Risks and safeguards

Ship Based Carbon Capture Systems utilizing chemical absorption

Deliverable D5.2.3

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Executive summary

Various low-carbon technologies are being investigated, including ship-based carbon capture (SBCC), which could offer a viable alternative to zero-emission fuels, such as ammonia and hydrogen. The EverLoNG project aims to promote the adoption of SBCC by demonstrating its application on LNG-fuelled ships and bringing it closer to market readiness.

This report has been prepared to meet the EverLoNG project deliverable D5.2.3, which involves identifying common safeguards from the risk assessments. It also contributes to fulfilling D5.3, which entails summarising the learnings from Work Package 5 and disseminating the insights gained to relevant international regulatory bodies. The report builds upon previous deliverables and activities in WP5.

The main safety hazards associated with an SBCC installation pertain to loss of containment in the chemical systems used during the CO2 capturing process and the hazards linked to loss of containment in systems employed for processing, storing, and off-loading captured CO2.

Chemicals employed in the capture process may possess toxic, flammable, and corrosive properties that the crew could be exposed to during replenishing work, maintenance, or system leaks. CO2 is an asphyxiating gas processed under pressure and utilises storage systems with high potential energy, which could be released in a damaging scenario.

An SBCC system encounters threats that differ from those faced by a similar stationary system on land, and these must be assessed and addressed in the design of a vessel employing carbon capture systems.

The nature of shipping implies that damages to a CO2 storage system from ship collisions and groundings must be considered. Additionally, dynamic loads due to ship movements, green seas on deck, vibrations, humidity, and the presence of chlorides are typically not design considerations in stationary shore-based systems.

Due to the relatively limited space on board, commonly applied safety distances and segregation from hazards such as fires, cargo handling, and ship operations cannot be maintained. Furthermore, a ship at sea must manage emergencies with limited options for escape for the people onboard. These special circumstances necessitate appropriate preventive and mitigating safety barriers, which is why marine regulations sometimes have stricter requirements than those governing installations on land.

The report addresses preventive and mitigating safety barriers that should be considered to reduce the frequency and consequences of hazardous events related to SBCC installations. The evaluation is based on a comprehensive assessment of hazardous events identified through multiple HAZIDs conducted in the EverLoNG project, which must be mitigated to ensure the safety of the ship and its crew.

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1. Introduction

International shipping moves goods and products between nations. It has the lowest carbon footprint per tonne for long-range transport but still creates around 3% of global CO_2 emissions. The IMO is now working on implementing the GHG strategy to ensure shipping follows the indicative checkpoints, reducing total GHG emissions by 20%, striving for 30% in 2030 and then 70%, striving for 80% in 2040 compared to 2008, and reaching the revised ambition to 'reach net-zero GHG emissions by or around 2050'.[1]

1.1 The EverLoNG project

Various low-carbon technologies are being investigated, including ship-based carbon capture (SBCC), which may offer a solution alongside zero-emission fuels like ammonia and hydrogen.

The EverLoNG project seeks to promote the adoption of SBCC by demonstrating its application on board LNG-fuelled vessels and advancing it towards market readiness.

1.2 Scope of this document

This report has been prepared to fulfil the EverLoNG project deliverables D5.2.3, which involves identifying common safeguards from the risk assessments. It also contributes to fulfilling D5.3, which entails summarising the lessons learned from Work Package 5 and disseminating the insights gained to relevant international regulatory bodies.

Deliverable D5.2.3 builds on previous deliverables and activity in WP5:

Deliverable D5.1.1 Regulatory review and CO_2 hazards
Deliverable D5.2.1 Concept SBCC HAZID – LNG carrier
Deliverable D5.2.2 Concept SBCC HAZID – SSCV Sleipner

This report consists of four main sections as follows:

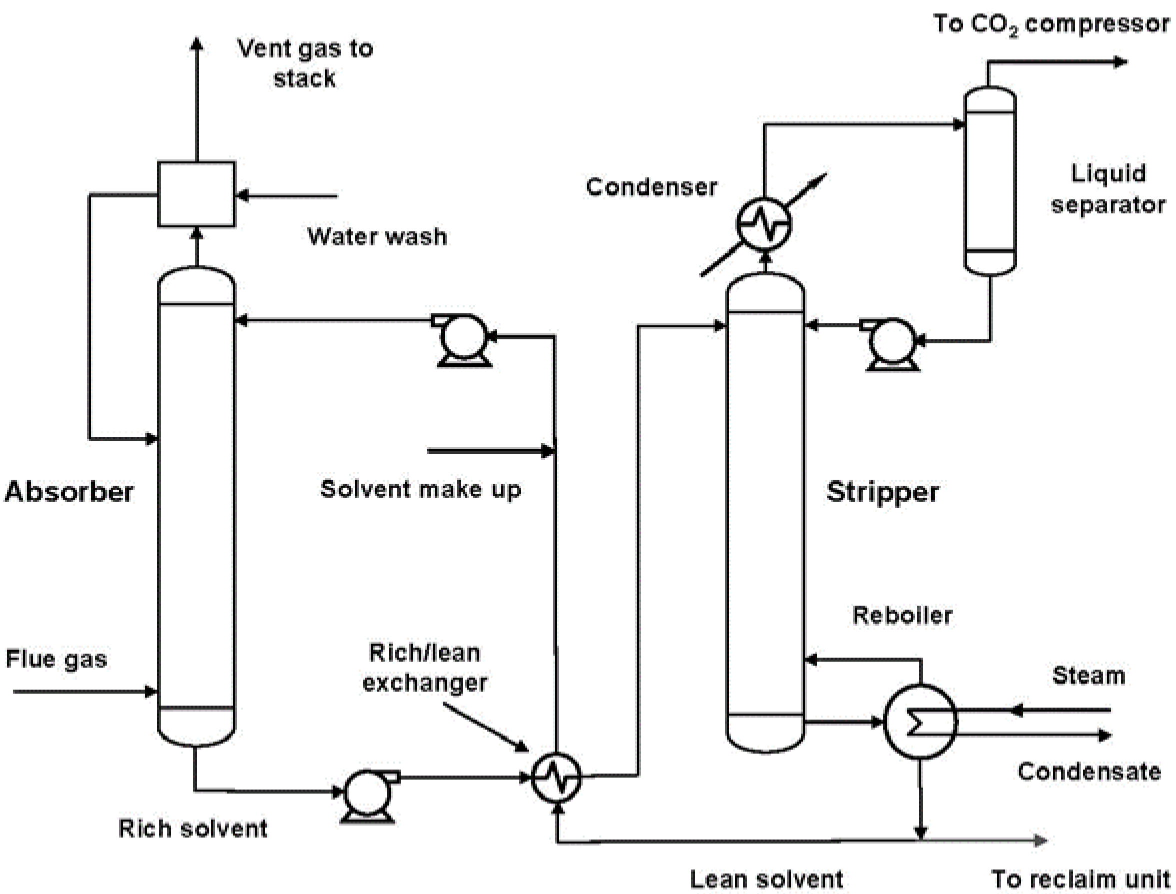
- Review of hazards related to SBCC installations
- Review of SBCC system threats
- HAZID findings
- Review of SBCC Risks and recommended safeguards

