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Transportation of CO_2 by ship

Transport de CO_2 par bateau

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Foreword

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This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In a carbon dioxide capture and storage (CCS) value chain, the main means for transportation of CO_2 from an emitter to storage are by ships or by pipelines. Transportation of gas in liquid state is well established in the shipping industry and has been done for decades. However, liquid CO_2 is different from other gases carried by ships and poses new challenges for both ship design and ship operation. Compatibility along the value chain is an essential element in the development of CCS. It is important to have a common understanding of how different aspects, such as cargo temperature and pressure, can influence the ship design and ship operation.

The purpose of this document is to support consistency and compatibility in the design of CCS value chains and address important areas where future development and standardization can add value. This document will discuss CO_2 ship types, ship logistics and interface-specific aspects related to the safe and reliable design and operation of CO_2 ships.

Transportation of liquified gas on ships is governed by the regulations, codes and conventions drawn up under the International Maritime Organization (IMO) which is referred to under United Nations Convention on the Laws of the Sea (UNCLOS). Ships carrying CO_2 are regulated by the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), which serves as the main technical regulation for CO_2 carriers under the International Convention for the Safety of Life at Sea (SOLAS).

Ship transportation of CO_2 is currently limited to commercial trade for small-scale use in industries such as the food or beverage industries and is served by a handful of small ships. However, the evolving industry around CCS will demand transportation volumes of a different magnitude and involve development of new ship designs and ship logistics concepts. These are introducing a need for knowledge-sharing related to type of transportation concepts, CCS value chain compatibility, technical and operational reliability and the safety of CO_2 carriers.

Quantification, verification and reporting along the different elements in the CCS value chain will become important. This document describes limitations and challenges to them and how they can be done onboard the ship.

In this document, CO_2 means a captured CO_2 stream, including potential impurities following the capture process, if not otherwise explicitly referred to as pure CO_2.

Transportation of CO_2 by ship

1 Scope

This document provides insights into the essential aspects of CO_2 shipping and provides basic descriptions of how the CO_2 carrier and technology therein is technically integrated with the CCS value chain. It also includes a description of specific challenges of transporting CO_2 as cargo, how this differs from other gases transported by ships today, and how this influences the ship design and operation. Finally, this document introduces how CO_2 ships are regulated within the existing international maritime regulatory framework. This document's main focus is on the technical aspects of CO_2 shipping. Commercial, liability and financial aspects are intentionally kept out of this document. However, general reference to commercial impact is made where relevant.

This document focuses on the ship transportation of CO_2 between loading and offloading facilities where the system boundaries are at the ship manifold equipment that connects the ship to the other components in the value chain. In the document, the basis for the description of ship operation is transportation between two shore-based terminals. A high-level description of other relevant interfaces is given on a conceptual level as this has impact on the ship design. However, any further description of potential solutions upstream and downstream from the CO_2 carrier is outside the scope. This document also gives a high-level description of the physical properties of CO_2 streams at the conditions relevant for shipping and how relevant impurities can impact the ship and ship operation.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
barge
floating unit carrying freight on canals, rivers and in ports, either under its own power or towed by another

3.2
cargo containment system
arrangement for containment of the cargo including, where fitted, a primary and secondary barrier, associated insulation and any intervening spaces, and adjacent structure, if necessary, for the support of these elements

Note 1 to entry: See Reference [9].

3.3
convention
written agreement between countries

Note 1 to entry: Conventions form a major part of maritime affairs governed by the International Maritime Organization (IMO).

3.4
CO_2 carrier
cargo ship or barge constructed or adapted and used for the carriage of CO_2 as cargo

3.5
CO_2 stream
stream consisting overwhelmingly of carbon dioxide

[SOURCE: ISO 27917: 2017, 3.2.10]

3.6
dynamic positioning system
equipment and system that is used for keeping a vessel at a given position using the thruster and propulsion of the vessel to compensate for the environmental loads, including waves, wind, current, etc.

3.7
export location
location where the ship loads the CO_2 for transport to the import location

3.8
flag state
jurisdiction under whose laws the ship is registered

3.9
heat ingress
transfer of heat from the surroundings into the cargo

3.10
heel
liquid cargo maintained at the bottom of the tank on the return voyage to maintain cargo tank temperature

3.11
import location
location where the ship offloads the CO_2 that is transported from the export location

3.12
inland waterway
natural or artificial navigable inland body of water, or system of interconnected bodies of water, used for transport, such as lakes, rivers or canals

3.13
intermediate storage
storage of CO_2 volumes before being loaded to a ship and storage after being offloaded from the ship

3.14
multi-lobe
bi-lobe
tri-lobe
cargo tanks which consist of two (bi-lobe) or three (tri-lobe) lobes where lobes represent cylinder segments partly merged and connected by a common bulkhead

3.15
muster area
location where the crew assemble in the event of an emergency

3.16
riser
flexible pipe that connects an offshore well to a ship or floating offshore unit

3.17
ship master
person in charge of the ship, its crew and any passengers or cargo it is carrying, on the water and in port

3.18
territorial seas
areas which extend up to 12 nautical miles from the baseline of a country's coastal line

3.19
triple point
temperature and pressure at which three phases (gas, liquid and solid) of a substance coexist in thermodynamic equilibrium

3.20
two-phase flow
simultaneous flow of gas and liquid

3.21
vapour return
connection between ship and terminal for vapour exchange to ensure pressure equilibrium between the shore storage tanks and the ship cargo tanks

3.22
vapour-liquid equilibrium
state where a substance's liquid and vapour phases are in equilibrium

4 Abbreviations

CO_2	carbon dioxide
CCS	carbon dioxide capture and storage
ESD	emergency shut down
FSIU	floating storage and injection unit
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
LNG	liquified natural gas
LPG	liquefied petroleum gas
NIST	National Institute of Standards and Technology
OCIMF	Oil Companies International Maritime Forum
SIGTTO	Society of International Gas Tanker and Terminal Operators
SOLAS	International Convention for the Safety of Life at Sea
UNCLOS	United Nations Convention on the Law of the Sea
IACS	International Association of Classification Societies
ES-TRIN	European Standard — Technical Requirements for Inland Navigation vessels

5 Regulatory regime for maritime and inland waterways for CO_2 transportation

5.1 General

International and national shipping are subject to an extensive and stringent set of laws and regulations which are enforced by international, regional and national regulatory bodies. Considering the large number of stakeholders and the significant environmental and economic impact the maritime industry has on the society, regulations are developed to enable cooperation between stakeholders and to promote and improve safety, security, efficiency and to prevent marine and atmospheric pollution by ships.

Marine transportation of liquefied gases, including CO_2 in bulk by dedicated gas carriers, is well regulated with proven and high safety standards developed by IMO and other governmental and industry organizations. Considering the increased focus on CCS, it is however expected that laws and regulations for maritime transportation of CO_2 will be further developed.

General description of the maritime governance scheme is explained in 5.2. It is followed by a description of the main regulatory regime for CO_2 carriers.

5.2 Maritime governance

International shipping involves vessels which operate across the oceans as well as territorial seas and exclusive economic zones. Other vessels are limited to coastal and inland waterways transport within territorial waters covered by the jurisdictions of a single state or multiple states. Maritime shipping is a mature industry with well-established international governance institutions; however, the regulatory scheme can be different depending on the area and type of operation. A generic overview of the maritime governance scheme and stakeholders involved in maritime shipping is shown in Figure 1.

