relevant information to be used by the Officer on watch to brief the Captain. Consider the need to visualise the most important process parameters on a (common) overview display, using smart visualisation techniques. The techniques should allow the operator to attain key information at a glance, support early detection and initial diagnosing. According to NUREG-0700 (2002), an *"overview display should support the personnel in understanding of the immediate health of the plant during ongoing operations and response to plant upsets. It should also serve to orient people entering the control room, including during shift turnover. The overview display should indicate major changes in plant condition, such as the presence of alarm conditions."* (p.315)
6.	Ventilating to the mast is allocated to the Engineer on watch (in the scenario). The proceeding in normal situations is for the ferry to leave the quay before ventilation is carried out.	Consider whether ventilation should always be allocated to the Tower operator to avoid confusion about task responsibilities. See #ID 51
7.	The operators of the truck most likely do not understand the first language of the rest of the bunkering crew.	Agree on a standard language of communication (working language) between the bunkering crew, e.g., English.

#ID	Learning points	Recommendations to barriers/Comments
8.	Not all crew personnel are comfortable speaking a second language. The operators of the truck most likely do not understand the first language of the rest of the bunkering crew	A certain level of language skills required for crew communication should be required. Working language must be agreed upon and mastered by those involved (Direktoratet for samfunnssikkerhet og beredskap [DSB], 2018). Train on cooperation in normal operation and incident situations. All personnel involved in bunkering should be included in such training sessions (including Truck operator) *«Where procedures are used by staff for whom the procedure language is not their first language, appropriate language training should be available to the subject staff and their supervisors»* (International Atomic Energy Agency [IAEA] 1998, p.14).

5.5.2 Human-system interface

#ID	Learning points	Recommendations to barriers/Comments
9.	Uncertain whether the touch screen for interacting with the control system by the bunkering station is suitable: Will it be possible to see the information in strong and low light conditions (day/night)? Does it work in cold weather, with gloves on? Is it dirt tolerant?	Ensure that screens (and other equipment) meet the requirements. Consider the advantages and disadvantages of having an operator by the bunkering tower during the bunkering process. Is remote operation and monitoring at a safe distance indoors an option for the Tower operator during the bunkering? See #ID 22, #ID 32, #ID 36
10.	Alarm priority and presentation: Activation of ESD is signalled by blinking lights and sound which should be visible from the bunkering tower and ferry. It is uncertain whether different alarm situations result in distinguishable sounds/blinking.	An alarm system (consisting of both audible and visible alarms) with distinctive signals used for each type of emergency is preferred (Pacific Northwest National Laboratory, n.d.-c).

#ID	Learning points	Recommendations to barriers/Comments
		A distinct audible or visual indication should be used for each alarm priority. The HSI shall provide the ability to silence audible alarm indications (i.e., without acknowledging the alarm) (ANSI/ISA 18.2, 2016).
11.	Uncertain whether there is prioritisation of alarms, based on level of risk and how quickly the problem must be resolved.	Prioritisation of alarms should be based on the consequences of the alarm and the allowable response time. There are requirements for the distribution of alarms per priority based on what is manageable for an operator (ANSI/ISA 18.2, 20016; NUREG-0700, 2002). Ensure a proper alarm system, using standards such as ANSI/ISA 18.2 (2016).
12.	Lack of information from detectors when there is no vacuum on pipes / Lack of detectors informing when there is no vacuum on pipes (it is uncertain whether the solution exists or will be implemented)	Information is needed as to whether there is vacuum or not in vacuumized pipes for assessing the leakage. The information can improve situational awareness and should be include in the control system´s HSI.
13.	It is difficult to know which layer (barrier) of pipes where the leak is.	Information is needed on which layer (barrier) of pipe where the leak is.
14.	If the bunkering system has not been tuned on correctly prior to the start-up phase of a new installation, many alarms can be triggered. This may result in operators not perceiving a situation as serious as it might be.	Alarms that are irrelevant to the current operational mode, such as start-up, maintenance and testing should be suppressed. These are nuisance alarms and contributes to unnecessary workload on operators. Furthermore, important alarms can drown during alarm floods caused by such as irrelevant alarms. A list of suppressed alarms should be provided (ANSI/ISA 18.2, 20016; NUREG-0700, 2002).
15.	The crew communication should be in English. If the HSI information (information on displays) is in the native language (not English), this can lead to miscommunication (translation errors) and unnecessary cognitive load on the crew.	HSI information should be in the same language as the crew communication to avoid miscommunication and unnecessary cognitive load on the crew (simultaneous capacity). See #ID 8
16.	With a handheld radio and no headset, the bunkering crew´s hands are not free (one hand holding the radio). In this case, there is a risk of putting the radio down and leave it.	Ensure that the radio and headset (and other equipment) meet the requirements.

