CO_2 Impurities and LCO_2 Carrier Design: Practical Considerations

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1 INTRODUCTION

The carbon value chain, which includes core elements like carbon capture, utilization, storage and transportation, is an integrated process for carbon emissions management, from source to potential utilization or sequestration.

As companies worldwide increase their carbon capture projects, transporting the captured carbon dioxide (CO_2) becomes essential. Ships built to transport liquefied carbon dioxide (LCO_2) as cargo are emerging as a vital link in the carbon value chain. These vessels help ensure LCO_2 is transported safely and efficiently from capture sites to utilization or storage facilities.

This publication explores the challenges of transporting LCO_2 by sea on specialized ships, focusing on the impact of impurities, as assessed in existing literature. It also provides a brief overview of the role and the challenges of CO_2 transportation within the broader carbon capture, utilization and storage (CCUS) value chain. Carbon capture, utilization and storage plays a crucial role in achieving climate goals, and CO_2 transport is a key component for its deployment.

2 OVERVIEW OF THE CCUS VALUE CHAIN

Understanding and improving the carbon value chain becomes increasingly important as the globe steps up its efforts to combat climate change. As it scales up, it will become apparent that the maritime industry is at the center of making this value chain a reality, as it accounts for a substantial portion of global trade.

Once extracted, CO_2 can be utilized for a variety of applications. Captured CO_2 can be used for everything from chemical and fuel production to boosting agricultural yields.

While CO_2 transportation has long been a practice in the food industry and oil industry for enhanced oil recovery (EOR), the new carbon capture projects involving various emitters, CO_2 producers and dedicated receivers across large geographical regions introduces new challenges. The most important among these challenges is the varying composition of CO_2 due to impurities, particularly in the marine transportation of LCO_2 at low operating pressures.

2.1 Role of CCUS in Decarbonization

The CCUS value chain begins with capturing CO_2 from emission sources, including power generation or industrial facilities. The captured CO_2 is then transported to its destination either in gaseous or liquid form. While carbon capture is a vital link in the value chain, it still requires more technological development.

The value chain is completed using the captured CO_2 as a feedstock or permanently storing it underground. A proven example is the EOR technique of injecting CO_2 into existing oil fields. Figure 1 illustrates the main elements of the CCUS value chain.

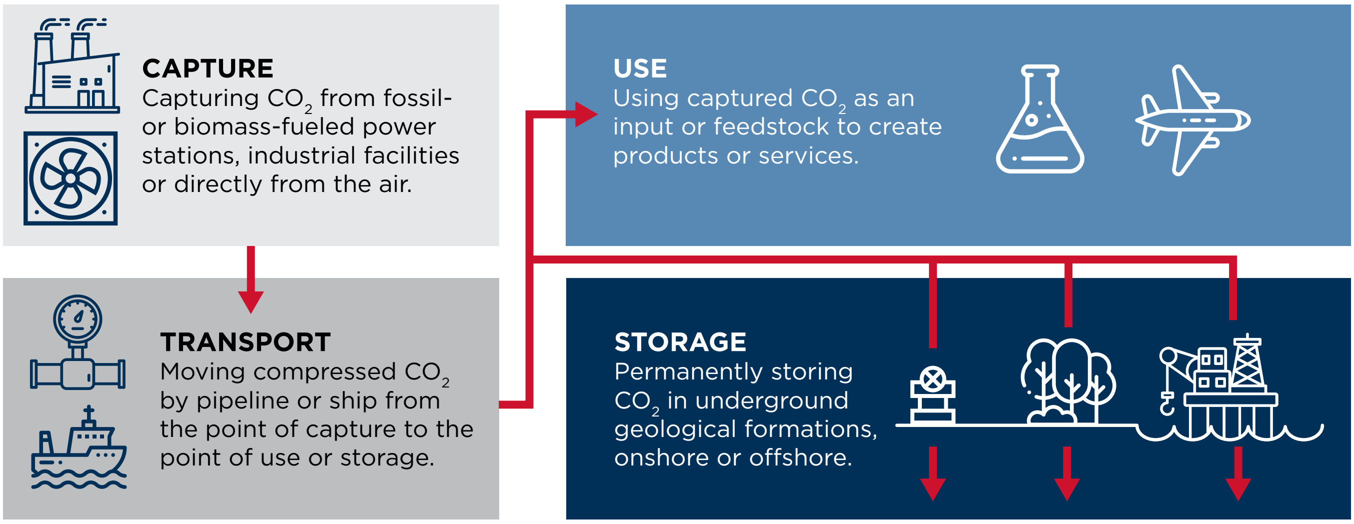

Figure 1: Carbon capture value chain.

The International Energy Agency (IEA) highlighted the importance of CCUS in achieving global climate goals. It is one of the few technologies that can directly reduce CO_2 emissions from heavy industries, such as cement and steel production, which are rarely decarbonized.

The rapid global deployment of CCUS technologies has accelerated in recent years, driven by increasing climate commitments and advancements in capture and storage systems. According to data from the Global CCS Institute, the number of operational and planned CCUS projects worldwide has significantly grown, with over 300 projects now at various stages of development as of the end of 2024. This expansion highlights the importance of addressing technical factors that impact CCUS efficiency, including examining CO_2 impurities. As CO_2 capture scales up across industries, understanding and mitigating the effects of impurities on transport and storage processes have become critical to ensuring the reliability and safety of these systems.

2.1.1 Carbon Capture Technologies

Carbon capture technologies are gaining significant traction due to their retrofit potential to existing emission sources, such as power plants and industrial facilities.

Post-combustion capture is one of the most mature and widely deployed onshore carbon capture technologies. This process involves the separation of CO_2 from flue gas after combustion. Post-combustion capture technologies can be divided into several subcategories based on the method used to capture CO_2.

Pre-combustion capture involves the conversion of fossil fuels into a mixture of hydrogen and CO_2 before combustion through a process known as reforming. The resulting CO_2 is captured, and the hydrogen can be used as a low-carbon fuel.