The risk assessment work undertaken in WP5 is based on the technology chosen for the EverLoNG project, which incorporates a post-combustion capture process that utilises amine-based chemical absorption to capture CO2 from the exhaust gases of engines (or other energy conversion technologies).

[1] Resolution MEPC.377(80): The 2023 IMO Strategy for the reduction of greenhouse gas emissions from ships.

1.3 The Shipboard Carbon Capture Process

The ship-based carbon capture process can be divided into four main steps: CO_2 capture, CO_2 liquefaction, onboard CO_2 storage and CO_2 offloading.



Principle of chemical absorption carbon capture process (Global CCS Institute, January 2012)

CO2 capture (chemical absorption): The CO2 capture process by absorption comprises three main sections: exhaust gas pre-treatment, CO2 recovery, and solvent regeneration. The exhaust gas undergoes pre-treatment in a direct contact cooler to reduce its temperature, adjust its pH, and eliminate impurities. These impurities can also be removed before this step. In the subsequent stage, the pre-treated exhaust gas enters the CO2 absorber column, where a solvent chemically captures the CO2 in the exhaust gas. The CO2-rich solvent from the absorber is heated by the lean solvent, which is returned to the absorber column in the lean-rich heat exchanger and then transported to a CO2 desorber column (stripper), where the CO2 is separated from the concentrated solvent. The lean solvent exiting the CO2 desorber is subsequently cooled in the lean-rich heat exchanger and redirected to the CO2 absorber. Finally, the CO2 from the desorber is purified and dispatched to the liquefaction unit.

CO2 liquefaction: The process consists of three main stages: CO2 compression, water removal, and CO2 liquefaction. First, the wet CO2 is compressed to the required liquefaction pressure, and water is removed through condensation to prevent hydration. After the compression stage, the remaining water content is extracted using a dryer. Finally, the CO2 is condensed, and non-condensable gases are removed. Several methods are available to condense the CO2, including the Joule-Thomson effect or liquefaction using a refrigerant or cryogenic fluid.

On-board CO2 storage: The captured and liquefied CO2 must be temporarily stored on board until it can be offloaded and moved further along the carbon capture and storage logistics chain. Suitable storage tanks are typically pressure vessels designed for a 7 to 20 bar pressure range. A higher storage pressure is more advantageous to minimise the energy required for liquefaction. The pressure and temperature within the storage tank are consistently maintained by reliquefying CO2 vapours or cooling liquid CO2.

CO2 offloading: The CO_2 will typically be offloaded through the ship's CO_2 offloading manifold to either a shore facility or another ship equipped to store and transport CO_2. Another option is to store the captured CO_2 in portable containers that can be lifted off the ship.

2. Hazards related to SBCC installations

The main safety hazards associated with an SBCC installation stem from the loss of containment in the systems used for the chemicals involved in the CO2 capturing process, as well as the risks linked to the loss of containment in systems utilised for processing, storing, and off-loading captured CO2.

Chemicals involved in the capture process can possess toxic, flammable, and corrosive properties, to which the crew may be exposed during replenishing work, maintenance, or system leaks. CO2 is an asphyxiating gas processed under pressure and utilises storage systems with high potential energy that can be released in a damage scenario.

2.1 CO_2 hazards

Asphyxiation

Asphyxiant gases displace and dilute oxygen in the air, leading to suffocation. Asphyxiants that do not have any other health effects are referred to as simple asphyxiants. Simple asphyxiants include methane, hydrogen, nitrogen, helium, and carbon dioxide. Significant leaks of carbon dioxide in enclosed spaces can pose a risk of asphyxiation due to oxygen depletion.

Most incidents of asphyxiation occur when entering confined spaces, with many injuries and fatalities reported each year from such accidents. A significant proportion of these fatalities involve rescuers attempting to assist the initial casualty. Therefore, it is crucial always to ensure that the air quality is acceptable before entering a space with potential CO2 leakages. It is important to note that even relatively small quantities of leaked liquefied CO2 will expand upon vaporisation and displace the oxygen within the space.

Carbon dioxide levels in normal room air are typically very low, around 0.04%. CO2 is colourless, odourless, and non-flammable, and being heavier than air, it tends to accumulate near the ground. These characteristics render enclosed environments prone to CO2 buildup, which can displace oxygen.