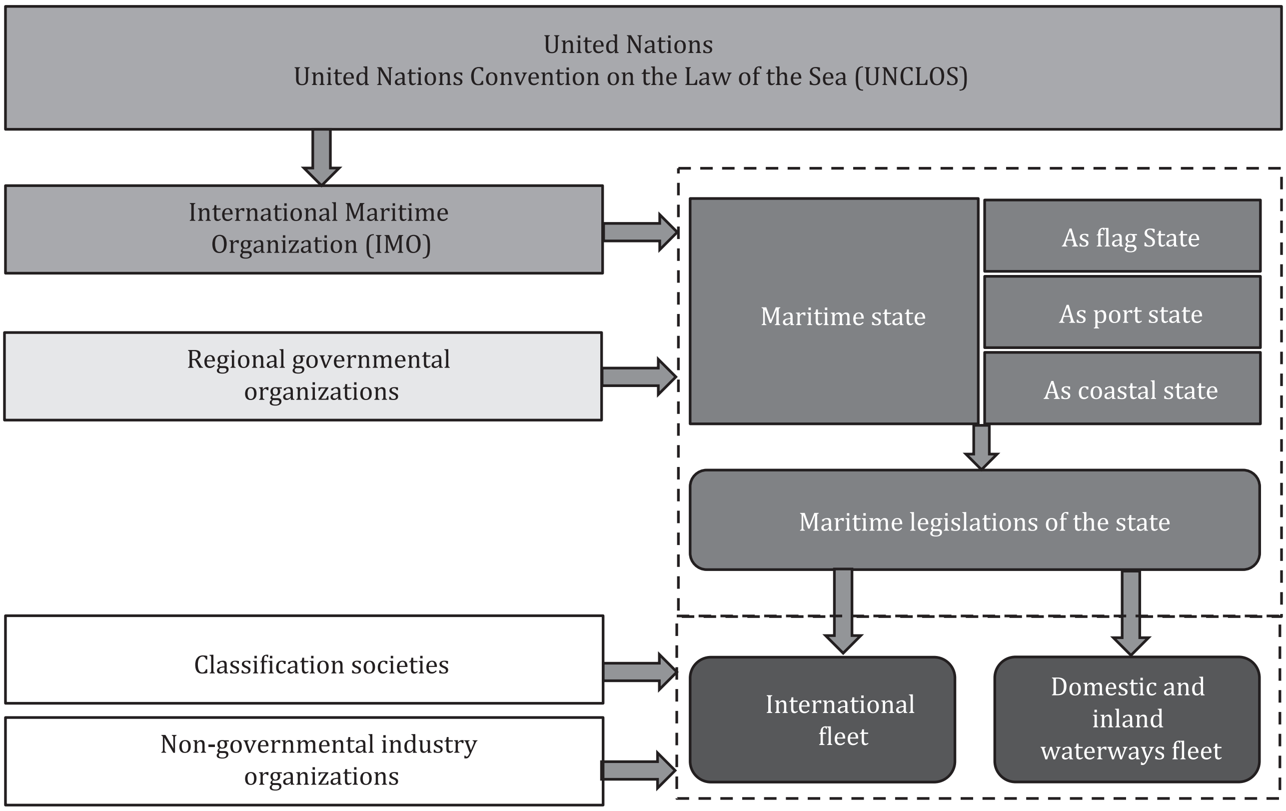


Figure 1 — Governance and stakeholders in maritime shipping

The governance of the ocean emerges from the United Nations. UNCLOS lays down a comprehensive regime of law and order in the world's oceans and seas by, *inter alia*, defining the maritime geographical jurisdiction, including the coastal states' sovereignty over their respective maritime zones.

IMO is a specialized agency under the United Nations that develops conventions containing detailed regulations to safety, security and environment, with the intention of establishing a global minimum standard for the shipping industry. Under IMO, more than 60 conventions, codes and regulations have been developed which serve the basis for the implementation in the legislations of the individual member states.

Regional governmental organizations can develop additional regulations which apply for specific geographical areas or member states. The European Union (EU) is an example of a regional governmental organization which through its regulations and directives aim at ensuring common standards among the EU member states.

The regulations developed by IMO or any other governmental organization are upon ratification implemented into the national laws of the ratifying states. The flag states enforce the regulations for ships registered under their flag. Port states exercise port state control on ships visiting their ports based on domestic laws, to ensure the ship's condition and equipment are in compliance with the provisions of international conventions and that the ship is safely manned and operated pursuant to applicable international law. Flag and port states can introduce additional regional or domestic regulations which apply within their jurisdiction.

Within the convention framework set by IMO and the regulations set by flag states, the classification societies play an important role as independent governance actors. The major classification societies form the International Association of Classification Societies (IACS), which works together with the industry and maritime regulators to ensure that the legislative framework is supported and enhanced by the practical implementation of classification rules. IACS has an observer role in IMO which allows them to provide support and advise to the IMO process. The classification societies develop and maintain technical rules and standards for the construction and operation of ships, and carry out classification, certification and verification services, as well as surveys to ensure compliance with the standards. The classification is the basis for the registration with the flag state and is required by IMO for international voyages. The classification standards are generally internationally recognized and in compliance with international maritime regulations.

The classification societies can, on behalf of a flag state administration, undertake statutory certification to the extent the society has been authorized to do so by the individual flag state administration. Statutory certification includes among others approval, surveys, and the issuance of statutory certificates.

Other non-governmental organizations such as International Chamber of Shipping (ICS), International Association of Independent Tanker Owners (INTERTANKO), Oil Companies International Maritime Forum (OCIMF), Society of International Gas Tanker and Terminal Operators (SIGTTO), are also important stakeholders in maritime shipping. These are industry organizations with the aim of sharing experiences, addressing common problems and establishing a framework of standards, guidelines, and best practices for the industry. Publications from these organizations often become industry standards and are important for ensuring standardization particularly regarding operational compatibility and safety. Several of these organizations have consultative status in IMO.

Considering the sovereignty of the territorial seas and internal waters as laid down in UNCLOS, the coastal states are not bound by the framework issued by IMO and other organizations when forming the legislative framework for ships operating within the territory of the state, unless the instruments are ratified by the individual states. Hence, the regulatory framework which is basis for the national legislations can differ from that of international shipping. Many states do however use the international legislative framework as a basis for their national frameworks, potentially with modifications and adjustments as found relevant depending on the type of ship and trade, the operational area, etc. regional (e.g. bi-lateral or multi-lateral) requirements and agreements can apply to specific operational areas within the territories of two or more states. One example is the regulations applicable for the inland waterways system in Europe, which is described in more detail in 5.3.

5.3 Technical safety regime for maritime transportation of liquid CO_2

The carriage of liquid CO_2 onboard ships for international trade is governed pursuant to the IMO framework and by the provisions in the SOLAS, and is further detailed in mandatory codes, depending on the mode of transport. The regulations distinguish between the carriage of the product in packaged form, e.g. as modular tank containers on cargo ships, and the carriage of the product in bulk on dedicated gas carriers as explained in more detail in the following. Carriage of product in package form is regulated by the International Maritime Dangerous Goods Code (IMDG) while the carriage of product in bulk on dedicated gas carriers is regulated by the IGC Code.

The IGC Code is the governing international technical standard prescribing the design and construction requirements of ships carrying liquid gases, including CO_2 in bulk. The IGC Code requirements are targeted to address the particular hazards related to different liquefied gases, including flammability, toxicity, asphyxiation, etc., including a set of specific requirements for the carriage of CO_2.

Classification societies normally have specific class notations which cover design and construction requirements for gas carriers. These requirements are normally based on the IGC Code, but are often more detailed on the specific requirements to ensure practical implementation of the requirements given in the Code and that the overall safety targets are met. Industry organizations such as SIGTTO have developed a series of best practices, guidelines and standards targeting liquified gas carriers and terminals. Although these are focusing on commonly transported products such as LNG and LPG, many of these can also be applicable for CO_2 transportation.

As explained in 5.2, an individual state is not bound to the international standards and codes described above for trades within the territory of the state, e.g. for inland waterways. Russia, Brazil, China, India, EU members, and many other countries have well developed inland waterway systems which can be an attractive alternative for CO_2 transportation. It is expected that a regulatory framework will be developed for the individual areas when and where this mode of transport becomes relevant, including cross border agreements. Some countries have existing regulations for transport of dangerous goods on inland waterways which can be relevant. It is, however, expected that IGC Code and other international standards will be used as supplementary references for establishing the regulatory framework for domestic and cross-border CO_2 trades on inland waterways.

Vessels used for goods transport on inland waterways within the European Union are regulated by the EU Directive 2016/1629 Technical Requirements for Inland Waterway Vessels, which is the mechanism for incorporating technical standards (e.g. ES-TRIN) into EU law. Within this framework the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways contains the provisions for the carriage of dangerous goods in packages and in bulk. Other countries, regions and territories can have other applicable regulations.

5.4 Greenhouse gas emissions

Ships today use fossil fuels for propulsion, with few exceptions, and in that sense ship transportation of CO_2 will have a CO_2 footprint depending mainly on the type of fuel and the ship size. IMO has an ambition to reduce the total emissions from the world fleet and in carbon intensity (CO_2 emitted per cargo-carrying capacity and nautical mile) by 2050. To meet the defined targets regulations are gradually being enforced.

Emissions from a ship's machinery during operation are reported through schemes defined by both IMO and EU (for vessels calling at European ports).

5.5 Trading and cross-border transportation

For cross-border transportation of CO_2 where the CO_2 is transported for the purpose of offshore storage, the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and its 1996 London Protocol are important. The London Convention is one of the first international conventions protecting the marine environment from human activities. Its objective is to promote the effective control of all sources of marine dumping and take all practicable steps to prevent pollution of the sea by the dumping of waste and other matter. The contracting parties (countries party to the London Protocol) eventually recognized the need for a more precautionary and preventative approach and undertook a full review of the Convention. This review resulted in the 1996 London Protocol.

The London Protocol is a stand-alone agreement that supersedes the London Convention for the states that are party to both instruments. This means that the London Protocol will prevail if there is a conflict between the two instruments. The Protocol is more restrictive and adopts a general ban on all dumping activities, with the exception of the wastes and other matter listed in Annex 1 of the London Protocol. The dumping of wastes and other matter listed as an exception in the London Protocol Annex 1 requires a prior permit issued in line with the London Protocol Annex 2 requirements. In 2006, the contracting parties to the London Protocol adopted an amendment to Annex 1, adding CO_2 to the list of exceptions, thereby creating a legal basis in international environmental law to regulate CO_2 storage in sub-seabed geological formations. This was necessary as storage falls within the definition of dumping.

Article 6 of the London Protocol prohibits the export of wastes and other matter across borders for dumping at sea. This presented a barrier for cross-border CCS operations as it prohibits the export of CO_2 for storage in other countries where the intended storage site is offshore. In order to overcome this barrier, Article 6 was amended in 2009 to allow for export of CO_2 for offshore storage by adding a second paragraph exempting CO_2 from the general ban. The new Article 6.2 sets out criteria for the export to occur, including the need for an agreement or arrangement between the states involved identifying and allocating permitting responsibilities. The amendment is not yet in force at the time of writing as an amendment requires two-thirds of the contracting parties to have formally accepted it. After ten years with little progress of reaching the required number, the contracting parties agreed to an interim solution of provisional application in 2019. This entails that the contracting parties can provisionally apply the 2009 amendment and export CO_2 across borders provided that the parties have deposited a declaration of provisional application to the IMO (who acts as the Secretariat for the London Convention and the Protocol).