#ID	Learning points	Recommendations to barriers/Comments
	A double-sided headset for radio communication, there is a risk of not hearing important sound in the area, such as a leak	
17.	Unsure whether the valve controlling the H_2 flow from the truck is (physically) visible or not and if it is easy to see that it has been closed.	Information about the H_2 flow and valve status can improve the situational awareness and should be included in the control system´s HSI on the bridge. The information will provide a confirmation on whether the flow has stopped and if further actions to stop the flow is needed. Valve status could include closed valve, open valve, error condition, manual or auto mode. Information about the H_2 flow could include current flow and flow trends. See #ID 28
18.	The HMI has not been configured to display and detect pressure changes and nor to display pressure changes per segment. It is uncertain how long it will take for the systems to detect abnormal pressures and temperatures. Pressure can be difficult to use as information. It may appear that the pressure is stable, and one may think that the situation is safe, although there is still actually a leak.	Information needed: Temperature, pressure, pressure changes, pressure changes per segment. Assess whether information on reliability should be included in the HSI, if any of this information cannot be trusted in certain situations.
19.	Unsure about how to know when the ventilation process is finished. Do the valves automatically return to the closed position after a certain time or is there other criteria (to be able to see when the ventilation is finished)?	Information about when the ventilation is finished, and status of valves (related to ventilation) is needed in the HSI. See #ID 6, #ID 31, #ID 48, #ID 49
20.	Monitoring equipment might be broken because of the leak.	Consider having a procedure for loss of monitoring equipment. Train on situations that includes loss of monitoring equipment.
21.	The wind direction and wind force are decisive for where the crew is to be evacuated and how great the risk of local accumulation of hydrogen is.	Information about wind direction and wind force are needed for situational awareness and for deciding where to evacuate the crew. See #ID 47

5.5.3 Facility design

#ID	Learning points	Recommendations to barriers/Comments
22.	Observation tasks (visual inspections) cannot be performed by the Tower operator: - There are obstacles in the line of sight from the roles work location, the bunkering station, to observe a leakage from the hose connecting the tower and the ferry. No camera surveillance available from the bunkering station. - For the Tower operator to have an overview of the bunkering process, this role needs to monitor the control system and cannot leave the control panel to perform visual inspection during bunkering. - There is no camera surveillance of the tower.	According to DSB (2018), the operator must be able to stop the bunkering from the emergency stop switch on land at the bunkering point and in addition from at least one other emergency stop located at a safe distance from the bunkering point. The operator must therefore visually monitor the bunkering operation from a suitable place on the quay (DSB, 2018). Some suggestions to consider: - Allocate the task to a role that can perform a safe visual inspection - Arrange for remote operation and monitoring at a safe distance (indoors) for the Tower operator. See #ID 9, #ID 32, #ID 36. - Portable device for the Tower operator to interact with the control system – allowing more flexibility in where the operator can move around - Provide camera surveillance of the tower and bunkering facility (critical areas) for the Engineer on watch.
23.	Uncertain whether it is possible to observe leakages from the bunkering tower/hose on the ferry side, considering construction that obstructs the view and lighting conditions. Uncertain whether the lighting is appropriate for spotting an eventual leakage.	Make sure there is enough light and appropriate camera coverage of the area.