While low carbon dioxide concentrations have minimal toxicological effects, elevated levels can be quite dangerous. At high concentrations, it may lead to unconsciousness and respiratory arrest within minutes. Levels exceeding 10% can cause convulsions, coma, and even death.[2]. Levels above 30% can result in rapid loss of consciousness, explaining why individuals affected by accidental intoxication may not react promptly to resolve the situation.

The US National Institute for Occupational Safety and Health (NIOSH) defines the Immediately Dangerous to Life or Health (IDLH) concentration as the maximum exposure concentration for a given chemical in the workplace from which one could escape within 30 minutes without experiencing escape-impairing symptoms or suffering irreversible health effects. The IDLH level for CO_2 in air is set at 40,000 ppm (4.0% vol/vol).

[2] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5380556/ - Permentier K, Vercammen S, Soetaert S, Schellemans C. Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department. Int J Emerg Med. 2017 Dec;10(1):14. doi: 10.1186/s12245-017-0142-y. Epub 2017 Apr 4. PMID: 28378268; PMCID: PMC5380556.

Pressure effects

Carbon dioxide cannot be liquefied at atmospheric pressure and must be stored under pressure. Liquid carbon dioxide forms at pressures exceeding 5.1 bar. The temperature dictates the phase of CO2 above this pressure.

Liquid CO_2 is expected to be temporarily stored onboard in independent pressurised storage tanks. The storage tank pressures are anticipated to range between 7 barg (low pressure) and 20 barg (medium pressure). A pressure of 15-20 barg is more favourable for reducing the energy required for liquefaction. The storage tank pressure and temperature will be regulated by reliquefying CO2 vapours or cooling liquid CO2.

The most serious hazard associated with SBCC would be damage to a pressurised storage tank, leading to a boiling liquid expanding vapour explosion (BLEVE). The Centre for Chemical Process Safety defines a BLEVE as a sudden release of a large mass of pressurised superheated liquid into the atmosphere. This sudden release would occur due to significant damage to the tank's containment system.

Low temperature

Carbon dioxide stored in a liquid state at low or medium pressure will be at a temperature below 0°C. When depressurised (e.g., in the event of an accidental release), the expansion into the atmosphere will lower the fluid's temperature. Temperatures below -30°C could become harmful and detrimental to carbon steel structures.

2.2 Hazards related to process fluids

Chemicals used to capture CO2 from exhaust gas (such as monoethanolamine (MEA), methyl diethanolamine (MDEA), and piperazine (PIP)) are circulated under pressure in manned machinery spaces, and caustic soda is commonly employed in scrubbers as part of the exhaust gas cleaning process. Lastly, depending on the composition of exhaust gases and the capture process, additional chemicals beyond those previously mentioned (e.g., for acid wash) may be utilised. The toxicity, flammability, and corrosivity of chemicals used in the SBCC process should be assessed case-by-case and considered in the design. Exposure to such chemicals should be avoided whenever possible.

Additionally, auxiliary systems such as steam and thermal oil systems may pose hazards due to high temperatures. Furthermore, auxiliaries for cooling during the CO_2 refrigeration process may involve using hazardous refrigerants like ammonia or cooling with liquefied natural gas for LNG-fuelled ships. These systems are commonly used for other purposes on board, and their risk mitigation strategies are considered to be sufficiently covered by Classification Rules and International Codes.

Hazardous event	Hazard	Related system(s)	Hazard Category
Loss of containment			
Amine	Flammability Toxicity Corrosivity Pollution	Capture system (rich and lean amine loop)	Safety, Environmental

Hazardous event	Hazard	Related system(s)	Hazard Category
Caustic soda	Chemical	Capture system (caustic soda storage and distribution)	Safety, Environmental
Thermal oil	Flammability High temperature Pollution	Capture system, Liquefaction system (if TO used for heating)	Safety, Environmental
Water	High temperature Pollution	Capture system, Liquefaction system (water drum, cooling water, water removal in compression)	Safety, Environmental
LNG	Flammability Cryogenic	Liquefaction system (if used to liquefy CO_2)	Safety
Operational hazards			
	Malfunction, poor operation	Capture, Liquefaction, Storage and Offloading systems	Safety
	Unburnt fuel, SOx, NOx "slip"	Capture system	Environmental
	Overpressure	Capture system (pumps), Liquefaction system (compression, drying, liquefaction)	Safety
	Cross-contamination	Capture system, Liquefaction system (heat exchangers)	Safety
	Noise, vibration	Liquefaction system (compressors)	Safety, Health
	Moving parts	Liquefaction system (compressors)	Safety
	Sloshing	Storage	Safety
	Lifting	Storage (if portable or containerised)	Safety

2.3 Exhaust systems

From a design perspective, it would be beneficial to interconnect the exhaust systems for M/Es and G/Es upstream of the CO2 capture plant, thereby establishing a single connection to the SBCC system. However, a common exhaust system for all engines raises the risk of a single failure, jeopardising the power generation plant. Many dual-fuel engines incorporate bursting discs as explosion pressure relief devices within the exhaust system. In these instances, the exhaust system must be configured so that the activation of one open burst disc does not lead to an unacceptable loss of power.

3. SBCC system threats

This chapter evaluates the causes that may lead to hazardous events. An SBCC system encounters threats that differ from those faced by a similar stationary system on land, and these must be assessed and addressed in the design of a ship that utilises carbon capture systems.

The nature of shipping necessitates that damages to a CO2 storage system resulting from ship collisions and groundings be taken into account. Furthermore, dynamic loads caused by ship movements, green seas on deck, vibrations, humidity, the presence of chlorides, and similar factors are typically not design considerations in stationary shore-based systems.

Due to the relatively limited space on board, commonly applied safety distances and segregation from hazards such as fires, cargo handling, and ship operations cannot be maintained. Furthermore, a ship at sea must manage emergencies with limited options for escape for the people onboard. These special circumstances necessitate appropriate preventive and mitigating safety barriers, which is why marine regulations sometimes have stricter requirements than those governing installations on land.