While the London Protocol has implications for cross-border transportation and offshore storage for its contracting parties, it can also impact non-contracting parties that wish to engage in such CCS operations. This is the case where a contracting party seeks to export CO_2 by pipeline or ship for offshore storage in a non-contracting party. In this scenario, the contracting party has a duty to ensure that the non-contracting party has a regulatory framework in place that is the same as, or provides better protection of the marine environment than, the provisions contained in the Protocol. This is to ensure that the contracting parties do not evade their obligations under the Protocol, and that the CO_2 is always stored according to the Protocol's requirements in a safe and long-term manner. The Protocol can therefore indirectly apply to non-contracting parties in these instances.

6 Ship transport of CO_2

6.1 General

The main option for transporting CO_2 by ships is in liquid state. CO_2 is different from other liquefied gases transported by ships as it cannot be liquid at atmospheric pressure regardless of temperature. CO_2 therefore needs to be pressurized to above the triple point pressure to exist in liquid form. The combination of temperature and pressure required to maintain the CO_2 in its liquid phase, as well as the high density, set high requirements for the tank design, tank supporting structure and tank material terms of the strength and low temperature properties.

The CO_2 is conditioned to a liquid at the specified pressure and temperature before it can be transported on a ship. This involves compressing, cooling and condensing the CO_2 as well as removing any impurities to an acceptable level.

6.2 CO_2 cargo transport conditions

6.2.1 General

For liquid CO_2 cargoes there are three different pressure and temperature regimes that are often referred to: low pressure/low temperature, medium pressure/medium temperature and elevated/high pressure/ambient temperature. There is no clear definition of the boundaries between these three categories, however, a designation in a CO_2 transport context is proposed in Table 1. There is nothing preventing transporting CO_2 between the below proposed pressure and temperature ranges.

Table 1 — Pressure and temperature regimes for liquid CO_2 cargo tank designs[a]

Cargo designation	Cargo vapour pressure (operation) bara[1)])	Equilibrium temperature[a] °C	Density of liquid CO_2[a] kg/m^3	Density of vapour CO_2[a] kg/m^3
Low pressure	5,7 to 10	−54,3 to −40,1	1 170 to 1 117	15 to 26
Medium pressure	14 to 19	−30,5 to −21,2	1 078 to 1 037	36 to 50
Elevated pressure[b]	40 and above	+5,3 and above	894 and lower	116 and higher

[a] Applies for pure CO_2 and properties taken from National Institute of Standards of Technology (NIST) database. Properties will depend on the other components in the CO_2 stream.

[b] Also referred to as high pressure.

Several factors through the CO_2 transport chain influence the choice of pressure and temperature of the CO_2 from capture to storage. For shipping the chosen condition of the CO_2 has a direct influence on the cargo tank size and cargo system, tank material grades, insulation and boil-off management and hence the investment cost and operation cost of the ships. The different pressure and temperature also result in different requirements to liquefaction upstream of ship transport and handling downstream of ship transport and hence the cost for the connecting elements of the value chain.

An alternative to transporting CO_2 in liquid state is to transport it as solid which can allow the use of container ships or bulk carriers. See 6.2.5.

6.2.2 Low pressure

Low pressure is the cargo condition where the liquid cargo is transported close above the triple point but with enough margin to avoid dry ice formation. The driver for transporting at low pressure is that it allows for larger tank diameter and hence a large tank volume, hence lower mass of metal per amount of CO_2. The density of CO_2 is also higher at this condition compared to medium or elevated pressure. A direct consequence of low pressure is that the temperature of the cargo is lower compared to cargo conditions with higher pressures.

A key challenge with a low-pressure cargo condition is the risk of dry ice formation in the cargo tank or cargo handling system in case of a pressure reduction below the triple point pressure. The risk of dry ice formation is also influenced by the impurities of the CO_2.

6.2.3 Medium pressure

Medium pressure is the cargo condition used for the small CO_2 carriers currently in operation for the food and beverage industry. With medium pressure the margin to the triple point is large and there is limited risk for dry ice formation during cargo operation.

Compared to low pressure transportation, a higher cargo pressure allows for higher design temperature for the tank material; however, the maximum tank diameter and the cargo volume of each cargo tank is limited.

6.2.4 Elevated pressure

At near ambient temperature (assumed here as above 5 °C) the CO_2 needs to be above approximately 40 bara to be in liquid state. With this pressure the diameter of a pressure cargo tank is smaller than for medium and low pressure, however the requirements to the cargo tank material properties becomes less challenging due to the higher temperature.

The heat ingress into an elevated pressure tank system will be less than for medium and low-pressure systems, which can simplify the insulation requirement and cargo boil off management.

1) 1 bar = 0,1 MPa = 10^5 Pa; 1 MPa = 1 N/mm^2.

6.2.5 Density effects

The density for liquid CO_2 increases with decreasing temperature, which increases the mass of liquid CO_2 that can be transported with the same tank volume. A space above the liquid level in the tank is occupied by CO_2-vapour and allows the liquid CO_2 to expand due to heat ingress.

To avoid large changes in temperature and pressure in the tanks on the return voyage, the pressure in the cargo tanks is usually similar on the return voyage as on the loaded voyage. The pressure and temperature are maintained by a small amount of liquid heel and a large volume of vapour (see 7). As the density of vapour increases with pressure, the mass of this returned CO_2 is lowest for low pressure CO_2. The returned vapour will eventually be re-liquefied at the export location.

When calculating the mass balance for liquid and gaseous CO_2 volumes on the loaded and return voyage, the net mass for CO_2 transported in the same tank volume is higher for low pressure compared with medium pressure. Correspondingly, the net mass of CO_2 transported in a medium pressure system is higher than for an elevated pressure system for the same cargo volume.

6.2.6 Solid state CO_2 (dry ice)

CO_2 can also be transported in bulk in solid form, i.e. as dry ice. Dry ice will keep its state at atmospheric pressure when the ambient temperature is lower than −78 °C. CO_2 in solid form can in principle then be transported onboard other ship types such as bulk carriers or container vessels designed for the low temperature. The sublimated CO_2 gas can be managed as boil off gas.

6.3 Cargo tank design

6.3.1 Cargo tank design considerations

The IGC Code defines different tank types which can be used for storage and transportation of liquefied gases in bulk. Figure 2 shows the most common tank categories for tanks for liquefied gases as given by the IGC Code. Independent tanks are self-supporting tanks which do not form part of the ship's hull. Tanks are further categorised into Types A, B and C based on shape, documentation approach and safety philosophy (see Figure 2). Internal pressure limitation for Type A and B are relevant only for tank of prismatic shape. For cylindrical or spherical shape higher internal pressures than 0,7 barg can be accepted. Membrane tanks are non-self-supporting tanks with a gas and liquid tight membrane supported through insulation by the adjacent hull structure.

As CO_2 needs to be kept above minimum 5.2 bara pressure to exist as liquid, the only available containment system covered by the IGC Code is independent type C tanks. Type C tanks are a special type of pressure vessels. These can either be of conventional cylindrical form or with multi-lobes (e.g. bi-lobe or tri-lobe).

Novel containment systems other than type C can be relevant for liquid CO_2. This can be non-cylindrical pressure vessel or pressure vessel designed to alternative design codes than the IGC Code. Concepts not directly covered by tank types defined by the IGC Code need to go through a qualification process to ensure that the safety targets of the IGC Code are met.

The tank types, sizes and configurations offer different possibilities and limitations when it comes to utilizing the ship cargo space. The high density of CO_2 can yield different ship design constraints than for other liquefied gas transportation.

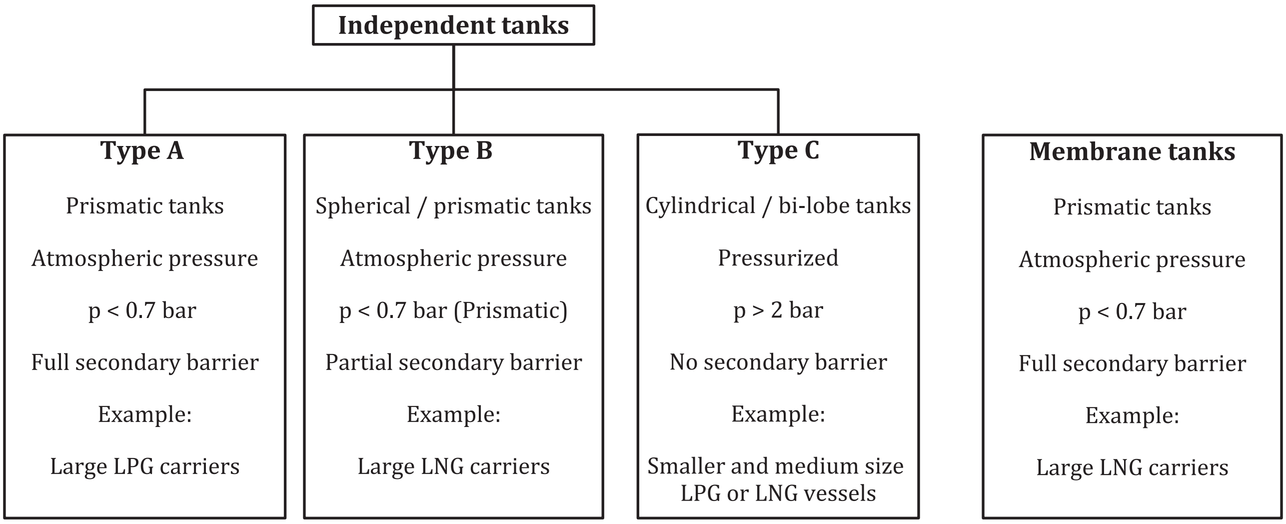


Figure 2 — Gas tank categorization as given in IMO IGC Code

6.3.2 Tank material

The applicable materials for a liquid CO_2 carrier cargo tank will be dependent on the selected design temperature. Due to the relatively high design pressure required for storage of liquid CO_2 compared to other gases carried by ships, materials which have a combination of high mechanical strength properties and a high performance at low temperatures are required for medium and low-pressure concepts.