Oxy-fuel combustion capture is a process that burns fossil fuels in nearly pure oxygen instead of air, resulting in a flue gas that is primarily CO_2 and water, making the CO_2 easier to capture.

In addition to the above, direct air capture, an emerging technology that captures CO_2 directly from the ambient air rather than from specific emission sources, could also be part of the decarbonization solutions.

2.1.2 Geological Storage

Permanent CO_2 storage projects play a key role in global climate change mitigation efforts, as denoted by the Zero Emission Platform (ZEP) [4]. There are a few permanent geological storage options to consider for CO_2, such as in saline aquifers or depleted reservoirs. One of the most common and proven solutions is offloading CO_2 to oil and gas wellheads (offshore and onshore) where the CO_2 would be used as a method of EOR while simultaneously being permanently stored.

Injection activities offshore, including existing oil and gas platforms and facilities – both fixed and floating – can be involved in injecting CO_2 for EOR or storage. In the latter case it may not be possible to reuse infrastructure if it was not designed and constructed with CO_2 injection service in mind. Geological sequestration of CO_2 is performed with the substance as a supercritical fluid, i.e., above its critical temperature and pressure on the phase diagram (See Figure 5). Due to differences in fluid pressure, temperature and necessary material properties, as previously mentioned concerning potential corrosion, pitting or cracking, it's impossible.

2.1.3 Utilization

Aside from treating it as a waste for permanent storage, CO_2 is also a key input in many industries. As presented in the ABS publication *Carbon Capture, Utilization and Storage*, the current demand for CO_2 is around 230 million tonnes (Mt) globally per year, and the fertilizer industry alone consumes 125 Mt per year as a raw material in urea manufacturing. Oil and gas producers use around 70 to 80 Mt annually for EOR. Carbon dioxide is also integral for food and beverage production, cooling, water treatment and agriculture, but the demand is relatively small. Additionally, CO_2 is utilized in the chemical industry: indicatively mentioned Sabatier synthesis (methane production), Fischer-Tropsch synthesis (liquid hydrocarbon (HC) production), hydrogenation to methanol and hydrogenation to formic acid.

The processing of the CO_2 stream differs from processing CO_2 for sequestration since CO_2 suitable for EOR or other industrial uses will not likely be fit for food and beverage production, and the purity impacts the carriage requirements.

2.2 Role of CO_2 Transportation in the Carbon Value Chain

Analyzing the role of CO_2 transportation should be concluded in order to build a complete CCUS business model, including understanding challenges, evaluating suitable methods, and considering engineering parameters. The development of new carbon capture projects from various emitters, and the necessity to sequestrate it in dedicated receivers in larger geographical areas make CO_2 transport an essential factor in enabling the deployment of CCUS.

Transport of CO_2 for sequestration requires the implementation of both a coordinated and efficient transportation network. The two main options for large-scale transport are pipelines and ships. Such pipelines are the most obvious solution, particularly where a constant flow from the CO_2 capture sites is required. Where economies of scale do not justify pipelines as the transportation method in a CCUS project, other possibilities include ships, railways and motor carriers [1].

2.2.1 Pipeline Transportation at Supercritical Conditions

Pipeline transport has been practiced for many years on a large scale. There are extensive networks of pipelines used for CO_2 providing injection media for enhanced oil recovery operating for over 50 years in the oil and gas industry. As mentioned by Rahmanian, nearly 360,000 kilometers (km) of pipelines may be required to transport the CO_2 captured from industrial processes by 2050. The U.S. projects to construct between 17,700 and 37,000 km additional CO_2 pipelines before 2050 [2].

For offshore storage, the CCUS industry will build a similar infrastructure to typical ones for oil and gas distribution. Terminal facilities will be needed to transition from land to subsea pipelines or ships. Subsea pipeline and termination manifolds, as well as riser connections to fixed or floating offshore platforms, are also already under study.

The transportation of the CO_2 stream occurs in pipelines above 73.8 bar and a temperature of 31.1° C to keep it in a supercritical state. Pipelines are designed and constructed for the required temperature and pressure characteristics and use necessary materials to avoid corrosion, pitting or cracking when considering the content of the CO_2 stream (e.g., accompanying water, nitrogen, hydrocarbons, oxygen, sulfur and sulfides). Risk management should consider inspections, maintenance, leak detection and other means to reduce the likelihood of a release and to minimize its extent in case a release does occur.

2.2.2 Shipping Transportation as Liquid — LCO_2 Carriers

Although pipelines are an established mode of CO_2 transportation, they require a continuous flow of compressed gas, and their costs are highly dependent on distance. Additionally, with the global expansion of CCUS, transporting CO_2 by ships presents a unique business case, particularly for remote emitters over long distances and smaller quantities. Figure 2 illustrates a projection of carbon trading routes based on previous ABS analysis. The importance of transporting CO_2 by ship has been recognized at the European Union (EU) level; in the European Taxonomy for Sustainable Activities and the EU Emissions Trading System (ETS) Directive, as well as at a national level, such as the Dutch SDE++ subsidy scheme and the United Kingdom's CCUS program [3].