3.1 Mechanical damage leading to CO_2 release

Substantial damage to the CO2 containment system could lead to a BLEVE, with the release of all the CO_2 stored onboard. Consequently, it is of the utmost importance that storage and distribution systems for CO_2 are sufficiently protected against external events that have the potential to damage them.

Collisions and groundings - The extent of damage to a ship involved in a collision depends on factors such as speed, displacement, draft, bow shape, and the angle of impact of the colliding vessel. Similar factors also determine grounding damages. High-speed light crafts and vessels engaged in coastal trade are presumably more vulnerable to grounding damage. CO2 tank placement and system arrangement must consider the potential for collision and grounding.

Fire - A CO2 system exposed to an external fire will heat up, causing the opening of safety valves and subsequent CO2 release. The fire may also damage the safety systems required to control the CO2 system, along with the tank and system insulation, and potentially the tank itself. Therefore, it is essential to identify high fire-risk areas onboard and ensure that storage tanks and systems possess adequate passive and active fire protection to mitigate the risk of fire damage from external events. Typical high fire-risk areas include the cargo area of tankers and container ships, cargo decks on Ro-Ro and Ro-Pax vessels, cargo holds on bulk carriers, and engine rooms.

Explosions - Ship explosions can severely damage CO2 storage tanks. It is essential to evaluate potential areas of explosion risk in relation to the location of storage tanks to minimise the impact on the CO2 system and prevent further escalation. Events to consider include oil and chemical carrier cargo tank explosions, dust explosions, boiler explosions, etc.

Cargo operations - Cargo operations can pose a significant threat to CO2 installations, potentially damaging CO2 storage tanks or the piping system (e.g., falling loads on the decks of OSVs, dry cargo ships, and container ships, as well as moving cargo on Ro-Ro vessels).

Ship operations - The energy in breaking mooring lines may be sufficient to damage CO_2 fuel tanks and systems. Broken mooring lines during CO_2 offloading could lead to a drift-off situation, with damage to the CO_2 system and a resulting spill of liquefied CO_2. With lifting above CO_2 storage tanks or systems, crane operations on the ship could cause damage in falling load scenarios.

Environmental conditions - Adverse weather conditions may harm CO2 storage tanks and systems—such as green seas on deck, loose objects on deck, or inadequate securing of items below deck. Equipment not designed for the marine environment might have a shorter lifespan than anticipated. Over time, exposure to sunlight, sea spray, ice, and snow could diminish the durability of tanks and exposed equipment.

The marine environment will subject the components of a SBCC installation to dynamic loads, vibrations, seawater, and the presence of chlorides.

3.2 Accidental leakages of CO_2 and process chemicals from tanks and systems

Component leakages - System leaks may occur within a system or result from an emergency release into the surroundings. Hazards can develop when CO2 accumulates in areas lacking adequate natural or mechanical ventilation to dilute the CO2 to non-harmful levels. Depending on the properties of the chemicals involved in the carbon capture process, hazardous events may pertain to flammability, toxicity, extreme temperatures, and corrosivity.

System leaks generally originate from valves, flanges, diaphragms, gaskets, seals, fittings, and hose connections. Leaks are usually caused by deformed seals or gaskets, valve misalignment, or failures of flanges or equipment.

If the safety valves installed to limit the tank pressure fail or develop a leak, CO2 will be released at the vent mast outlet.

Pressure ruptures - Liquefied CO2 will gradually warm to the ambient temperature, and if it is confined (for example, in a pipe between two valves), the pressure will rise. If the pressure from the trapped volume of warming CO2 exceeds the design pressure of the containment, failures may occur.

Brittle fractures - System components may fail due to materials being used below their transition temperatures or being cooled down by accidental events.

Corrosion failures - Pure CO2 is non-corrosive; however, when it interacts with free water, it forms carbonic acid, which can be highly corrosive to carbon steels. If impurities are present in the CO2 stream, they may significantly increase the corrosion rate by generating additional acids, such as sulfuric and nitric, and modifying the solubility characteristics of water. To address corrosion challenges, stainless steel is a commonly used material in CO2 systems. The most prevalent form of corrosion exhibited by stainless steel is pitting, occurring when the surrounding conditions overpower the passive film. Stainless steel is also susceptible to crevice corrosion, which arises from deposits that create crevices on metal surfaces. External stress corrosion cracking in stainless steel manifests as cracks in areas with high tensile stresses, typically at welds, and is linked to saltwater retained on the material surface.

Fatigue - Components that undergo frequent load cycles can experience local fatigue failures. Due to dynamic loads and vibrations, this risk is typically higher on ships compared to shore-based installations. Systems for liquefied CO2 encounter load cycles associated with heating and cooling, whereas high-pressure compressed CO2 systems are often subjected to loading and unloading due to pressure differences.

Maintenance - Mechanical damage to the fuel containment system during maintenance could result in leaks later. CO2 leaks may occur when the system is opened for maintenance if the serviced part is not properly isolated from the rest of the system. Poor workmanship during maintenance or repairs, including the use of unsuitable replacement parts, could lead to system failures. Likewise, inadequate or lack of maintenance can cause system failures.

Offloading - CO2 leakages during offloading operations pose a significant safety concern, exacerbated by the fact that such operations can occur near populated areas. Leakages may result from relative movements between the offloading vessel and the reception facility, a faulty CO2 transfer hose, manifold leakages, etc.