The IGC Code lists requirements for materials that are to be used in cargo tanks for liquefied gases. Materials complying with these requirements can hence be used for CO_2 transportation. Materials not meeting these requirements can also be used if the material has successfully undergone a dedicated qualification process which demonstrates the applicability for the intended use (see Clause 8).

The maximum diameter of a cargo tank for liquid CO_2 is a function of the cargo design pressure, the material properties and the maximum achievable tank wall thickness. In principle, high mechanical strength properties of the tank material are essential to maximize cargo tank diameter. However, the combination of high strength properties and toughness performance at the design temperature relevant for liquid CO_2 is challenging, particularly for medium and low pressure. To maximize the cargo tank diameter and size it is essential to use materials with strength properties beyond what is typical covered by the IGC Code. Hence a material qualification process of materials with high mechanical strength properties for relevant design temperature is important for the development of large CO_2 carriers for low and medium pressure.

Fatigue becomes more critical with use of high strength material and with increasing cargo tank size.

Fatigue properties for steel are normally independent of the strength properties. Since high strength steel allow higher stresses the fatigue challenges generally increase. The IGC Code implicitly includes a limitation to how much high strength steel can be utilized to increase the cargo tank diameter. Fatigue of structural details, such as tank supports, is also critical due to the high density of liquid CO_2 compared to other gasses transported in similar cargo tanks. This can be a limiting factor for the achievable size for CO_2 tanks as the forces transferred to the supports increases with increased cargo volume.

6.3.3 Novel materials

Materials that are not listed in the IGC Code can be considered for CO_2 ship tanks. The reason for this is to use materials that have high mechanical strength properties, sufficient toughness at the design temperature, good welding properties and that are cost efficient.

6.3.4 Design pressure

The design pressure for a cargo tank is the maximum allowable pressure. During operation the pressure within the tanks needs to be kept below the design pressure. Depending on the cargo temperature, ambient temperature and the insulation system, heat will ingress into the CO_2 cargo from the surroundings. Vaporisation of CO_2 due to heat ingress causes the pressure in the tank to increase (see 8.4.3). A pressure relief system is installed to prevent that the design pressure is exceeded.

The amount of pressure increase will depend on the cargo temperature, the tank and insulation system, the ambient temperature, the tank liquid filling and the duration of the voyage. To allow for some pressure increase, there needs to be certain margin from the operating cargo pressure, at the start of the voyage, to the design pressure. Strategies for handling the heat ingress and pressure increase need to be incorporated in the cargo tank design (see 8.4.3).

6.3.5 Insulation

For medium and low pressure, heat ingress into the CO_2 tanks is usually minimised by tank insulation. For elevated pressure, insulation might not be needed as the temperature is at ambient or close to ambient. Tank insulation can be based on insulation systems from gas carrier design for other gasses.

The tank insulation can be designed according to the cargo vapour management philosophy (see 8.4.3).

6.4 CCS ship transport concepts

6.4.1 General

For oil and liquefied gas transport there are different concepts for loading and offloading of cargo which are also relevant for liquid CO_2 ship transport. These concepts include conventional onshore terminals for loading/offloading, floating production, buoy-based offloading solutions and others. They can also be envisioned for CCS but there are some novel aspects that are introduced with liquid CO_2.

In Figure 3, the CO_2 is exported from an onshore or floating terminal. This CO_2 can come from a pipeline, a nearby CO_2 capture plant or reloaded in liquid form from barges, trains or trucks. Loading arms or hose solutions are used to load the CO_2 onboard the CO_2 carrier.

The import facility is either connected directly to the reservoir or to a CO_2 pipeline system which then leads to storage. The transported CO_2 can also be used as a feedstock to form other products.

For all the concepts involving offshore offloading, the ship is equipped with additional features as opposed to vessels being designed for terminal-to-terminal operation only. These include an onboard process plant with pumping, offshore offloading solution and a dynamic positioning system. These features come with additional requirements to power, manoeuvrability and safety for the crew.

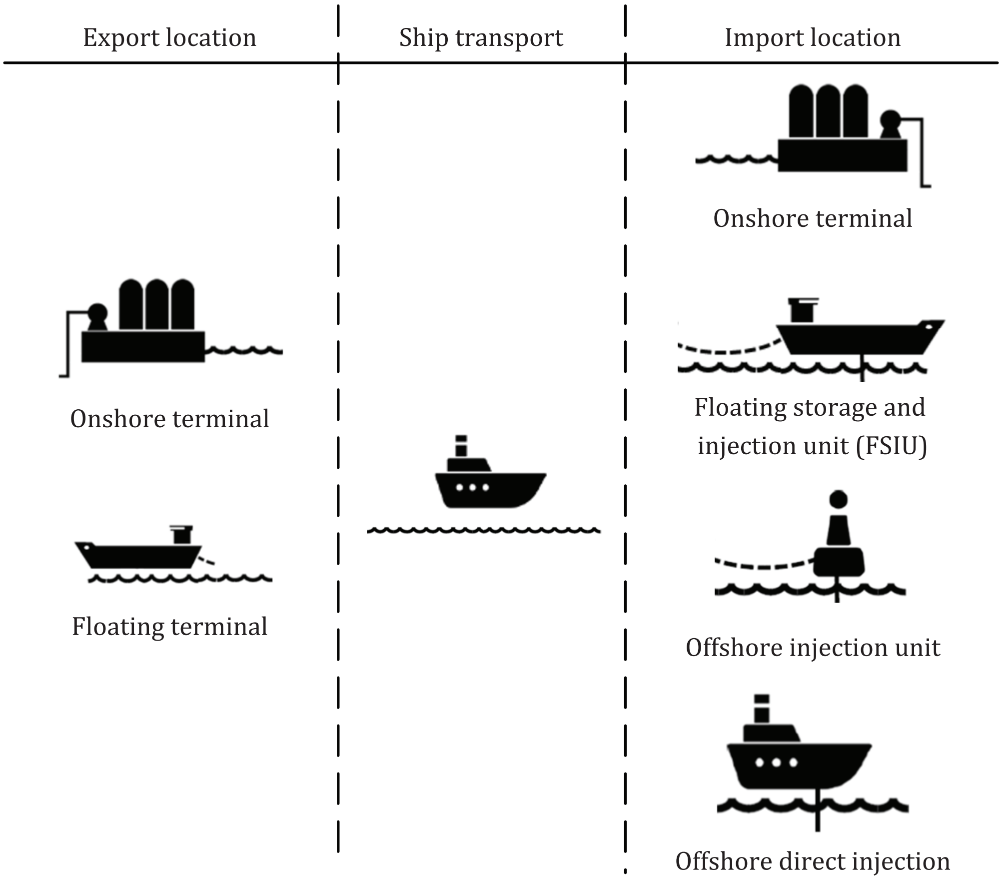


Figure 3 — CCS ship transportation concepts

6.4.2 Ship terminal to terminal

Ship terminal to terminal is the standard logistic chain for gas carriers today where the ship transports the dedicated cargo between two onshore terminals. The only CO_2 carriers operating today transport CO_2 between onshore terminals.

6.4.3 Barge terminal to terminal (inland waterways)

For a CCS logistics chain where the source is located inland it can be relevant to transport CO_2 on barges on inland waterways. As most barges are not suited for sailing in open waters, CO_2 can be transferred to a CO_2 carrier which can further transport the cargo to the final destination.

6.4.4 Offshore floating storage and injection unit (FSIU)

For CCS projects where the reservoir location is offshore, the CO_2 carrier can offload to a so-called offshore FSIU instead of an onshore terminal. The offshore floating unit acts as an intermediate storage and has dedicated equipment to inject the CO_2 into the reservoir.

This concept is similar to what is done in the offshore oil industry where oil shuttle tankers transport oil from a Floating Production storage and Offloading unit (FPSO) to an onshore terminal, however, in an opposite direction and with another type of cargo.

6.4.5 Offshore injection unit

It is also feasible to offload through an offshore fixed platform, tower or floater that does not contain intermediate storage. The CO_2 is conditioned to be injected into the reservoir on the offshore unit, which is connected to the underground storage.

6.4.6 Offshore direct injection

Injection to the storage reservoirs can be done directly from the ship through a riser, platform or pipe that it connects to. As opposed to an offshore injection unit, the CO_2 cargo is conditioned on the ship before injection in this case.

6.5 Multi Gas and dedicated carriers

6.5.1 General

Dedicated liquefied gas carriers are designed and optimized to carry one grade of cargo. Typically, carriers undertake the transportation of liquid cargo one way, and return without any cargo.