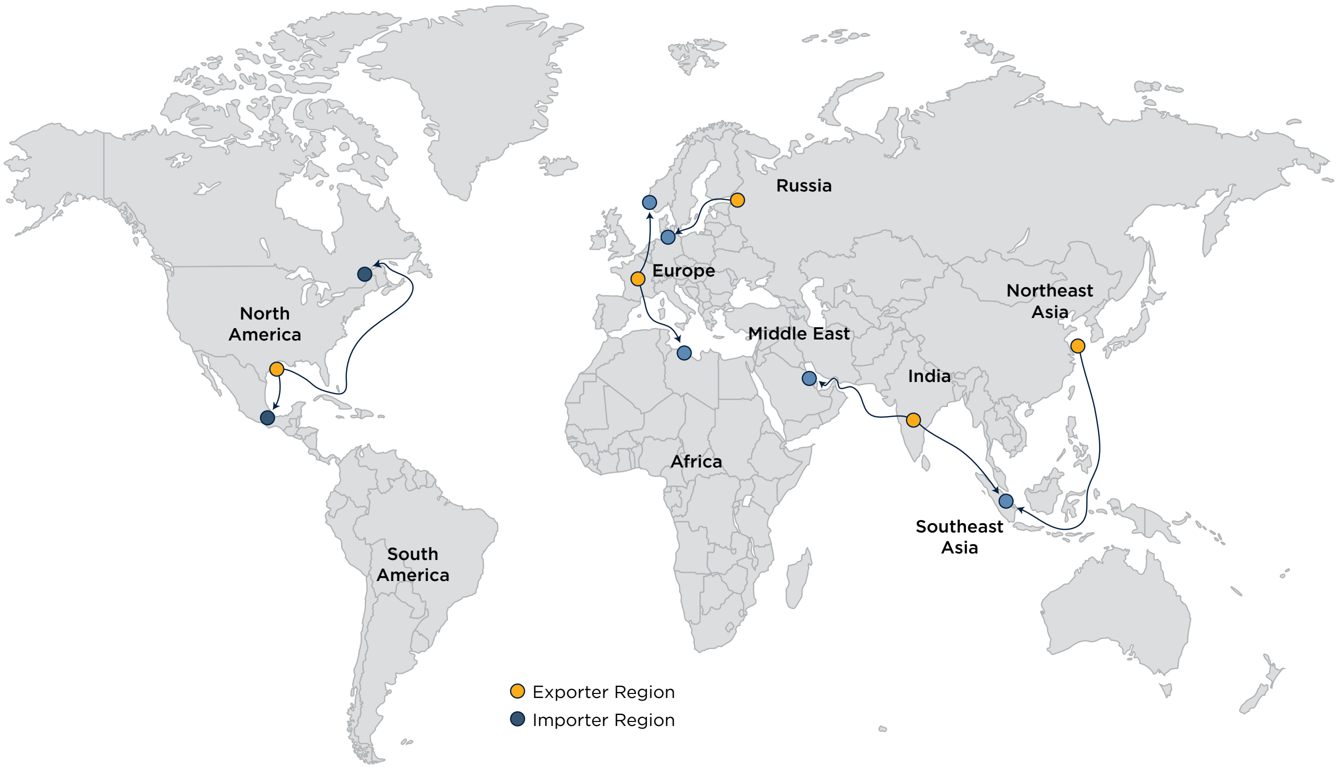

Figure 2: Global carbon trade routes projection.

Unlike the supercritical conditions required for transportation through pipelines, CO_2 is currently transported as LCO_2 with ships. At the range of temperatures and pressures used for LCO_2, its volume is approximately 1/500th of the CO_2's volume at standard temperature and pressure.

Figure 3 presents a schematic of the shipping chain from the source to storage. It illustrates the process of capturing CO_2 from a power plant, liquefying and storing it, loading it onto an LCO_2 carrier and delivering it to the final port of destination, where it connects to the endpoint transmission line.

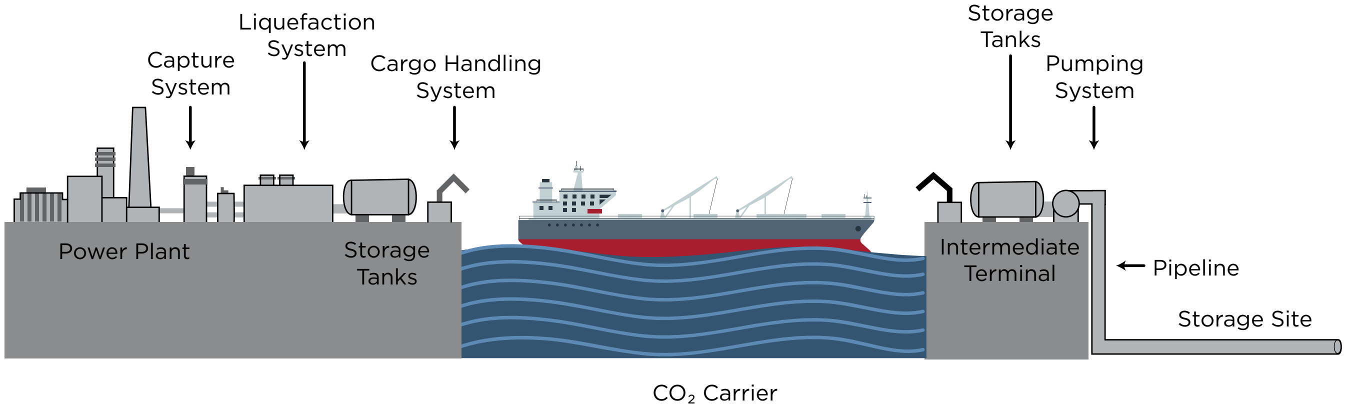

Figure 3: Carbon dioxide shipping chain [1].

Transfers from ship-to-ship or from ship to floating platform will require detailed analysis of the relative motion parameters to support the design of the transfer system, similar to recent developments for the liquefied natural gas (LNG) ship-to-ship transfer systems.

On a global scale, the total cross-border movement of captured CO$_2$ within the CCUS ecosystem via shipping could approach ~170 MtPA by 2050, driven by routes in both Asia Pacific and Europe. Globally, the number of vessels required to facilitate this would range from 100 to 200, depending on realized shipping routes globally and the capacity of the vessels for Europe [29].

The current fleet includes seven LCO$_2$ carriers in service and six on order, with deliveries planned for 2025 to 2026 (See Table 1).