3.3 Operational and emergency events resulting in CO_2 releases

An unavoidable consequence of storing cold liquefied gas in a closed volume is the necessity for pressure relief devices to prevent tank overpressure by discharging the tank contents to open air via a vent system. CO2 stored at the boiling point will continually transition from liquid to gas due to heat influx into the storage system. This boil-off gas (BOG) will elevate the tank pressure. Unless the tank can accommodate a pressure build-up by maintaining the BOG at equilibrium or is equipped with systems to manage the BOG safely, the safety valves will ultimately open to relieve the pressure.

4. Findings from HAZID Workshops

The EverLoNG project has installed a demonstrator onboard the LNG Carrier "Seapeak Arwa" and the Heerema Marine Contractor's Semi-Submersible Crane Vessel "SSCV Sleipnir". The demonstrator's operational risks were assessed during a Hazard and Operability (HAZOP) workshop. A full-scale concept design employing the same technology and working principles has also been subjected to risk evaluation through two separate HAZID workshops (Work tasks 5.2.1 and 5.2.2) This chapter presents an overview of the findings from these sessions.

4.1 Implementation of full-scale SBCC on LNG Carrier

The Bureau Veritas Solutions Marine & Offshore (BVS M&O) risk team facilitated a two-day Hazard Identification (HAZID) workshop on November 18 and 19, 2024, to assess the implementation of SBCC on a Minerva Gas LNG Carrier.

Therefore, the objective of this HAZID workshop was to derive design recommendations for the SBCC integration and operation onboard the LNG carrier, identify any showstoppers, and serve as the basis for identifying applicable rules/regulations. The scope of the HAZID workshop was limited to the SBCC system, its interfaces and potential interactions with other systems onboard the LNG Carrier and separated into three (3) different nodes:

- CO_2 Capture Process area
- Liquefaction area
- LCO_2 tanks & offloading

Many details will likely be missing since the design is still at the concept stage.

Findings

Among the risk-ranked scenarios identified during the HAZID workshop, 12 out of 117 (10.2%) scenarios were classified as High Risk, while a total of 38 out of 117 (32.5%) were categorised as Medium Risk, and 67 out of 117 (57.3%) were designated as Low Risk. Many of the high-risk scenarios were ranked as "High" due to the limited information available at this concept stage. In a more detailed design phase, these issues would be addressed by implementing sound shipbuilding and operational practices and applying class rules. Conducting a HAZID at the basic design stage is recommended, as it is easier to modify the safety concept at that point, before carrying out a second risk assessment during the detailed design stage to confirm the adequacy of the system(s).

The high-risk scenarios and the points of high vigilance for the more detailed phase of the design identified were:

CO_2 Capture Process area

- **Loss of containment** due to the activation or failure of a burst disc on one engine exhaust, releasing exhaust gas from all other engines in the Engine Room (E/R) since all exhaust lines are interconnected. This poses potential risks of personnel asphyxiation, injuries, and loss of propulsion and power generation at sea.

- **Operational hazards** during the maintenance of the CO_2 capture system or regular chemical bunkering could lead to potential safety issues for personnel.
- **Accessibility challenges** to equipment or columns within the engine casing, potentially causing safety risks to personnel.
- **Hazardous and toxic areas/spaces created by the CO_2 capture system** could interact with existing hazardous areas and lead to potential personnel injuries.
- **Emergency situations** in the engine casing could result in personnel being trapped and pose safety concerns.

Liquefaction area

- **Operational hazards** during the maintenance of the liquefaction module could lead to potential safety issues for personnel.
- **Accessibility challenges** to equipment or columns in liquefaction- or NH3-space, potentially causing safety risks to personnel.
- **Hazardous and toxic areas/spaces created by the CO_2 Liquefaction module** (including NH3 space used for refrigeration), which could interact with other existing hazardous areas and lead to potential personnel injuries due to the toxicity aspect of NH3 and CO_2.
- **Lifting/handling** equipment in the liquefaction space could pose potential safety risks to personnel.

LCO_2 tanks & offloading

- **Operational hazards** due to the location of LCO_2 tanks, resulting in winching area impairment caused by obstructions at the sides, delays in medical evacuation, and incompatibility with several LNG terminals (e.g., insufficient free space in front of the manifold for ship-to-shore gangway access), and a significant impact on LNGC trading.

4.2 Implementation of full-scale SBCC on Hereema's crane-vessel Sleipnir

The Lloyd's Register (LR) Advisory Services B.V.'s Hazard, Risk & Reliability (HRR) team facilitated a 2-day HAZID workshop on the 31st of January and 1st of February 2024 regarding the full-scale concept design of a Ship-Based Carbon Capture (SBCC) system onboard the SSCV Sleipnir (IMO 9781425).

It should be noted that the design was at a concept stage. Consequently, design details were invariably missing. Therefore, the objective of this HAZID workshop was to derive design recommendations for the installation onboard the SSCV Sleipnir and, where possible, generalise these for applications onboard other vessels.

The HAZID workshop was limited to the SBCC system, its interfaces, and potential interactions with other systems onboard, which were considered to pose a risk. Although criminal intent and terrorist activities were out of scope for this HAZID and considered the prerogative of the Port State, the minimum safe actions the crew could safely take to limit consequences were discussed.

Findings

A total of 33 risk rankings were deferred, all related to well-understood design aspects. While CO_2 behaves differently from substances like LNG vapours, the same dispersion analysis methods can be utilised to enhance the design and ensure that reasonably foreseeable venting scenarios do not pose a risk of injury or death to personnel.

Similarly, ammonia-based refrigeration systems are now commonly used in the marine and offshore industries.

Ideally, the control and monitoring systems of any SBCC system should operate as autonomously as possible, both for safety reasons and crew number considerations. For CO_2 offloading, we can expect similar protocols to those used in LNG bunkering, including pre-transfer discussions, coupling methods, testing arrangements, and the establishment of safety zones.