Multi-gas carriers can transport a wide range of liquefied gases. Typically, during a voyage, they are limited to carrying one grade of cargo due to the additional time involved in cargo tank preparations to make cargo changes (see 8.3). These carriers are designed for the product with the most stringent requirements for all the relevant design parameters. If the properties of the different cargoes are very different it is challenging to get an optimized, cost efficient ship design for the specified cargoes.

CO_2 carriers can be designed to also carry other liquefied gases. Due to the differences in cargo properties the ship design will need to account for the highest cargo density, the lowest design temperature and the highest design pressure.

6.5.2 Existing ship conversion

For all relevant CO_2 cargo transport conditions (see 6.1), liquid CO_2 has different properties (pressure, temperature, density) from what the current fleet of gas carriers is designed for. In most cases this prevents the possibility to convert the cargo tanks, cargo handling system and hull to carry liquid CO_2 in an efficient way.

Although it can be technically feasible to convert an existing ship into a CO_2 carrier, there are several aspects that need to be considered. In addition to the pressure, temperature and density differences of liquid CO_2 already mentioned, these aspects include the safety system, fire and gas detection, age and size of the ship, installed equipment, certificates, market situation, capital cost, operational cost and others.

6.6 Ship design

Ship design for CO_2 carriers follows the same principles as design of other liquefied gas carriers. However, the high cargo density of CO_2 and the resulting tank designs result in different constraints for the CO_2 ship design. Important design parameters for CO_2 carriers include the cargo capacity, the size, shape and number of cargo tanks, the ship speed, engine power and capacity, ship fuel, fuel consumption and greenhouse gas emissions. Whether the ship is intended to be suited for other than terminal to terminal transport is also important as this can add requirements to dynamic positioning, cargo conditioning equipment and system to connect to an offshore cargo transfer system.

The selection of the cargo tanks pressure and material as discussed in 6.2 influences the tank dimensions and thus has a significant influence on the ship design. The ship design also faces constraints given by the ports in question, such as draught, air-draught, maximum length, width and the interfaces with the terminal.

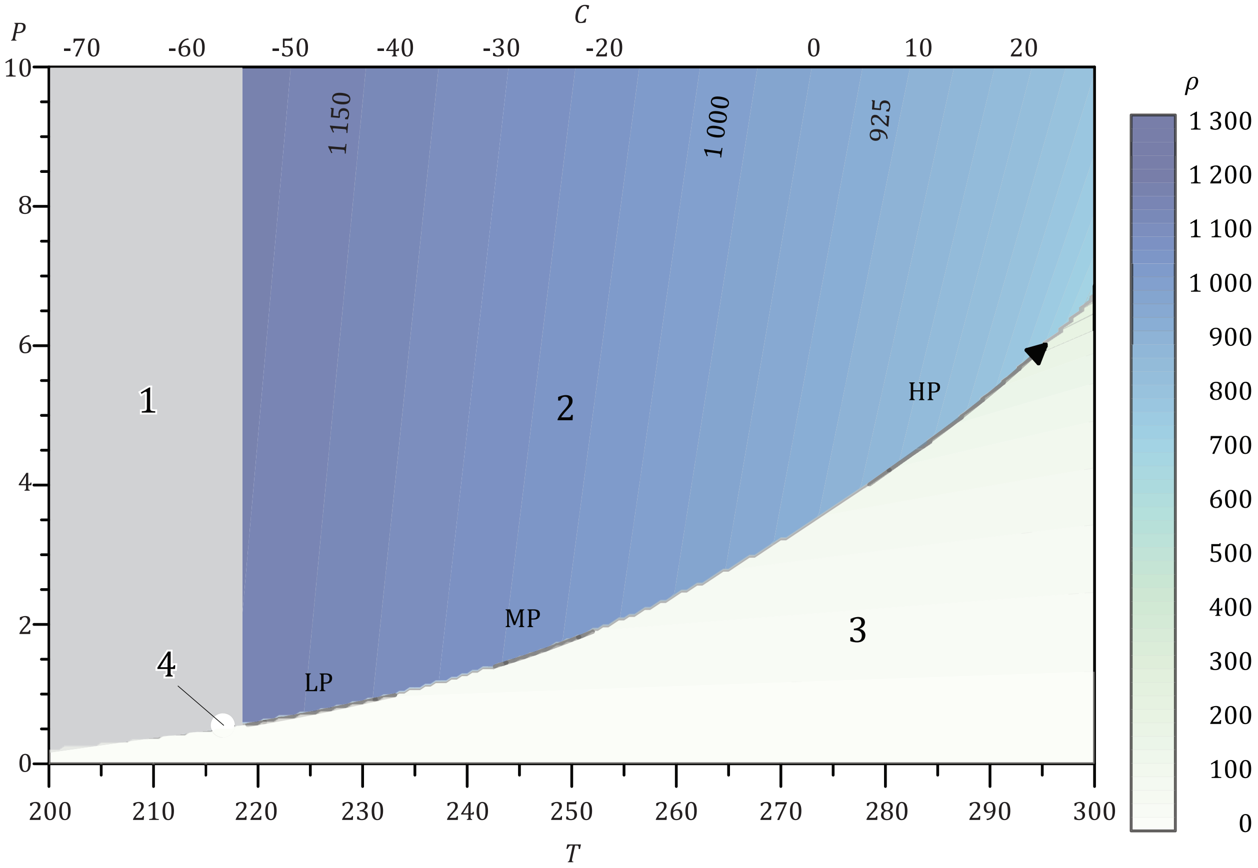
7 Properties of CO_2, CO_2 streams and mixing of CO_2 streams influencing the ship transportation

7.1 Thermodynamic properties of CO_2 and CO_2 composition

At atmospheric pressure CO_2 can only exist in solid or gaseous state. To transport CO_2 in liquid state the CO_2 needs to be contained in pressurized tanks above the triple point. The CO_2 cargo tanks will not be completely filled, allowing some room for vapour, which enables easy uptake of heat ingress. As the molecular exchange between the two phases is relatively fast, conditions at the liquid surface remain close to vapour-liquid equilibrium. Further away from the vapour-liquid interface, the conditions cannot be in equilibrium. This can lead to both temperature and concentration gradients, in both the vapour and liquid phase in the tank.

Figure 4 shows the thermodynamic phase diagram for pure CO_2, displaying how phase equilibrium varies with pressure and temperature. At certain conditions CO_2 exists in different states; solid, liquid and gas (vapour). Changes in the conditions of the CO_2 change its enthalpy and move the associated position of the considered point on the diagram.

The triple point of pure CO_2 is at −56,6 °C and 5,19 bara, this is the point at which the solid, gas and liquid phase are in equilibrium and can co-exist. The critical point of pure CO_2 is at 31,1 °C and 73,8 bara. Distinct gas and liquid phases do not exist in thermodynamic equilibrium at temperatures and pressures above those at the critical point (supercritical condition). At subcritical pressures and temperatures, the line on the diagram that connect the triple and critical point marks where liquid and vapour CO_2 phases co-exist in thermodynamic equilibrium.



Key

P	pressure in MPa	3	stability field of fluid CO_2 of low density (gas)
T	temperature in K	4	triple point
C	temperature in °C	LP	approximate conditions for low-pressure transportation
ρ	density of fluid CO_2 in kg/m^3	MP	approximate conditions for medium-pressure transportation
1	stability field of solid CO_2	HP	approximate conditions for high-pressure transportation
2	stability field of fluid CO_2 of high density (liquid)	HP	approximate conditions for high-pressure transportation

Figure 4 — Thermodynamic phase diagram for pure fluid CO_2

Changing pressure and temperature conditions result in changes of the phase fractions in the tanks and in phase densities. Heat ingress of the CO_2 cargo cannot be avoided, hence liquid CO_2 evaporates and the mass fraction of liquid and gas cargo changes during transportation. When volume is constrained and the cargo cannot expand, the pressure within the tanks rises which drives the pressure and temperature conditions along the phase boundary in the direction of the critical point of CO_2.

Conversely, during loading and offloading of the cargo the pressure-temperature conditions can also move in the direction towards the triple point of CO_2, at which a solid phase will form. To avoid this an operational safety margin in pressure and temperature is maintained between the triple point conditions and the specified conditions within storage tanks. In addition to an operational safety margin, special mitigations to prevent the pressure from dropping will probably also be required; methods for cargo voyage management are described in 8.4.3.

7.2 CO_2 impurities and trace components

7.2.1 Common impurities

Impurities impact the thermodynamic, physical and chemical properties of the CO_2 stream. Captured CO_2 streams will include some impurities from the CO_2 source which can introduce challenges across the CCS value chain, these are described in Clause 8. Levels of impurities acceptable for ship transportation, as well as for the other parts of the CCS value chain, are uncertain and research is ongoing to define the acceptable limits. Hence the first CCS projects including ship transportation of CO_2 have high requirements for CO_2 purity.

A small heel is normally kept in the cargo tank after offloading to avoid large changes in the transport conditions before next cargo loading (ref 8.1). To maintain pressure conditions during loading and offloading gas normally exchanged between cargo tanks and terminal. Over several cycles of transporting CO_2 streams could lead to the accumulation of greater quantities of non-CO_2 components which have a high relative volatility and low solubility in CO_2. Over time this accumulation can surpass safe limits or create adverse and unpredictable reactions.