Among the vessels in service, one – the *Excool* – is used for research and development and serves as a demonstration project for the transportation of CO$_2$ (conducted by Japan's New Energy and Industrial Technology Development Organization – NEDO) and is owned by Sanyu Kisen. Four other vessels are currently serving the food and beverage industry, transporting small capacities (~1,700 tons CO$_2$) at operating pressures of 15 to 19 bar(a). The remaining two vessels in service, with a capacity of 7,500 cubic meters (m^3) at operation pressure of 13 to 18 bar(g), support the Northern Lights project.

Shipyard	Type	gt	Built	Status	Company
Hyundai Mipo	LCO$_2$/LPG Carrier	21,034	2025	On Order	Capital Gas
Hyundai Mipo	LCO$_2$/LPG Carrier	21,034	2026	On Order	Capital Gas
Hyundai Mipo	LCO$_2$/LPG Carrier	21,034	2026	On Order	Capital Gas
Hyundai Mipo	LCO$_2$/LPG Carrier	21,034	2026	On Order	Capital Gas
DSOC	LCO$_2$ Carrier	8,035	2025	On Order	Northern Lights
DSOC	LCO$_2$ Carrier	8,035	2026	On Order	Schulte Group
DSOC	LCO$_2$ Carrier	8,035	2024	In Service	Northern Lights
DSOC	LCO$_2$ Carrier	8,035	2024	In Service	Northern Lights
Royal Bodewes SY	LCO$_2$ Carrier	2,506	2005	In Service	Nippon Gases Europe
Royal Bodewes SY	LCO$_2$ Carrier	2,506	2005	In Service	Nippon Gases Europe
Royal Bodewes SY	LCO$_2$ Carrier	2,474	2004	In Service	Nippon Gases Europe
Frisian Shyd.	LCO$_2$ Carrier	1,825	1999	In Service	Nippon Gases Europe
MHI Shimonoseki	LCO$_2$ Carrier	996	2023	In Service	Sanyu Kisen

Table 1: LCO$_2$ carrier in service and orderbook/ABS analytics.

Techno-economical assessments have shown that LCO_2 will predominantly be transported at cryogenic conditions [5].

Currently, no ship transports CO_2 in the 6 to 8 bar(g) pressure range. However, significant progress is being made in joint industry projects, such as the one between Ecolog, Hanwha Ocean, Babcock LGE and ABS, which recently issued an approval in principle (AIP) for a low-pressure, 40,000 m^3 LCO_2 carrier. Unlike onshore CO_2 handling systems and transportation by pipelines, the lack of comprehensive engineering data presents certain challenges during the feasibility study stage for low-pressure transportation. These challenges include the cargo handling at low pressure near the CO_2 triple point and ensuring appropriate material selection.

3 BASIS OF DESIGN FOR LCO_2 CARRIERS: PARAMETERS AND CONDITIONS FOR DESIGN

The design of the cargo tanks must comply with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, (IGC Code). The IGC Code has been the basis for the design of cargo tanks for liquefied petroleum gas (LPG) carriers since the 1960s.

While most designs take into consideration pure CO_2, the development of LCO_2 carriers requires a comprehensive understanding of the behavior of CO_2 as cargo. Impurities that may exist in the mixture of different carbon capture methods and processes can have a significant impact on:

- Health and safety matters with toxic substances
- Thermophysical properties of CO_2 mixture (phase diagram, density)
- Corrosivity and material selection (corrosion through reactions, free water)
- Reliquefication plant design (incondensable)

3.1 Health and Safety Matters

The primary hazard of CO_2 is that it can be designated as an asphyxiant, while at high concentrations it can also be classified as toxic. Table 2, taken from a publication by the Society of International Gas Tanker and Terminal Operators (SIGTTO) [28], summarizes the exposure limits from various standards.

Source	Threshold limit value (TLV) (ppm)	Short-term exposure limit (STEL) (ppm)
HSE (U.K.) [6]	5,000 (8 hours)	15,000 (15 minutes)
OSHA (U.S.) [7]	5,000 (8 hours)	-
NIOSH (U.S.) [8]	5,000 (10 hours)	30,000 (15 minutes)
ACGIH (U.S.) [9]	5,000 (8 hours)	30,000 (15 minutes)
Directives 91/322/EEC [10] and 2000/39/EC (EU) [11]	5,000 (8 hours)	-
Ordinance on Health Standards in the Office (MHLW Japan) [12]	5,000 (8 hours), 40 hours/week	-
GBZ2.1-2019 (China) [13]	5,000 (8 hours)	9,000 (15 minutes)

Table 2: CO_2 toxicity levels.

3.2 Thermophysical Properties (Phase Diagram, Density)

Carbon dioxide is a non-flammable gas at atmospheric pressure and ambient temperature. It can be liquefied at various pressures between the triple point (5.18 bar(a), -56.6° C for pure CO_2) and critical point (73.8 bar(a), 31.1° C). Figure 4 illustrated the phase diagram of CO_2.