5.5.4 System design

#ID	Learning points	Recommendations to barriers/Comments
24.	It is uncertain whether the filling stops automatically. Overflow should in principle not be possible. However, overflow is possible if the ferry storage tank is not emptied to the lowest level before refilling. There are some barriers, as there is both a high (H) and high-high (HH) alarm.	Implement automatic stop of filling at a defined set-point. In LNG bunkering, an overflow control by implementing a high liquid level alarm giving an audible and visual warning when activated, and a sensor activating an automatic shut-off valve is required (Europan Maritime Safety Agency [EMSA], 2018). Information needs: Current level in storage tank, setpoints for high and high-high alarms and setpoint for desired level.
25.	There are no hydrogen sensors on top of the tower (where the leak is). Based on an assessment, it has been concluded that the wind makes it difficult to register a hydrogen leak with a sensor.	Consider using an encapsulated device with hydrogen sensor around strategic points.
26.	There are no technologies that can detect small hydrogen leaks at an early stage. This affects the time from leakage occurrence to detecting the leak, understanding the situation, and deciding on actions (if ESD is not triggered). If a (small) leakage does not trigger ESD, the situation depends on leakages being detected by personnel (Seaman or Tower operator), either visual or auditory. This is also depended on the operators´ alertness (See #ID 32). While the leakage is very small: will not be seen nor detected.	Technical solutions for detecting small leakages from such as hoses should be investigated. DNV (2021) suggests using acoustic leak detection to detect small leaks from high-pressure tanks. A small leak can escalate into a larger leak. Leaks should be detected as early as possible (DNV, 2021).
27.	It is difficult to understand which layer (barriers) of pipes that the leak is coming from.	Technical solutions for providing information about which layer of pipes that a leak is coming from should be investigated. The information is needed to be able to limit the consequences of a leakage.

#ID	Learning points	Recommendations to barriers/Comments
28.	If the ESD is not triggered when it should, it may be possible to stop the hydrogen supply valve from the OS at the bunkering station (by the Tower operator), but this is not certain. Other valves along the line cannot be closed through interacting with the OS, which means that there is a larger segment of the hydrogen supply (piping and hose) that can potentially leak.	Implement technical solutions for controlling (and seeing the status of) valves along the line in the OS´s HSI. The possibility to close valves along the line from the OS, when ESD is failing, can reduce the segment from which LH_2 can leak.
29.	The bunkering system and the information from the control system might be less reliable in the start-up phase than after a while in operation. A long period with debugging may result in operators lacking trust in the facility/system.	Carry out FAT, SAT, and tune the bunkering system and alarm system properly before start-up. This is important for operators´ trust in the facility/system. Furthermore, integrated system validations (ISV) throughout the design process and as a final check before start-up as described by ISO 11064-7 (2006) is recommended.
30.	It might be possible to ventilate too quickly, which may pose a risk. Hydrogen that normally goes straight up in the air (due to very low density), may behave differently when ventilated at near cryogenic temperatures. If subcooled hydrogen gas is released directly to the atmosphere, it may freeze the oxygen in the air and create frozen oxygen particles. When these oxygen particles heat up again it can be a cloud of gas with a very potent explosive mixture near the leakage point. It may be that it is to be ventilated at a fixed rate, but which can be adjusted to a slower rate if necessary.	A barrier is needed in the system that prevents too rapid ventilation. See #ID 31 If fixed ventilation rate: Visualise information about the fixed ventilation rate in the HSI. Controlled release of hydrogen to avoid freezing of oxygen in the atmosphere around the exit of the ventilation pipe.