Table 2 describes common impurities, the potential effects and the associated risks to ship transport of CO_2. This table compares the characteristics of a CO_2 stream containing the named impurities with that of a pure CO_2 stream. The effects of these impurities can apply to the bulk liquid CO_2 stream that is being transported, or to other parts of the ship transport system where the CO_2 stream is in gas phase, such as in pipes, vapour return systems, and other equipment.

Table 2 — Common impurities, the potential effects and the associated risks to ship transport of CO_2

Characterization	Species	Effects	Risks
Water	H_2O	— Form carbonic acid with CO_2 — Form hydrates at low temperatures — Form ice — Form free (liquid) water in a gas phase of the CO_2 stream — Form aqueous phases in presence of water-soluble impurities	— Solid formation — Corrosion — Liquid accumulation
Oxygen	O_2	Oxidising component	Corrosion
Carbon monoxide	CO	Toxic	Health and safety
Non-condensable	H_2, N_2, Ar, CH_4, etc.	Relative to pure CO_2; increased fractions of non-condensable components in a CO_2 stream: — increase the CO_2 stream saturation pressure; — increase the CO_2 stream critical pressure; — reduce the CO_2 stream density.	Operation management
Water soluble	Amines, glycols, C_{2+}, etc.	When dissolved with water in the CO_2 stream these form an aqueous phase and reduce H_2O concentration in the CO_2 stream	— Solid formation — Corrosion
Acid-forming	H_2S, SO_2, NO_2	— Form sulphuric/sulphurous acid, nitric acid and elemental sulfur — H_2S is toxic	— Corrosion — Health and safety

Many ship transport projects form a part of a wider transport chain in which pipeline transport is significant. When considering the compatibility of different transport modes, the overall project transport specification needs either to meet the strictest requirement at the capture plant or include additional processing facilities at mode transfer points (trans-shipment hubs).

7.3 Flexibility and mixing of CO_2 streams from different sources

If different emitters feed CO_2 streams of different compositions into a CO_2 transport network, there can be a variability of CO_2 stream composition in all parts of this transport network. This variability can be a result both of variable mass flow rates and compositions of the feed streams. In such networks, mixing/dilution schemes can be applied, i.e. a relatively pure stream is combined with a stream from another emitter containing higher impurity levels. Depending on the time scale of the variations, some "averaging" of CO_2 stream composition can occur during intermediate storage prior to or during ship loading itself.

A variability of mass flow rates and CO_2 stream compositions will particularly affect chemical reactions in the CO_2 streams and, in turn, the composition and the physical properties of the CO_2 stream. In such cases, CO_2 specifications for the transport network will be composed of maximum impurity concentrations and maximum acceptable variability of impurity concentrations. To define these, several aspects need to be considered, including:

— The maximum acceptable concentration of a single impurity will depend on the concentration of the other impurities. The CO_2 specifications can only be defined project specifically, unless strict specifications are chosen.

— Cross-chemical reactions are more likely when CO_2 stream composition is changed, for example by addition of CO_2 streams at mixing points.

— More experimental data on cross-chemical reactions, formation of aqueous, acidic phases and implications for material corrosion at relevant pressure and temperature conditions are needed to:

— test and validate suggested CO_2 specifications;

— provide a basis for corrosion predictions by simulations. For this, kinetic data are essential.

Additionally, the quantification and verification of cargo is impacted by the presence of impurities as these introduce uncertainty into the precise composition of the fluid and therefore the precise fraction of CO_2 in the liquid and vapour phases. The consequences of stream mixing and impurities on cargo measurement is discussed in Clause 11.

8 Ship operation

8.1 Ship and terminal modes of operation

Before being loaded onto the carrier, the CO_2 is liquefied to a suitable condition (pressure and temperature) for transport by the ship. Temporary storage in liquefied form in a land-based intermediate storage (or barge) tank, can be necessary.

For terminal-to-terminal shipping, CO_2 is offloaded to land based intermediate storage (or barge) tanks and conditioned at the import terminal for pipeline transport and injection. For offshore offloading the CO_2 is conditioned on the CO_2 carrier, or on an offshore facility, before injection.

During a ballast voyage in a normal CO_2 transport operation, the cargo tanks and cargo handling system are maintained filled with CO_2 vapour and liquid (heel) as illustrated in Figure 5 "Regular circle". This is done to avoid the process of cooling down the cargo tanks alongside the terminal prior to loading.

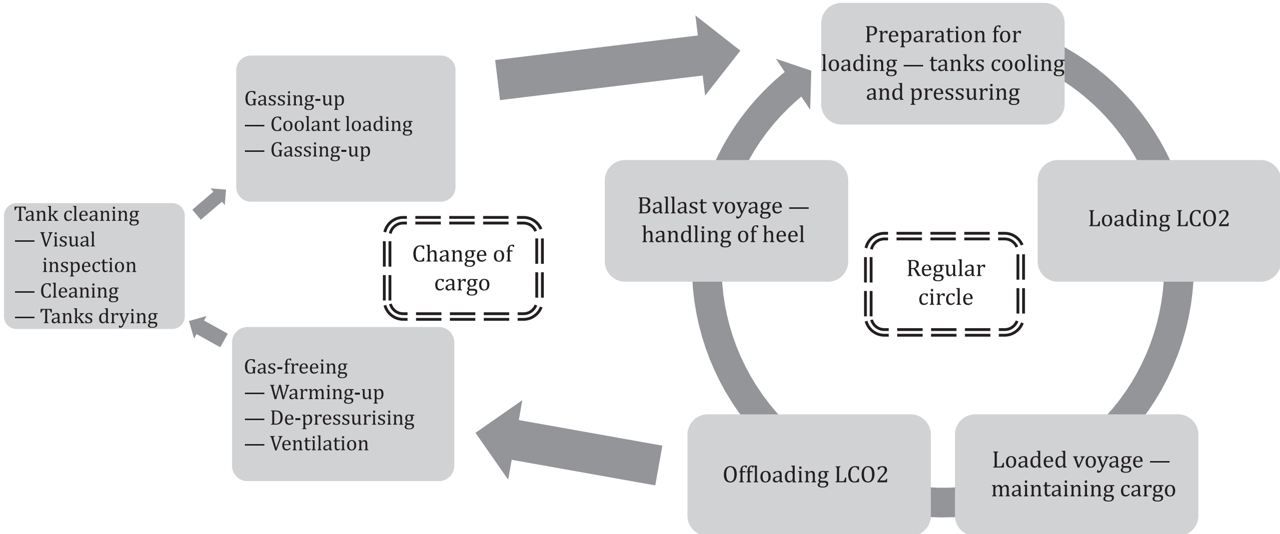


Figure 5 — Cargo operation phases

If the ship is capable of carrying cargoes other than CO_2, it is possible to switch between different grades of cargo. To prepare the ship for other cargo, a process "Change of cargo" (left part of Figure 5) usually follows after offloading CO_2 cargo. This process takes several days or potentially weeks to complete.

8.2 Compatibility and interface

The ship needs to be compatible with the loading and offloading terminals to safely arrive, moor, conduct cargo operation and depart.

Typical aspects of compatibility for a CO_2 carrier are:

— approaches to the import/export locations (navigable waters);

— berth and ship size compatibility;

— mooring compatibility;

— cargo handling compatibility, including:

  — cargo pressure and temperature;

  — cargo transfer rate;

  — cargo composition (specification);

  — cargo custody transfer arrangements;

  — cargo quality assurance practices;

  — ship-shore cargo lines connections compatibility;

— safety protocols compatibility;

— safe access to the ship arrangements;

— other aspects, specific to the location and the ship.

To facilitate compatibility, organizations such as the World Association for Waterborne Transport Infrastructure (PIANC), SIGTTO and OCIMF (see 5.2) have a role developing guidelines and best practices which are used as references documents when designing and constructing ships and terminals.

8.3 Cargo operations

8.3.1 Responsibilities

The responsibility for safe conduct of operations when the ship is alongside the terminal is shared between the ship master and the terminal's representative. The procedure for cargo transfer (sequence, maximum and minimum flow rates, tank pressures, emergency procedures, etc.) is agreed between the ship and terminal representative. To facilitate a safe cargo transfer, a ship-shore safety checklist based on industry guidance is typically used to ensure the appropriate checks are formally agreed upon, carried out and recorded.

8.3.2 Manifold operations

The principal objective of the procedure for connection and disconnection of the cargo transfer system is to eliminate any risk of leakage of cargo. Once the cargo arms or hose is connected it is standard practice to replace the air in the interface with a dry medium that is compatible with the product being transferred. The connections are then pressure tested prior to the start of cargo operations. Once cargo operations are complete the interface at the manifold is drained and depressurised prior to disconnection.

8.3.3 Loading operations

During loading operations, the CO_2 is transferred from the terminal to the ship. The transfer can be done using cargo hoses or marine loading arms. Due to the properties of liquid CO_2 the design of the cargo transfer system needs to account for the possibility of two-phase flow.

Loading operations can be performed with or without vapour return from the ship to the terminal. Vapour return will ensure pressure equilibrium between the shore storage tanks and the ship cargo tanks and ease the vapour pressure management.