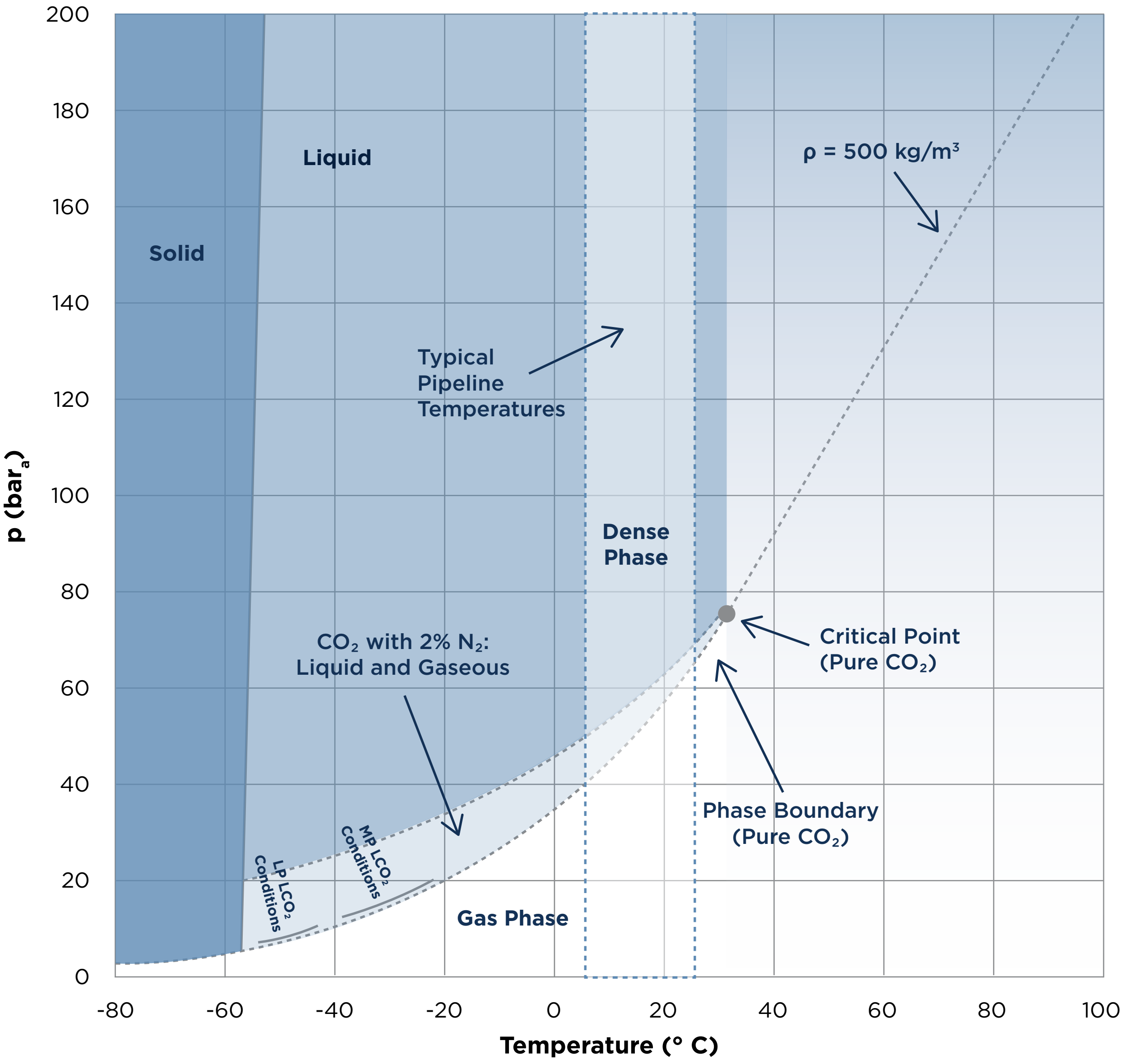

Figure 4: Phase Diagram of CO_2 with pressure areas of transportation [3].

Consideration of the physical properties of CO_2 is crucial to the design parameters of the tanks, specifically the vapor-liquid phase behavior of CO_2. Tables 3 and 4 summarize the Norwegian Ministry of Petroleum's assessment of vessel transportation of CO_2 under three different conditions. Although the report concludes that these solutions are technologically feasible, a number of different considerations must be carefully evaluated. Low-pressure conditions, although associated with higher propensity for dry-ice formation due to the proximity to the triple point, enhance cargo efficiency due to its high-density state.

Condition	Low-pressure (0.7–0.8 MPa, 223 K)	Medium-pressure (1.5 MPa, 248 K)	High-pressure (4.5 MPa, 283 K)
Advantages	• High density • Established know-how on LPG experience • Scalable tank size and ships	• Commercially mature concept in the food and brewery industries	• Low conditioning costs • Most appropriate condition for direct-injection from ship
Challenges	• Proximity to solid phase • High conditioning costs • Complex insulation	• Relatively high volume of steel in the tank • Technically challenging tank structure	• Complex design of tanks • Low TRL • Low density • Risk for cold boiling liquid expanding vapor explosion (BLEVE)

Table 3: General assessment of alternative transport conditions for CO_2 shipping [1].

	Low-pressure	Medium-pressure	High-pressure
Temperature (° C)	-55 to -40	-30 to -20	0 to 15
Pressure Bar(g)	5 to 10	15 to 20	35 to 50
Density (kg/m³)	1,170 to 1,120	1,080 to 1,030	930 to 820
Tonnes cargo weight per m³	1.2 to 1.1	1.1 to 1.0	0.9 to 0.8

Table 4: Pressure and temperature of the three conditions considered for CO_2 transportation [14].

For reference, CO_2 at ambient conditions has a density of approximately 1.8 kg/m^3, while at liquid phase (close to -50° C and 7 bar(a)) it reaches approximately 1,100 kg/m^3. A higher density means more CO_2 mass can be transported under a fixed volume. For LCO_2, the density increases when the pressure is reduced due to the lower equilibrium temperature.

3.3 Corrosivity and Material Selection (Corrosion Through Reactions, Free Water)

Type C tanks are considered the most suitable for LCO_2 transportation and are traditionally cylindrical or bi-lobe shapes arranged in vertical or horizontal configurations. Plate thickness is correlated to design pressure and governs the maximum diameter and tank capacity.

The material selection must account for the low-temperature operating conditions. According to the CO_2 phase diagram, a pressure of 6 bar(g) corresponds to a temperature of -50° C, which is close to the limit for carbon-manganese steel. If the pressure is higher, higher steel plate thickness will be required, increasing the tank weight, complexity of tank construction, and weldability. These factors limit the tank capacity and increase the number of cargo tanks required to achieve the desired carrying capacity.

For the case of LCO_2 carriers, material selection should always comply with the IGC Code's Chapter 6 requirements for steel plates up to 40 mm thickness. Above 40 mm and up to 50 mm, IACS UR W1 applies. As per IGC Code 6.6.2.2, post-weld heat treatment (PWHT) is required. An exemption to post-weld stress relief heat treatment based on an alternative approach (e.g., engineering critical assessment) must be approved by the classification society or adhere to recognized standards.