It is reasonable to assume that the unacceptable risk of CO_2 storage tank bursts due to collisions or allisions can be reduced through careful design using existing methods and concepts. Specifically, it may be possible to achieve a level of protection similar to that provided for LNG fuel tanks, along with a deck that is adequately strengthened to guard against reasonably foreseeable dropped objects.

Overall, the risks identified in the HAZID workshop are well understood by all parties involved, and there is sufficient scope to mitigate them to a level that is as low as reasonably practicable.

5. SBCC Safety Risks and possible prevention and mitigation strategies

This chapter discusses preventive and mitigating safety barriers that should be considered to reduce the frequency and impact of hazardous events associated with SBCC installations. The evaluation is based on a thorough assessment of hazardous events identified through multiple HAZIDs conducted during the EverLoNG project, which may pose significant risks to the ship and its crew.

5.1 Damage to CO_2 containment and piping systems by external events

From a risk perspective, the consequence of damaging the CO_2 storage system could be catastrophic, and the ship design and arrangement should make the likelihood of such an event as low as possible.

Figure 0-1 illustrates tank and system damage as the top event in a high-level bow tie, where potential threats are listed on the left side and possible consequences on the right side. Preventive safety barriers should be in focus (on the left side of the bowtie) because it will be technically challenging to mitigate the consequences of a tank rupture reliably.

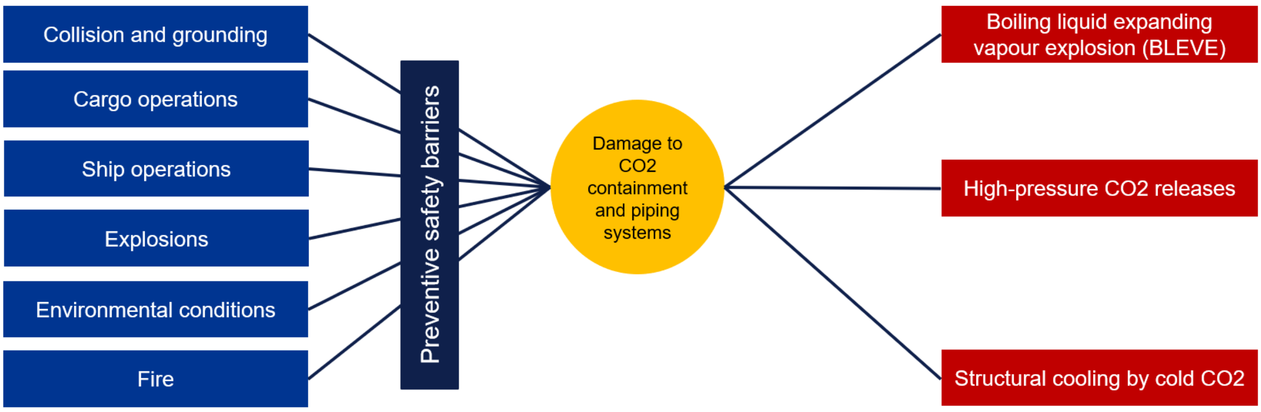


Figure 0-1 - Mechanical damage threats may lead to loss of containment and corresponding consequences for stored carbon dioxide in liquefied and compressed form (High-level bow tie illustration).

Safety barriers aimed at minimising the probability of mechanical damage to CO_2 containment systems should address the following:

- CO_2 tanks and piping systems should be kept away from areas likely affected by collision and grounding damage.
- CO_2 tanks and piping systems should be kept away from areas where loading and offloading pose a damage risk or be provided with some form of mechanical protection strong enough to withstand worst-case damage from the cargo operation.

- CO_2 tanks and piping systems should be kept away from areas where ship operations pose a damage risk or be provided with mechanical protection strong enough to withstand worst-case damage from ship operations.
- CO_2 tanks should be kept away from areas on the ship with a high fire risk.
- CO_2 tanks and piping systems should be suitable for the marine environment with dynamic loads, vibrations, sea spray and sun radiation and protected against mechanical damage from green seas, snow, and ice loads.

5.2 CO2 releases on the open deck

The consequences of releasing CO2 on an open deck depend on the specific circumstances. A storage tank venting substantial amounts of CO2 in a completely unrestricted open-air environment is a relatively minor event from a safety risk perspective. However, a major release of liquefied CO2 could pose a greater risk of asphyxiation, particularly if the open deck configuration limits natural ventilation.

Figure 0-2 illustrates carbon dioxide releases on an open deck as the top event in a high-level bow tie, where potential threats are listed on the left side and possible consequences on the right side.

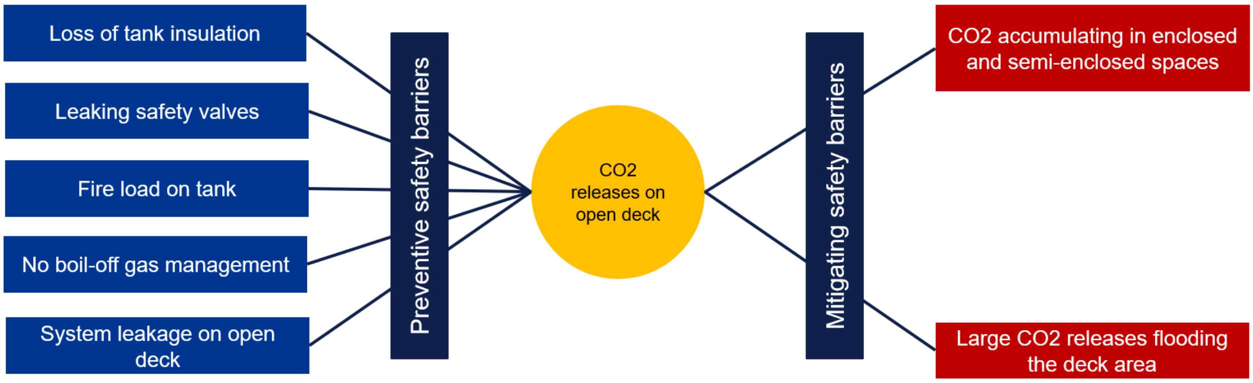


Figure 0-2 Releases from liquefied or compressed fuel containment systems on an open deck with corresponding threats and consequences (High-level bow tie illustration).