Loading without vapour return simplifies the ship-shore interface but requires pressure management on both the ship and the terminal. The pressure will decrease in the shore storage tanks, and it can be compensated through CO_2 vaporisation for example, on the other hand, pressures will increase in the ship cargo tanks and can need to be handled with a reliquefaction system. To achieve a minimum loading rate as required by the project it is likely that the export terminal will need to be designed to be able to handle the vapour return from the ship during cargo operations.

8.3.4 Offloading operations

During offloading operations, the CO_2 is transferred from the ship to storage tanks at the import location and the displaced vapour from storage tanks is sent back to the ship through a vapour return line or handled onshore. The transfer can be done using cargo hoses or marine loading arms. Same as for loading operation, due to the properties of liquid CO_2 the design of the cargo transfer system needs to account for the possibility of two-phase flow.

8.4 Cargo management

8.4.1 General

The condition of the cargo when loaded and the receiving terminal requirements can determine the requirements for the cargo management. For the low or medium pressure carriage concept, the cargo is loaded at a pressure and temperature closer to the lower limit of the operating range to allow for the safe transportation of liquid CO_2 during the voyage from export to import location.

8.4.2 Cargo tank preparation

It is essential to avoid the presence of free water in the tanks before and during CO_2 loading as it has the potential to form undesirable components such as hydrates, carbonic acid, ice, or other aqueous phases in the tanks which can cause adverse effects. To avoid this, the cargo tanks need to be adequately dried to a dew point corresponding to the cargo tank design temperature, e.g. for medium pressure conditions, tank design temperature is −35 °C. Since CO_2 is an inert gas, drying can be done with either dry air or nitrogen.

The cargo tanks are gassed up and pressurized with CO_2 vapour, either directly in vapour form, or alternatively in liquid form before being vaporised onboard. In this process, presence of air or nitrogen, or both, in the cargo tank can be judged by measuring their concentration in a gas sample. To avoid potential formation of dry ice in the cargo system, cargo tanks and piping need to be pressurized with vapour to above the triple point of CO_2 before introducing any liquid CO_2 from shore. Once pressurized, the tanks' cool down can be started by spraying with liquid from shore.

During normal operation, the cargo tanks and cargo handling system are not emptied (depressurised) with CO_2 after offloading. Therefore, the drying, gassing up and pressurising process are not needed before loading of new cargo. See Figure 5 for cargo operation phases.

8.4.3 Cargo voyage management

Heat ingress into cargo tanks will result in the natural evaporation of the cargo, also known as boil-off. Boil-off gas (BOG) produced during the voyage needs to be effectively managed to prevent over-pressurising the cargo tanks that leads to a venting situation. To maintain the cargo tank pressures within the design range either one or a combination of the following methods can be used for CO_2 cargo:

— pressure accumulation;

— reliquefaction of cargo vapour;

— liquid cargo cooling.

Cargo voyage management for traditional type C tanks are normally handled by having a margin between the loading pressure and the design pressure sufficient to allow for pressure accumulation during a certain period without any treatment of the cargo. In the case of longer voyages it can be challenging to have sufficient margin from the loading pressure to the design pressure.

The rate of pressure increase is normally greatest at the ballast voyage where there is only a small portion of liquid in the cargo tank (heel). Hence the ballast voyage is often dimensioning for the needed design pressure.

The amount of non-condensable components in the CO_2 will influence the cargo vapour management and hence the needed cargo tank design pressure.

Boil off management is most relevant for medium and low-pressure carriage condition systems. In the elevated pressure carriage conditions, the relatively small temperature difference between the cargo and ambient temperature results in less heat ingress than medium- or low- pressure cargo containment systems.

8.4.4 Cargo losses

During normal operations of the ship no leaks or venting of the cargo is expected. The cargo is maintained in fully enclosed system during loading, transportation and offloading. Any leakages of cargo on board the ship is of accidental or emergency origin only. Numerous operational and design measures are in place to minimize chances of such leakages. For example, ship's cargo piping and systems are of welded construction, minimising the use of flanges. The equipment and systems used on ships are approved by the classification society, ensuring they meet standards and are fit for purpose for the applications.

9 Technical gaps and development

9.1 Applicability and precision of existing requirements

The technical requirements relevant for international ship transportation of liquid CO_2 are described in Clause 5. It is to be noted that prescriptive regulations applicable to liquid CO_2 transportation exist, but that equivalent level of safety still needs to be demonstrated, as the feedback from experience of transporting liquid CO_2 by sea is very limited.

9.2 Identification of additional relevant requirements such as practices onshore

For onshore applications there are regulations and requirements that can be relevant guidance for ship transportation of CO_2.

In the EU, the Pressure Equipment Directive (PED) is a mandatory directive that is applied to pressure equipment subject to a maximum allowable pressure greater than 0,5 bar, with some exceptions. Under this directive, European standards (EN) provide rules for design, fabrication and inspection. In the USA, this mandatory code is the American Society of Mechanical Engineers (ASME) standard.

PD 5500 "Specification for unfired, fusion welded pressure vessels" (previously known as the BS 5500) is a widely used code of practice that provides rules for the design, fabrication, and inspection of pressure vessels) published by the British Standards Institution.

For pressure vessels, relevant practices can also be found in American Petroleum Institute (API) standards that are applicable to LPG storage but can then be applied for liquid CO_2 storage tanks, similarly some ASME parts (these also define liquid CO_2 storage tanks).

In terms of handling and required training, some references can be found in the European Industrial Gases Association (EIGA) set of documentation, with some of them specifically addressing the particularities of liquid CO_2. These cover the issues of:

— general behaviour and hazards associated with CO_2 (including toxicity);

— re-pressurization of a tank after an uncontrolled depressurisation event and the associated risk of dry ice formation and tank temperature below the brittle capacity of the tank;

— ice plugs and clogging with dry ice when purging a line.

For CO_2 compositions some International Standards and guidelines already exist, such as the ISO 27913 for CO_2 transport by pipeline. At the moment shipping transportation limits have not yet clearly been defined, except some specific projects such as the Aramis project in Netherlands and for the Northern Lights project in Norway.

9.3 Qualification and process for new technology

For ship transportation of CO_2 innovative technology can be relevant. When a technology comprises innovations that deviate from applicable prescriptive statutory regulations, the provisions of the relevant IMO Guidelines have to be followed to run an approval process to the satisfaction of the concerned ship's classification society and flag administration.

Novel tank designs (e.g. composite tanks, with different standards to IGC Code), require an equivalence design process, as described by IMO, to get it approved by flag administration or the recognized organization acting on its behalf.

For non-metallic material (composite tanks for example) ISO 11119 can be used as reference for the design, construction and testing, however this International Standard is restricted to tanks of small volume, as composite tanks for compressed liquefied gas of large quantity (>1 000 m^3) are not generally used on board ships.

Equipment installed onboard ships is to be approved or certified by a classification society. This is also applicable for equipment on CO_2 carriers and potentially also covers transfer equipment such as liquid CO_2 transfer hoses, if located onboard the ship, and hoses used in different offloading methods such as direct injection. Generally, the methodology of equivalent design approach is applied for qualification of new technology and submitted for approval to the flag state and classification society.

9.4 Gaps and need for development

There are some areas where there is a potential for development and which would be needed to further optimize CCS value chains where parts of the transportation are done by ships. The most important challenges identified for CO_2 shipping that need attention for the industry to optimize the logistic chains and ensure safety are:

— CO_2 specification for ship transportation, including maximum acceptable level of impurities;

— handling of commingling or blending CO_2 cargo from different sources;

— cargo tank material qualification requirements for low temperature performance of materials with high mechanical strength properties;

— measurement and reporting of CO_2 cargo discharged for injection and storage.

10 Safety and risks

10.1 Health, safety and environment (HSE)

10.1.1 Toxicity and asphyxiation

Any gas that is present in sufficient quantities to lower oxygen levels will act as an asphyxiant. However, even if there is sufficient oxygen to support life, CO_2 can be dangerous and hence can also be considered as toxic. For CO_2 to reduce the oxygen concentration in air down to a level that is immediately dangerous to life, the CO_2 concentration would need to be in the order of 50 % volume to volume. It is also reported, however, that CO_2 does create an immediate threat to life at a concentration of only 15 % in air due to the toxicological impact it has on the body when inhaled at this concentration. Apart from the immediate threat to life, a low concentration of CO_2 can also be toxic depending on the time of exposure. Depending on the CO_2 concentration inhaled and exposure duration, toxicological symptoms in humans range from headaches (in the order of 3 % for 1 h), increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma and death (in the order of > 15 % for 1 min) (see Reference [17]).

Impurities that follow the CO_2 from the source can be toxic and be a danger for humans in case of a leakage. Threats of relevant impurities including toxicity and danger for humans are listed in ISO 27921. Depending on concentrations, the impurities could be more toxic than the CO_2 itself. See ISO 27921:2020, 6.4, where the toxic effects of impurities in case of leakage is discussed.

10.1.2 Hazards of liquid CO_2

In addition to the hazard posed by CO_2, and potentially the impurities, if inhaled, there are additional hazards associated with liquid CO_2. These can arise when a release occurs, and the pressure suddenly falls or is lost completely, where the fluid phase changes from liquid to mixture of solid (dry ice) and vapour. These hazards include cryogenic burns and embrittlement of piping and structure. Provision of personal protective equipment and emergency response plans will help to minimize the risk of cold burns.

10.2 Measures to mitigate risks

10.2.1 Gas detection

Gas detection for CO_2 carriers will, in general, follow the same principle as used for other gas carriers. CO_2 detectors will be placed at appropriate locations, such as nearby potential leak or release points and at potential place of CO_2 accumulate or be carried around to prevent suffocation accidents.