#ID	Learning points	Recommendations to barriers/Comments
31.	During ventilation, pressure can be monitored. If the pressure increases, it may be necessary to increase the rate of ventilation to the mast. In situations with too much H_2 in the pipes, it may be unfortunate to increase the rate, but in other situations it may be desirable to increase the rate - how should the system handle the logic to ensure barriers?	Consider whether the option to override barriers when needed is required, and whether a decision support system is needed. Information needs: Current pressure during ventilation, rate of ventilation, amount of H_2 in the pipes, the influence of the ventilation rate on system health. Consider smart visualisation techniques to provide the operators an understanding of safe zones and consequences for the combination of pressure rate and amount of H_2.

5.5.5 Work environment/ Time of day

#ID	Learning points	Recommendations to barriers/Comments
32.	Observations of the facility/equipment is conducted outside during the 1-hour bunkering process at night-time, possibly in cold weather or rain. This can affect the alertness of all personnel involved in the bunkering process outdoors: The Tower operator, Truck operator and Seaman.	Arrange for CCTV and control system monitoring indoors: A small control room by the quay for both Tower operator and Truck operator. See #ID 3, ID# 9, ID# 22, ID# 36

5.5.6 Work environment

#ID	Learning points	Recommendations to barriers/Comments
33.	It can be difficult to hear a (small) leak if it is not quiet on the quay / in the area.	Ensure a proper coverage and quality of sensors and other technical means to detect leakages. Ensure a proper alarm system, using standards such as ANSI/ISA 18.2 (2016). See #ID 26

#ID	Learning points	Recommendations to barriers/Comments
34.	It could involve a risk if personnel hear a sound that sounds like a leak and go closer to confirm what the sound is.	Assess whether operators should be in the safety zone during bunkering. See #ID 3, ID# 9, ID# 22, #ID 32, #
35.	Possible distractions and factors that can affect the identification and interpretation of information: Unauthorised traffic (boats), colleagues who come for a chat, other (random) people, noise level in the area, rain, and snow.	A risk analysis should be carried out to assess whether there is a need for a physical demarcation of the safety zone.
36.	Both Seaman (on ferry deck), Tower operator and Truck operator are positioned in an area where they can be exposed to risk in case of large leakages or leakage escalation (burst/rupture, unplanned disconnection of hoses due to such as weather conditions or inadequate connection)	CCTV, detectors, and other possible technology for remote monitoring. A risk analysis should be carried out to assess whether a Seaman (on ferry deck), Tower operator and Truck operator actually need to be present in the safety zone during bunkering. ESD, valves etc can be operated and monitored through the control system. See #ID 3, ID# 9, ID# 22, #ID 32

5.5.7 Competence and training

#ID	Learning points	Recommendations to barriers/Comments
37.	A small leakage can be perceived as condensed water by personnel with little experience / personnel who have little experience with small leakages.	Develop appropriate training plans that includes training on situations with small leakages that has a potential of increasing to a large leakage. See #ID 39 Develop a procedure detailing the response to small leakages. See #ID 26
38.	A small leakage is not readily visible. There are many unknown factors related to small leakages and it is difficult to know when the situation is safe.	See #ID 37

#ID	Learning points	Recommendations to barriers/Comments
39.	Bunkering occurs infrequently and there are several shifts that take turns performing the bunkering tasks. Operators might be uncertain about the bunkering process. The training quality and frequency, and how confident the operators are about the process, can affect their actions.	Perform walk through/ talk through of the bunkering procedure prior to any bunkering. Develop appropriate training plans to ensure that employees have the necessary skills, both for handling normal and abnormal situations safely (Lovdata, 2009). Training plans should include training related to such as potential job hazards, the introduction of new or modified equipment or information and hydrogen safety procedures (Pacific Northwest National Laboratory, n.d.-b). Periodic retraining should be provided (Pacific Northwest National Laboratory, n.d.-b). *"The company must ensure that employees have the necessary skills and provide training so that all work tasks can be carried out in a safe manner both during normal operations and during abnormal situations and operating conditions. The training must also include routines and precautions in the event of accidents"* (Lovdata, 2009, §7). Research on performance related to training frequency is needed to understand what an appropriate training frequency is for personnel who are rarely involved in bunkering. See Chapter 5.3
40.	Overestimating/Underestimating the risk: A possibility that the personnel act according to an incorrect level of emergency response.	Train on different levels of emergency response situations. Develop and implement monitoring systems with relevant information (e.g., pressure, temperature, and flow trend plots) that are simple and intuitive to use. These monitoring systems should be designed so that the operator can quickly get an understanding of the severity of the situation (e.g., a momentarily change in pressure is normally less severe than a pressure build-up over time).