Safety barriers aimed at minimising the probability and consequences of CO_2 releases on the open deck should consider the following:

Preventive measures

- The CO_2 containment system should be designed to minimise operational discharges by preventing CO_2 from heating up too quickly through effective tank insulation and providing the means to manage the boil-off gas in normal operation.
- CO_2 piping systems should be designed and arranged to minimise the probability of leakages. This implies using materials suitable for the system's design temperature, arranged and supported to ensure that operational conditions do not cause undue stresses, are connected by welding as far as possible and avoid using leak-prone components like bellows and flexible hoses as far as possible, and set requirements for manufacture, workmanship, and testing.

Mitigating measures

- The CO_2 containment system and the system providing pressure relief should be arranged to ensure that any CO_2 discharged accidentally or through normal operation is routed to open air at the safest possible location onboard.
- The CO_2 containment system, pressure relief system, and deck layout should be arranged to prevent discharged CO_2 from accumulating in confined and congested areas or being drawn into the accommodation or machinery spaces via ventilation system inlets at unacceptably high concentrations.
- Any leaks from tanks and piping systems should be detectable and automatically isolated from the source of the CO_2 supply.

5.3 CO_2 releases in a confined space

CO2 discharges in confined spaces can result in the displacement of breathable air and a risk of asphyxiation. On a ship, high-risk areas generally include locations for processing captured CO2 and tank hold spaces.

The leakage of liquefied CO2 can also result in significant cooling effects, subjecting materials to temperatures below the ductile-to-brittle transition temperature. This could damage load-bearing structures, compromise the gas-tightness of safety barriers, and impact the integrity and function of safety equipment. The evaporation of liquefied CO2 can rapidly displace a breathable atmosphere. Evaporated CO2 will expand and potentially cause a pressure increase in enclosed spaces.

Figure 0-3 illustrates carbon dioxide releases in enclosed spaces as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side.

Figure 0-3 Liquefied or compressed CO2 released in enclosed spaces can have serious safety implications (High-level bow tie illustration).

The consequences of CO_2 releases in enclosed spaces can be severe and should be avoided. Consequently, safety barriers should be designed to prevent carbon dioxide release and avoid asphyxiating atmospheres from forming if leaks do occur. Safety barriers and systems that may be exposed to low temperatures from leakages should be designed accordingly.

Safety barriers aimed at minimising the probability and consequences of CO_2 releases in confined spaces should consider the following:

Preventive measures

- CO_2 piping systems routed through enclosed spaces to be protected within a secondary enclosure that can contain any leakage.
- CO_2 piping systems should be designed and arranged to minimise the probability of leakages. This implies using materials suitable for the system's design temperature, arranged and supported to ensure that operational conditions do not cause undue stresses, are connected by welding as far as possible and avoid using leak-prone components like bellows and flexible hoses as far as possible, and set requirements for manufacture, workmanship, and testing.

Mitigating measures

- Any leaks from tanks and piping systems should be detectable and automatically isolated from the source of the CO_2 supply.
- Segregation valves could be arranged to limit the amount of CO_2 being discharged after a leakage is detected and stopped.
- CO_2 systems should be designed to minimise the consequences of leakage by limiting the inventory of CO_2 in the system to what is necessary for operation. Introducing flow restrictions and excess flow devices could also be useful in this respect.
- Spaces containing CO2 processing equipment and storage tanks should be designed with ventilation systems capable of diluting CO2 leaks and directing them to a safe discharge into the open air. A pressure differential between spaces should also be maintained to ensure that any atmospheric changes move from a non-hazardous to a hazardous space. Furthermore, ventilation ducts may act as pressure relief mechanisms in the event of liquefied CO2 releases in enclosed spaces.
- Spaces containing CO_2 process equipment and storage tanks should be alarmed to warn against accessing an oxygen-depleted space. In enclosed spaces, the location of gas detectors and the geometrical shape of spaces where gas leaks may occur need to account for the density of the leaking gas.

5.4 CO_2 releases during offloading

Leakages related to the offloading operation can release significant quantities of liquefied CO2 near the offloading station. This scenario might result in structural damage due to low temperatures and pose an asphyxiation risk to personnel and third parties in the surrounding area.

Figure 0-4 illustrates leakages during offloading as the top event in a high-level bow tie, where potential threats are listed on the left side and potential consequences on the right side.

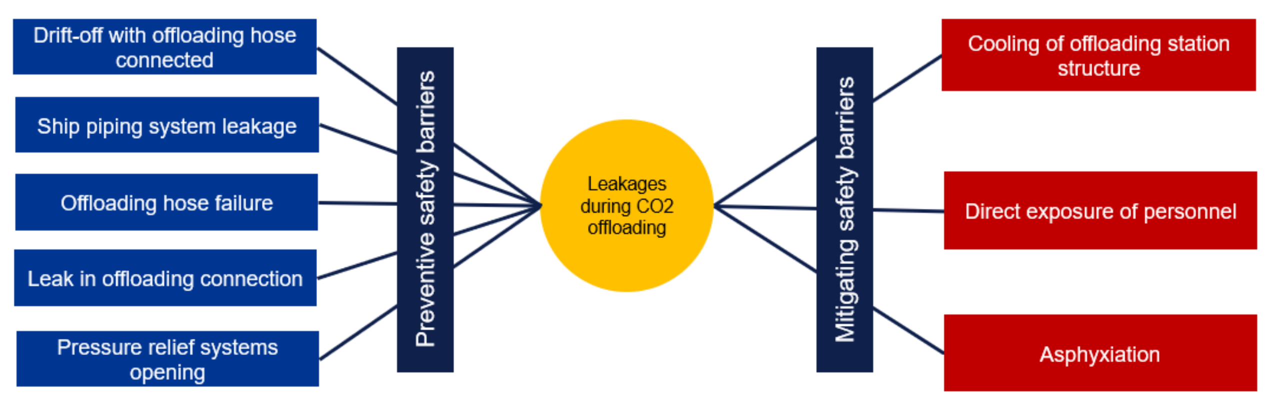


Figure 0-4 Leakages during offloading (High-level bow tie illustration).