Table 5 shows the materials currently used for the LCO_2 carriers under construction in the shipyards. While 5 percent and 9 percent nickel steels can be suitable for LCO_2 applications, they are typically more expensive. New carbon-manganese steel materials of higher strength, such as LT51 and F550, are being developed by steel mills and are subject to approval from classification societies.

	LT36	P690
Specific Min. Yield Strength (MPa)	355	690
Specific Min. Tensile Strength (MPa)	490	770 to 940
Application	Low-pressure	Medium-pressure

Table 5: LCO_2 cargo tank materials.

Among others, the challenge with the above is the composition of the CO_2 stream. The quantitative impact of the impurities in the CO_2 mixture needs to be investigated through proper research for shipboard transportation.

4 CO_2 QUALITY SPECIFICATIONS AND BEHAVIOR AS A CARGO

Commercializing CO_2 for industrial applications such as welding, food and beverage production, chemical manufacturing, medical application and laboratory use requires strict requirements concerning purity grades. The presence of impurities, even in trace amounts, can cause interference or contamination. For instance, in the U.S., the Food and Drug Administration (FDA) mandates that beverage-grade CO_2 purity cannot contain more than 0.09 percent hydrocarbons. In the EU, the European Commission (EC) regulates food-grade CO_2 with stated minimum purity criteria for food-grade gases such as CO_2, nitrogen and oxygen. Each must adhere to a number code and must be of high purity.

Using CO_2 as a waste product requires a different approach. The fundamental question for the carbon value chain is: What is the composition of the CO_2 cargo?

Currently, there are no commercial drivers to establish a standard for permissible impurity levels in CO_2 for carbon capture and storage (CCS). Existing agreements, such as those for EOR, are business-specific, with requirements for the CO_2 compositions defined in contracts between suppliers, transporters, and storage operators [15]. However, one significant challenge in the future CCUS business model is the varying impurity compositions from different sources that may have practical, health, safety and/or environmental impacts on CO_2 transport and storage systems.

The commonly accepted minimum CO_2 stream purity is greater than 95 percent mole (mol), aligning with the guidance given in ISO/TR 27921:2020 [13 to 16].

4.1 CO_2 Stream Composition and Cross Cutting Issues for CCUS and LCO_2 Carriers

Currently, there are no established standards for CO_2 as shipping cargo, but only project-specific recommendations. The experience of the marine industry and knowledge of the impact of impurities comes from onshore systems and EOR processes. This publication examines the type of impurities and their potential impact on the vessel design by addressing any cross cutting issues, emphasizing the need for simulation and experiments.

The ISO/TR 27921:2020 technical report provides information about the gas composition in carbon capture, transportation and geological storage, but due to limited data and understanding, it does not define a fixed maximum concentration of a single impurity when other impurities are or may be present [16].

The CO_2 stream composition affects the design and operation of the entire carbon value chain, including the capture process, final purification, transportation and sequestration. However, it is difficult to identify thresholds for individual impurities for two main reasons:

- Site-specific risk studies are usually carried out by operators, assessing project-specific data and environmental factors.
- The impacts due to the interaction between multiple impurities and their surroundings can differ from those of a single impurity in the CO_2 stream.

As a result, impurity concentration thresholds are case-specific and subject to optimization for the entire CCUS process with respect to safety, environmental protection, cost and energy demand.

4.2 Common Impurities in the CO_2 Stream

The CO_2 captured from various sources contains a variety of trace gases depending on the chemistry of the source's feedstock, the carbon capture technology, the solvents or absorbents utilized, and the downstream clean-up technology deployed. As per the ISO document, recognized impurities in a CO_2 stream typically include the following:

- Oxygen (O_2)
- Water (H_2O)
- Nitrogen (N_2)
- Hydrogen (H_2)
- Sulfur oxides (SO_x)
- Nitrogen oxides (NO_x)
- Hydrogen sulfide (H_2S)
- Hydrogen cyanide (HCN)
- Carbonyl sulfide (COS)
- Ammonia (NH_3)
- Amines
- Aldehydes
- Particulate matter (PM)

Two primary factors determine how impurities affect CCUS systems:

- Physical effects: Impact on phase behavior and transport conditions
- Chemical effects: Corrosivity, toxicity and interactions with materials

4.2.1 Sources of CO_2 Impurities

The source of impurities depends on the sourcing process, the capturing technology and the additional separation or purification process. Table 6 illustrates an indicative CO_2 composition based on the following capturing technologies:

- Pre-combustion
- Post-combustion
- Oxy-fuel

The composition of CO_2 impurities is similar in pre- and post-combustion capture methods, whereas the oxy-fuel capture method produces a significantly different composition of certain impurities.

Impact	Component	Post-combustion	Pre-combustion	Oxy-fuel
	CO_2	> 98 vol% purity	> 98 vol% purity	> 85 vol% purity
Corrosion	H_2O	Before Compression: High moisture up to 5% by mass. After Compression: < 2200 ppmv. Needs further drying.	Depends on the solvent. < 600 ppmv. No need further drying.	High moisture up to 20% by weight depending on the moisture content in coal.
Corrosion and Compression	O_2	Low, < 2 to 3%	Low, < 2 to 3%	High, < 5%
Corrosion and Health and Safety	H_2S	Low levels	Low, up to 100 ppm (depending on separation process)	Low levels
Compression	N_2	Low, < 2 to 3%	Low, < 2 to 3%	High, < 6%
Compression	H_2	Low, < 2 to 3%	Low, < 2 to 3%	
Compression	Ar	Low, < 2 to 3%	Low, < 2 to 3%	High, < 5%
Compression	CH_4	Low, < 2 to 3%	Low, < 2 to 3%	
Health and Safety	HCN			
Compression	O_2	Low, < 2 to 3%	Low, < 2 to 3%	High, < 5 %
Corrosion	CO	Low concentration levels (20 ppm)	Low concentration levels (400 ppm)	Low concentration levels (50 ppm)
Health and Safety	SO_2	Low STEL levels (Requires SO_2 levels of < 10 ppmv to reduce amine losses)	Low concentration levels	High SO_2 depending on sulfur content of the fuel (up to 2,000 ppmv)
Health and Safety	NO_x	Low concentration levels (< 20 ppm)	Virtually zero concentration levels	Higher NO_x content when compared to combustion on air (< 100 ppm)
Health and Safety	Hg	Below detectable levels	Below detectable levels	Needs separation
Health and Safety	Amine			
Health and Safety	Glycol			
Health and Safety	NH_3	50 ppm		
Health and Safety	CH_3OH		200 ppm	

Table 6: Composition from different technologies [17].