#ID	Learning points	Recommendations to barriers/Comments
41.	Uncertain what type of training the truck operator will have, only training on the truck system or also on the specific bunkering system? It is possible that there will be different truck operators for each bunkering.	Rigorous training on hydrogen properties and behaviour, for both the operators of fuelling equipment and emergency responders is needed (Pacific Northwest National Laboratory, n.d.-a).

5.5.8 Procedures

#ID	Learning points	Recommendations to barriers/Comments
42.	When the ESD is triggered, the flow from the truck should be stopped automatically. Information that the flow has stopped will be displayed on the screens of the OS. The Truck operators' task is to confirm that the flow has stopped. The emergency procedure does not say that the Engineer on watch should ask for confirmation from the trailer operator that the flow has stopped.	Consider whether it provides an additional barrier to include in the emergency procedure that the Engineer on watch requests confirmation from the Truck operator that the flow from the truck has stopped after ESD has been triggered. This is to ensure that the OS used by the Engineer on watch provides the right information or the same information as the OS used by the Truck operator. The OS or monitoring equipment on the bridge might be affected by the leakage (see #ID 20).
43.	In the event of a (small) leakage where the ESD is not triggered, the pressure and leakage will increase. The leakage will continue and possibly escalate.	Alternative actions: - Manual activation of ESD. - If manual activation of ESD does not work, stop the flow from the truck. The flow from the truck should be possible to stop from the OS used by the Truck operator and the OS used by the Tower operator and Engineer on watch. See #ID 28.

#ID	Learning points	Recommendations to barriers/Comments
44.	If the ESD fails to activate and operators must stop the hydrogen flow from the truck, the order of actions will affect the pressure and leakage. Closing the manifold on the LH_2-storage tank before equalising the pressure and closing the fill valve on the truck will increase the pressure and leakage.	Ensure that procedures specify the order of actions (manual actions directly on physical valves or actions through interacting with the control system). Assess whether a barrier should be implemented in the control system to ensure right order of closing valves, e.g., a visualisation of preferred order or providing the operators the possibility to override system settings if necessary. The order of closing of valves is not critical if the actions are performed quickly one after the other. Train the personnel in handling a situation where the ESD does not function. See #ID 28.
45.	There is a (small) possibility that all equipment is not shut down as it should after ESD has been triggered, e.g. the valve on the truck has not been closed.	Include verification step in the procedure: a manual verification that the facility/bunkering system is in the correct state. Verification steps *«should be used where appropriate in the procedures to ensure that equipment responses and operator actions have occurred and are correct".* (NUREG-0899, 1982, p.22)
46.	Procedures and emergency action plans are written in the native language. The truck operators most likely do not understand this language.	Procedures and emergency action plans should be written in the same language as the agreed working language. See #ID 8