The consequences of CO_2 releases in a semi-enclosed offloading station are severe and should be avoided when crew is present. Consequently, safety barriers should be designed to prevent the release of carbon dioxide and to avoid the formation of carbon dioxide as much as possible. Safety barriers and systems that may be exposed to low temperatures from leakages should be designed accordingly.

Safety barriers aimed at minimising the probability and consequences of CO_2 releases in relation to offloading should address the following:

Preventive measures

- Piping systems used for offloading CO_2 should be designed to minimise the probability of leakages, contain leakages if they occur, and avoid cold surfaces.
- The construction and support of the offloading manifold should be strong enough to prevent damage to the offloading system in a drift-off, where the offloading hose is the only point connecting the ship to the bunkering facility.

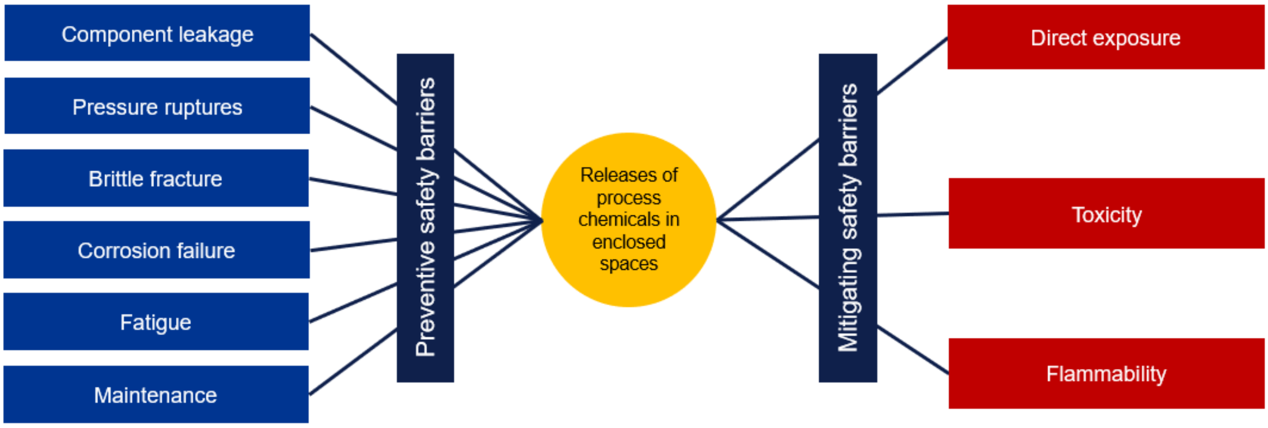
Mitigating measures

- The ship's CO_2 offloading station should be arranged to reduce the consequences of a release event as far as possible. This implies preferably locating the offloading station on the open deck. If an open deck arrangement is not possible, the offloading system should be arranged to minimise the need for manned operations and possibly be fitted with additional forced ventilation to dilute minor leakages.
- The CO_2 offloading station should be arranged to withstand the consequences of cold leakages from the offloading arrangements.
- Personnel involved in offloading operations should be outfitted with appropriate personal protective equipment.
- The offloading hose should be arranged to separate the ship and the bunkering facility without releasing CO_2 or overloading the ship or reception facility manifolds.
- The offloading system should be arranged with means to detect leakage and systems to stop the offloading process automatically.

- The offloading system should have a shut-down valve in the offloading station to facilitate the emergency closing of the CO_2 discharge.
- An emergency shut-down communication system should be arranged between the ship and the reception facility.

5.5 Exposure to hazardous chemicals

The toxicity, flammability, and corrosivity of the chemicals used in the SBCC process should be assessed case-by-case; however, exposure to such chemicals should be avoided whenever possible. Furthermore, the temperature of the fluids utilised in the capture process may pose a risk of harm upon direct exposure.



Safety barriers aimed at minimising the probability and consequences of system releases and exposure of personnel should address the following:

Preventive measures

- Piping systems should be designed and arranged to minimise the probability of leakages. This implies using materials that will not be deteriorated by the fluid (e.g. resistant to corrosion, compatible with the chemical), are suitable for the system's design temperature, are arranged and supported to ensure that operational conditions do not cause undue stresses and are connected by welding as far as possible. Where welding is not possible, joining methods are chosen to minimise the probability of leakage.

Mitigating measures

- Piping systems should be designed to ensure that operational releases from purging, gas freeing and pressure relief are managed safely. This is also applicable for emergency releases due to system leaks and loss of vacuum insulation on tanks and systems.

- Any leaks from tanks and piping systems should be detectable, and it should be possible to isolate the leak point from large reservoirs of the hazardous fluid in question.
- The chemical containment and piping systems should be arranged to contain and drain any leakage.
- Ignition sources should be controlled, leak sources should be adequately shielded, and suitable passive and active fire safety measures should be arranged if the process fluid constitutes a fire risk.
- Spaces containing chemical storage tanks should be arranged with ventilation systems able to dilute chemical leakages and transfer them to a safe discharge in the open air.
- Suitable PPE, operating and maintenance procedures and training should be available to relevant personnel. Eyewash and safety showers should be provided at the appropriate location(s).

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