If any leaks are detected, the process is stopped, and corrective actions taken to isolate the leak.

In case of gas leaks, a CO_2 alarm is activated, the area is evacuated immediately, and proper personal protective equipment is obtained. Observing the wind direction, cross or upwind of the hazard evacuation is done to a designated muster area. If the designated muster area is not accessible or is unsafe due to wind direction, the personnel will proceed to an alternate muster area.

10.2.2 Emergency shut down

In order to minimize the risk of a potential CO_2 spill to the environment an emergency shutdown system is typically used. Emergency shutdown (ESD) is a safety system designed to stop CO_2 transfer operations to minimize the consequences of an incident. The ESD can be activated either from shore terminal or carrier. The ESD interacts with other safety systems on the carrier.

10.2.3 Emergency release system

Emergency release system is installed on marine loading arm to provide a means for safe isolation and quick release of the marine loading arm. The functionality is provided to protect the marine loading arm, jetty, and the carrier during cargo transfer operations.

10.3 Special risks with liquid CO_2 as ship cargo

10.3.1 Solid formation

There is a risk of solid CO_2 formation when operation is close to the triple point. Solids entrained in fluid flows can damage process equipment, particularly rotating machinery. There is a risk of damaging pump blades and casing, leading to mechanical failure, and a risk of depositing solids in pipes and heat exchanger tubing which reduces efficiency and leads to less predictable performance.

Rapid depressurisation of a CO_2 tank can result in a quantity of solid CO_2 being formed inside the tank and around openings as the temperature drops. This carries a particular risk of blocking safety valves in a relief scenario.

10.3.2 Material integrity

Corrosion is the deterioration of materials through a reaction with their environment. This typically leads to a reduction in the mechanical properties of the material which can lead to an increase of stress and probability of mechanical failure of equipment.

The presence of water can form corrosive compounds when combined with a number of other species (H_2S, SO_2, NO_2, etc.) and notably produces carbonic acid when combined with CO_2.

Several compounds of impurities can also physically affect tank and equipment materials in a way that might promote mechanical failure. For example, hydrogen embrittlement is caused by the small hydrogen molecules permeating the solid metals and reducing the ductility of the material, making fracture more likely to occur.

10.3.3 Electrostatic charge

When liquid CO_2 is released into the atmosphere, it undergoes a phase change from liquid to a mixture of gas and solid (dry ice). During this process, collisions and frictions between dry ice particles and nearby objects can generate static electricity. This static electricity can have enough energy to ignite a mixture of flammable vapour and air and can lead to an explosion. Thus, it is hazardous to release liquid CO_2 into an environment where flammable vapour is present.

11 Quantification and verification of CO_2 cargo

11.1 General

Accurate quantification and measurement of cargo are vital to prevent disputes among all stakeholders involved in the CO_2 ship transport chain, such as the emitter, the transporter, and the import side.

For the fiscal metering needed to export CO_2 between countries and the bill of lading (legal document stating the CO_2 quantity loaded, the loading point and the expected offloading point), an option is to use mass flow meters that could be installed onshore at the loading terminal. The advantages of onshore metering compared to onboard installation are numerous such as ease of calibration, accuracy, access and a more straightforward process for third-party verification, including limited equipment installation.

11.2 Quantification and measurement

11.2.1 General

The usual method of cargo measurement on ships is to calculate the volume of the cargo based on the instrumentation, which consists mainly of level gauges and temperature sensors in the cargo tank. Further, the cargo tank calibration tables are used in the calculations. The level gauging can be automated, which provides continuous volume measurement at any given time, which uses the calibration tables and temperature measurement obtained from the sensors and applies necessary correction factors for the ship trim and list.

For custody transfer, the cargo is quantified in terms of its mass. The volume can be measured on the ship, and the density of the liquid CO_2 will be provided by the onshore terminal or onboard for calculating the mass loaded and offloaded. Cargo composition and specification measurements will be undertaken at the loading and offloading terminal, and no such devices are fitted on ships.

11.2.2 Cargo measurement

Liquid cargoes are generally quantified by measuring the volume accurately and multiplying it by the density of the cargo. Since the cargoes are at their boiling points in equilibrium with their vapours, the cargo exists partly as a liquid and partly as a vapour. Therefore, it is necessary to account for both liquid and vapour in cargo calculations.

The measuring instruments on board liquified gas carriers enable an accurate cargo volume calculation. The level of liquid and the temperatures in the liquid and vapour space of the tank are measured, and the ship’s trim and list are determined.

All ships are provided with a calibrated tank table for each cargo tank. The tank tables enable liquid and vapour volumes to be found from a measurement of the liquid level. Tank tables are based on ambient temperature and pressure after the ship is built, and the volume given in the table normally assumes the ship to be upright with no trim. The calibration tables, therefore, contain correction factors for ship's list and trim, and cargo tank temperatures and pressure. The export terminals can provide the liquid and vapour densities for a range of temperatures for the quality of CO_2 loaded each time to allow the carrier to calculate the mass transferred.

Initial volumes of liquid and vapour are measured before loading or offloading of liquid CO_2. The final measurement is implemented immediately after loading or offloading. The difference between the initial and final measurements gives the volume of cargo loaded and offloaded. However, this method can be shown to be difficult for offshore injection where the ships movement can be considerable.

11.2.3 CO_2 quality

The receiving side of the ship transport chain has a specification on the CO_2 cargo it can receive in terms of the allowed content of other components than CO_2. This is often related to limiting corrosion and safe transportation on ships. These components are typically water, H_2S, SOx, NOx, oxygen, and degradation products from the CO_2 capture process and are listed in 7.2.1. There might also be volatile components in the CO_2 and a vapour pressure limitation on the cargo can limit the content of these.

The export terminal can be required to provide a quality certificate as part of the cargo documentation, which contains the specification, including relevant impurities in the CO_2.

11.2.4 Co-mingling

The effects of mixing different impurities in the CO_2 stream from different sources, such as pre-combustion, post-combustion, and oxy-combustion, are not well understood. Such mixing on a ship can lead to dropouts leading to corrosion (see 7.2). Safety and operation-related issues can arise on the ship with co-mingling cargoes in the same or different tank.

There will also be challenges in determining the mass of cargo transferred due to the uncertainties in the density of the comingled product.

11.2.5 Onboard carbon capture

If ships are fitted with onboard carbon capture, appropriate measuring instruments are required to determine the quantities captured on board and offloaded. Assessing the quality of the onboard capture process requires measurement of the CO_2 stream composition and would normally be required to meet tolerance requirements.

11.3 Verification

Verification is a periodical process for evaluating the measurements of CO_2 to determine if the results are materially correct within acceptable ranges of uncertainty as required in the project.

The export terminal will provide the CO_2 quality and density range as part of the cargo documentation for the carrier. Depending on the agreement between the export terminal and receiver, the calibration and verification of quality measurement instruments can be done periodically as defined in a project contract.

The ship's instrument verification is conducted per the maker's instruction under their planned maintenance system. Further verification is undertaken independently by the classification society at regular intervals.

12 Summary status and development needs for CO_2 ship transportation for CCS value chains

CO_2 carriers can be designed and constructed within existing regulatory regimes and by use of technologies which are widely adopted by other conventional liquefied gas carriers. While the operation and cargo management for conventional shore to shore transportation generally follow well-established gas carrier principles, it is essential to acknowledge and address additional challenges specific to liquid CO_2 transportation.

Cross border transportation of CO_2, for the purpose of storage, is subject to implications due to the lack of ratification of the London Protocol and amendments, as described in 5.5. However, potential workarounds involve the establishment of bi-lateral agreements between the countries involved in the CO_2 transport. Additional regional regulations can influence cross border transportation, potentially requiring further investigation.

Optimization and efficiency of the transportation and logistics of the captured CO_2 is important to reduce the overall cost of CCS. To enable this there are several areas where additional work and development is necessary. The most important focus areas identified throughout the development of this document are (see 9.4):

— CO_2 specification for ship transportation, including maximum acceptable level of impurities for the different pressure/temperature regimes considering safety, design and operational aspects;

— handling and management of CO_2 streams from different sources when operating ships between different terminals with cargo operation by vapour return;

— corrosion barriers considering risk of comingling of impurities creating a corrosive environment including alternatives to cargo operation with vapour return;

— qualification of extra high strength material for relevant design temperatures;

— measurement and reporting of CO_2 cargo offloaded for injection and storage.

Development within these areas will be important to:

— reduce the need for preparation of the CO_2 stream prior to ship loading and transportation;

— increase utilization and flexibility of ships across different trading routes involving different loading terminals with CO_2 streams originating from different type of emitters;

— allow for larger cargo tanks and hence increased cargo capacity of CO_2 carriers;

— increase flexibility for the ship designer enabling more optimized CO_2 carrier designs;

— ensure accuracy, confidence and transparency for CO_2 stream injected to permanent storage.

The focus areas listed above are already being discussed in the CCS industry with ongoing research and development efforts. It is expected that standardization will be an important element in optimising CCS value chains and CO_2 shipping. However, considering the very early stage of the industry, where development are ongoing and different concepts and solutions are being investigated, it is considered premature to initiate standardization work specifically tailored to CO_2 shipping. This will become more relevant when the industry has acquired more insights and experience.

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