#ID	Learning points	Recommendations to barriers/Comments
47.	There is no procedure for the Captain that describes which emergency response level should be chosen (evacuation or mustering of crew to a specific location or not) depending on wind strength and wind direction. Little/no wind increases the risk of local accumulation of hydrogen. In a situation with a leak, it is unfortunate if someone in the crew is in areas where there is a risk of being exposed to the leakage. There is no need to ask a sleeping personnel to muster to a specific place if it is safe to stay in the cabins. Some roles, such as the Tower operator and Truck operator, might have tasks that must/should be executed before they evacuate (see Chapter 5.2). The expected or perceived severity of the situation might influence the decision of when to evacuate.	Adapt procedure(s) to different emergency response levels and define entry conditions per procedure if different emergency levels are to follow different procedures. Entry conditions are the conditions under which the procedure should be used (NUREG-0899, 1998). See #ID 21
48.	Uncertainty about when the ventilation process has been completed. Do the valves automatically return to the closed position after a certain time or is there other criteria (to be able to see when the ventilation is finished)? The risk of not knowing when ventilation is finished can cause a dangerous situation for those that are to inspect the system after an incident.	The procedure for the ventilation process should include information about actions, what to monitor and check/verify, such as closing of valves. Criteria for when to consider the ventilation as finished should be included in the procedure. *"the objective of a sequence of actions should be conveyed to the operator so that he or she will know the purpose and end results of the sequence of actions".* (NUREG 0899, 1982, p.22) *Verification steps «should be used where appropriate in the procedures to ensure that equipment responses and operator actions have occurred and are correct.»* (ibid, p.22) See #ID 6, #ID 19, #ID 31, #ID 49
49.	Not sure what is sufficient information to be able to decide on whether to ventilate or not; what are the criteria for when ventilation can be started?	Define entry conditions for the ventilation procedure. Train on scenarios that involves ventilation. See #ID 6, #ID 19, #ID 31, #ID 48

#ID	Learning points	Recommendations to barriers/Comments
50.	Uncertain when or at what condition it is safe for the Tower operator to perform visual inspections after ESD has been activated after a small leakage incident, where the leakage develops and spreads. The timeframe might be 10 or 24 minutes after ESD. After a small leakage it is more uncertain when it is safe to perform a visual inspection after ESD (see Chapter 5.2).	A risk analysis should be carried out to assess when it is safe to perform visual inspections after ESD has been activated; should it be a specific timeframe, or should it be done according to a predefined procedure (based on calculations for different hydrogen release rates and ambient conditions)?
51.	Uncertainty concerning when or at what condition it is safe for the ferry to leave in case of a small leakage. The proceeding in normal situations is for the ferry to leave the quay before ventilation is carried out. Discussions related to when the ferry can leave the dock: Should the ferry leave before ventilating the tower to avoid the gas-cloud, is it safe for the ferry to leave before ventilating given the risk of explosion, what are the criteria for controlled ventilation while the ferry is docked, can the ferry leave before ventilating as they are a part of the emergency response team.	A procedure for handling (small) leakages needs a description of when the ferry can/should leave the dock. See #ID 6
52.	What are the criteria for defining whether it is a small or large leakage when deciding on e.g., what is the right emergency response level and when it is safe to conduct visual inspections.	Define entry conditions per procedure; the conditions under which the procedure should be used (NUREG-0899, 1998).
53.	Duty of notification to 110 (Fire and emergency services) is unclear in case of a large leakage, where the ESD has been activated.	Clarify when to notify 110.

5.5.9 Emergency response

#ID	Learning points	Recommendations to barriers/Comments
54.	The emergency response team consists of personnel from the ferry crew and personnel onshore at the quay. The Captain is the emergency manager while the ferry is at the dock. Who will oversee the emergency situation if the ferry leaves before the situation is under control (before ventilation)?	Assess and clarify the structure of the emergency response team.

5.5.10 Time available

#ID	Learning points	Recommendations to barriers/Comments
55.	The bunkering opportunity window may be small as it depends on the weather. The decision to start bunkering or not may be motivated by wanting to take advantage of the small window. Stress might be a risk in such a situation.	

6 Safety guideline – Human Factors

This Safety guideline includes recommendations on what to include or consider to ensure safe refuelling/bunkering of H2 and to support the human operators, i.e., the bunkering team, in succeeding. These recommendations are based on a use case study on a shore-based liquid hydrogen (LH2) bunkering facility for ships.

Human-centred approach

The human factors perspective and end-user involvement is needed both early in the design phase, and iteratively throughout the design process as more knowledge is gained. The greatest potential for improvements is in the early phases of an iterative design process before changes are too costly to implement.