The typical sources of CO_2 are coal and gas refineries, fired power plants, the steel and cement industries, and integrated gasification combined cycle (IGCC) systems. While the composition of impurities in CO_2 streams is generally similar across sources, there are some notable variations depending on the specific source. However, aside from these variations, the composition of impurities is largely independent of the CO_2 source.

The World Resources Institute's CCS Guide offers detailed information about the composition of impurities based on different CO_2 sources. Additional insights can be found in projects such as Sintef's IMPACT and the Northern Lights initiative in Norway, which consolidate data on impurities by emission activity.

Table 7 provides an overview of the expected CO_2 stream compositions for six CO_2 sources and their associated capture technologies responsible for the most extreme impurity levels. Concentrations are provided on a volume basis, with values expressed in parts per million (ppm) unless otherwise indicated as a percentage.

CO_2 source Capture technology	Coal-fired power plant Amine-based absorption	Coal-fired power plant Ammonia-based absorption	Coal-fired power plant Selexol-based absorption	Coal-fired power plant Oxy-fuel combustion	Natural gas processing Amine-based absorption	Synthesis processing Rectisol-based absorption
CO_2	98.8%	99.8%	98.2%	95.3%	95.0%	96.7%
N_2	2,000	2,000	6,000	2.5%	5,000	30
O_2	200	200	1	1.6%		5
Ar	100	100	500	6,000		
NO_x	50	50		100		
SO_x	10	10		100		
CO	10	10	400	50		1,000
H_2S			100		200	9,000
H_2			1.0%			500
CH_4			1,000		4.0%	7,000
C_2+					5,000	1.5%
NH_3	1	100				
Amine	1					

Table 7: Overview of expected typical CO_2 stream composition [18].

4.2.2 Effects of CO_2 Impurities

Per the design basis of a CCUS system, common impurities are grouped based on three aspects:

- Thermophysical effects on phase boundaries (N_2, O_2, Ar, CH_4, H_2)
- Corrosivity (O_2, H_2O, SO_x, NO_x H_2S)
- Health and safety considerations: These are determined by short-term exposure limits (STEL) and long-term exposure limits (LTEL) as per local regulations (include NO_2, CO, H_2S, SO_2, HCN, COS, NH_3, among others)

Impurities are typically classified into two main types – condensable and non-condensable. Non-condensable impurities are further divided into the following three categories:

- Major impurities: Present at concentrations above 0.5 percent
- Minor impurities: Typically, at ppm levels but less than 0.5 percent
- Micro-impurities: PM with varying composition percentages

Not all impurities impact the system the same way, with some having a more significant influence than others (Refer to Table 8). For instance, non-condensable impurities can alter the thermodynamic and physical properties of the CO_2 stream, such as increasing the saturation pressure and lowering the critical temperature [2, 16, 19, 20].

The impurity composition directly affects several parameters:

- Available volume and mass of containment: High impurity levels can significantly reduce volumetric capacity. For example, a 10 percent hydrogen concentration can reduce capacity by 27 percent.
- Physical properties and transport conditions: Impurities influence compression, liquefaction and power demands.
- Material durability: The composition can impact corrosion, fracture, and failure of metallic and non-metallic components.
- Hydrate formation: Certain impurities increase the likelihood of hydrates forming in the system.

Component	Limit	Reason	Reference
Water	300 ppm	To prevent corrosion damages in presence of CO_2, H_2S, SO_2 and NO_x	Murugan et al., 2020 [5]
	< 60% water saturation level in gas stream	Below solubility limit of water in CO_2.	WRI CCS Guideline, 2008 [6]
	30 lb/MMcf (~600 ppm wt)	Corrosion risk	IEAGHG, 2016 [7]
N_2, O_2, Ar	< 4 vol%	Can increase compression required power and decrease storage capacity	De Visser et al., 2008 [8]
O_2	< 10 ppm	• In CO_2-EOR application due to growth of bacteria and combustion of hydrocarbons • Significant impact on corrosion rate	Murugan et al., 2020 [5]
H_2	< 4 vol%	Can increase compression required power and decrease storage capacity	De Visser et al., 2008 [8]
CO	< 1,000 ppm 900 to 5,000 ppm	• For CO_2-EOR applications • Health and safety considerations	Murugan et al., 2020 [5]
H_2S	200 ppmv	• Immediately dangerous to life or health • Corrosion Risk	NETL, 2012 [9]
SO_2	100 ppmv	• Immediately dangerous to life or health • Corrosion Risk	NETL, 2012 [9]
NO_x (NO, NO_2)	100 ppmv	IDLH level	Sim et al., 2013 [4]
Mercury	Gas processing: <0.01 µg/m^3 CO_2-EOR: 0.3 gal/MMcf	Toxicity and corrosion impact on some metals	De Visser et al., 2008 [8]
Particulates	0 to 1 ppmv	• To prevent damage or equipment fouling • Can block geological storage pores	NETL 2012 [9]
Glycol	0.3 gal/MMcf	Process fluid	Murugan et al., 2020 [5]
NH_3	25 ppm	Toxicity and potential particulate formation with nitric/sulfuric acids	Murugan et al., 2020 [5]

Table 8: Summary of Impurity Specifications in CO_2-rich Streams and their Impacts in the CCUS Chain [21].