End user involvement

Involve end user representatives in the system development and evaluation to bridge the gap between the requirements of the users, system solution providers, and other stakeholders.

Allocation of tasks and responsibilities

The allocation of tasks and responsibilites needs a thorough assessment. Topics of consideration includes such as: Lines of authority and responsibility, team structure, regulatory requirements, intercommunication, competence, training, job rotation, location of roles and workload. Avoid confusion about task responsibilities when different team compositions are active in different situations, such as normal operation vs. emergency.

Communication

Agree on a standard language of communication (working language).

Training

- Develop appropriate training plans to ensure that employees have the necessary skills, both for handling normal and abnormal situations safely. This includes training on situations with small leakages that has a potential of increasing to a large leakage.
- Training plans should include training related to such as potential job hazards, the introduction of new or modified equipment or information and hydrogen safety procedures.
- Train on cooperation in normal operation and incident situations. All personnel involved in bunkering should be included in such training sessions.
- Train on different levels of emergency response situations.
- Research on performance related to training frequency is needed to understand what an appropriate training frequency is for personnel who are rarely involved in bunkering, both in terms of normal operation and Defined Hazards and Accidents Situations (DSHA), to maintain knowledge and thus also safety.

Alarms

Ensure a proper alarm system, using standards such as ANSI/ISA 18.2 (2016), to avoid unnecessary workload, misunderstandings and unnoticed alarms caused by such as nuisance alarms.

Information

Develop and implement monitoring systems with relevant information (e.g., pressure, temperature, and flow trend plots) that are simple and intuitive to use. These monitoring systems should be designed so that the operator can quickly get an understanding of the severity of the situation (e.g., a momentarily change in pressure is normally less severe than a pressure build-up over time).

The right level of information, and the representation of the information in the HSI, will improve the situational awareness and response time to abnormal situations. Information recommended to be included in the control system´s HSI is extracted from the results of the scenario analysis and does not represent a full list of information that might be needed in the scenario of leakage during bunkering of H_2. The references to an #ID refer to a weak point that is described in Chapter 5.5. The information needed is as follows:

- Status on the vacuum (insulation) around the hydrogen supply pipes. and information about possible leakages in the vacuum (#ID 12).
- Status of valves (closed, open, error condition, manual or auto mode) (#ID 19, #ID 28)
- A visualisation of preferred (safe) order of closing valves (#ID 44)
- Wind direction and wind force (for situational awareness and for deciding where to evacuate the crew) (#ID 21, #ID 47).
- Information about which layer (barrier) of pipes where the leak is (#ID 13 and #ID 27).
- Storage tank: Current level in storage tank, setpoints for high and high-high alarms and setpoint for desired level (#ID 24, #ID 42).
- Temperature (#ID 18)
- Current H_2 flow and flow trends (#ID 17, #ID 40)
- Pressure, pressure changes (trends) and pressure changes per segment. Assess whether information on reliability should be included in the HSI, if any of this information cannot be trusted in certain situations. (#ID 18)
- Ventilation: When the ventilation can be concluded as finished and the status of valves related to ventilation (closed, open, error condition, manual or auto mode) (#ID 19)
- Ventilation: Current pressure during ventilation, rate of ventilation, amount of H_2 in the pipes, the influence of the ventilation rate on system health. If fixed ventilation rate: Visualise information about the fixed ventilation rate in the HSI. Consider smart visualisation techniques to provide the operators an understanding of safe zones and consequences for the combination of pressure rate and amount of H_2. (#ID 30, #ID 31)

Remote operation

Technology such as sensors, surveillance cameras, digital control system and automation allow for remote operation and removal of personnel from the immediate sources of risk. Taking advantage of these technologies should be considered.

System design

- Technical solutions for detecting small leakages from such as hoses should be investigated
- Implement automatic stop of filling at a defined set-point, and a high liquid level alarm giving an audible and visual warning when activated, and a sensor activating an automatic shut-off valve
- Technical solutions for providing information about which layer of pipes that a leak is coming from should be investigated.
- Implement technical solutions for controlling (and seeing the status of) valves along the line in the OS´s HSI

- Carry out FAT, SAT, and tune the bunkering system and alarm system properly before start-up. Furthermore, integrated system validations (ISV) throughout the design process and as a final check before start-up as described by ISO 11064-7 (2006) is recommended.
- A barrier is needed in the system that prevents too rapid ventilation

Procedures

- Procedures and emergency action plans should be written in the same language as the agreed working language
- Develop a procedure detailing the response to small leakages
- Adapt procedure(s) to different emergency response levels and define entry conditions per procedure if different emergency levels are to follow different procedures. Entry conditions are the conditions under which the procedure should be used.
- Ensure that procedures specify the order of actions (manual actions directly on physical valves or actions through interacting with the control system).
- Procedure when ESD is activated: Include verification step in the procedure: a manual verification that the facility/bunkering system is in the correct state.
- Procedure for the ventilation process: Should include information about actions, what to monitor and check/verify, such as closing of valves. Criteria for when to consider the ventilation as finished should be included in the procedure.
- Visual inspections after activation of ESD: Specify the safe condition for conducting visual inspections. A risk analysis should be carried out to assess when it is safe to perform visual inspections after ESD has been activated; should it be a specific timeframe, or should it be done according to a predefined procedure (based on calculations for different hydrogen release rates and ambient conditions)?
- Include in relevant procedure: Wen the ferry can/should leave the dock in normal situations and different emergency situations.

Emergency response

- Clarify the structure of the emergency response team. Topics of consideration includes who should be the emergency manager while the ferry is at the dock and is not at the dock.

Time available

- Consider such as stress and conditions for safe operation when planning or requiring limitations to bunkering duration.

7 Summary

This report has studied human factor issues and aspects related to the hydrogen refuelling and bunkering of liquid hydrogen (LH2) for a small-scale maritime application. This human-centred approach includes considering the human functions, role, tasks, teamwork, and information needed in the light of potential hazards. A real-world case study on filling and bunkering of LH_2 on-board a ferry soon to be placed in operation was used as a basis for the research. The research conducted in this study is part of the H2Maritime project (WP2).

The first research question in the H2Maritime project concerning scenarios involving hazards/risks related to bunkering where humans are involved was completed via a thorough literature survey. Based on this, 14 different scenarios were identified. One of these scenarios was then used as inspiration for the two scenario analyses performed and described in this report: (1) A small hydrogen leakage that develops and spreads, and (2) A sudden/acute large leakage. Both scenarios concern a leakage in a hose connection.

The scenario analysis was used as a method and instrument to discuss human functions, responsibilities, roles, tasks, and teamwork in relation to possible hazards during the refuelling and bunkering of a real-world use case. Information that should be included in the control system´s HSI is also described in this report. This information was extracted from the results of the scenario analysis and does not represent a full list of information that might be needed in the scenario of leakage during bunkering of LH_2 or during normal bunkering operations.

Several learning points related to safety in human operation of hydrogen bunkering were identified. These learning points are grouped into the following categories: (1) Teamwork, task allocation, and communication (2) Human-system interface, (3) Facility design, (4) System design, (5) Work environment/Time of day, (6) Work environment, (7) Competence and training, (8) Procedures, (9) Emergency response, and (10) Time available.

From these learning points, a Safety guideline was derived. The Safety guideline includes recommendations on what to include or consider to ensure safe refuelling/bunkering of H2 and to support the human operators in succeeding. These recommendations are based on a use case study on a shore-based liquid hydrogen (LH2) bunkering facility for ships.

The results from this study suggest that successful integration of a hydrogen bunkering system for maritime applications should include a human-centred approach, focusing on the human factors and how to support the human operators in succeeding. Furthermore, from this study, it can be concluded that involving end user representatives in the system development and evaluation is important to bridge the gap between the requirements of the users, system solution providers, and other stakeholder.

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