Because of the nature of the impurities, there are effects such as corrosion due to the relation between CO_2 composition and injection and storage and the effects of impurities on the external safety of pipelines and hubs for geological storage.

Thus, a lot of projects are setting requirements for specifications. Some recommended specifications, modeled data and real-life composition data obtained from various projects are available in the literature. The maximum acceptable concentration of some common impurities as per three different projects and the maximum value available in the literature are provided in Table 9. The upper limits may be chosen for safer design and operational flexibility but may be less cost-efficient.

Effects	Constituent		CarbonNet proposed specs	NPL report	Dynamis	Max in lit
	CO_2	min	97.5% V	95% V	95.5% V	90% V
Corrosion	H_2O	max	100 ppmv	30 ppmv	500 ppmv	50 ppmm
Compression	N_2	max	0.8% V	4% V	4% V	4% V
Compression	H_2	max	0.8% V			4% V
Compression	Ar	max	0.2% V			4% V
Corrosion	O_2	max	200	50 ppmv	4% V	
Compression	CH_4	max	500	0.7% V	4% V	4% V
	Other HC	max	2% V			
	Total HC			5% V		
Health and Safety	HCN	max	0.002% V			
Health and Safety	CO	max	5,000 ppmv	1,000 ppmv	2,000 ppmv	5,000 ppmv
Corrosion	H_2S	max	200 ppmv	10,000 ppmm	200 ppmv	1.3% V
Health and Safety	SO_2	max	2,000 ppmv		100 ppmv	50,000 ppmv
	S	max		35 ppmm		
Health and Safety	NO_x	max	2,500 ppmv		100 ppmv	2,500 ppmv
Health and Safety	Hg					Stel 0.003 ppmv
Health and Safety	Amine					Stel 6 ppmv
Damage sealing materials	Glycol					174 ppbv
Health and Safety	HF					3 ppmv
Health and Safety	HCl					5 ppmv
Health and Safety	C_2H_4O					50 ppmv
Health and Safety	NH_3					50 ppmv
Explosive	C_3H_8					1% V
Explosive	C_2H_6					1% V
	Particulate					1% V

Table 9: CO_2 composition for different projects.

A generic impurity level, based on end-use requirements, as indicated in the ENCAP project (Enhanced Capture of CO_2 – EU Funded) is provided in Table 10.

Component	Concentration	Limitation
H_2O	500 ppm	Technical: Below solubility limit of H_2O in CO_2. No significant cross effect of H_2O and H_2S, cross effect of H_2O and CH_4 is significant but within limits for water solubility.
H_2S	200 ppm	Health and safety considerations
CO	2,000 ppm	Health and safety considerations
O_2	Aquifer < 4 volume %, EOR 100 to 1,000 ppm	Technical: Range for EOR, because lack of practical experiments on effects of O_2 underground.
CH_4	Aquifer < 4 volume %, EOR < 2 volume %	As proposed in ENCAP project
N_2	< 4 volume % (all non-condensable gases)	As proposed in ENCAP project
Ar	< 4 volume % (all non-condensable gases)	As proposed in ENCAP project
H_2	< 4 volume % (all non-condensable gases)	Further reduction of H_2 is recommended because of its energy content
SO_x	100 ppm	Health and safety considerations
NO_x	100 ppm	Health and safety considerations
CO_2	> 95.5%	Balanced with other compounds in CO_2

Table 10: Recommended CO_2 Quality for CCS taken from the DYNAMIS project [22].

4.3 CO_2 Compositions Requirements for Project Sequestration and Impurities Thresholds

Specifications for CO_2 transportation can vary depending on whether they are designed to meet end-user needs or transport requirements. Additionally, the requirements for transporting CO_2 by ship differ from those for transportation through pipeline. While pipeline transportation of CO_2 is already well-established, shipping transportation is still in its early stages. This is due to a lack of sufficient academic and bibliographic references related to the design and handling of CO_2 cargo, particularly when impurities are present.

4.3.1 CO_2 Compositions Requirements for Piping

Before CO_2 is transported through pipelines, it is typically dehydrated to ensure water levels remain below 50 μmol mol-1. Maintaining this threshold is critical to prevent pipeline corrosion and ensure safe operation. According to an article by the World Resources Institute, CO_2 pipelines can be categorized into three main types based on the different purity levels of CO_2 that can be present [15] (Refer to Table 11).

Parameter	Type I	Type II	Type III
CO_2 — % by volume	> 95	> 95	> 96
H_2S	< 10	< 20	< 10,000
Sulfur — ppmbw	< 35	< 30	-
Total hydrocarbons — % by volume	< 5	< 5	-
CH_4 — % by volume	-	-	< 0.7
C_2 + hydrocarbons — % by volume	-	-	< 23,000
CO — % by volume	-	-	< 1,000
N_2 — % by volume/weight	< 4	< 4	< 300
O_2 — ppm by weight/volume	< 10	< 10	< 50
H_2O — #/mmcf* or ppm by volume**	< 25	< 30	< 20
C_2 = carbon; CH_4 = methane; CO = carbon monoxide; CO_2 = carbon dioxide; H_2O = water; H_2S hydrogen sulfide; mmcf = millions of cubic feet; N_2 = nitrogen, ppm = parts per million; O_2 = oxygen; ppmbw = ppm by weight			

Table 11: Acceptable purity levels of CO_2 for the different types of pipelines used for CO_2 transportation.

Indicatively, a prescribed impurity limit, as indicated in the CO_2 Europipe project, is provided in Table 12.

Impurity	Limit	Impurity	Limit
CO_2	> 95% by volume	NO_2	75 ppm
H_2O	No free water	CO	2,000 ppm
Ar	Together < 5% by volume	H_2S	200 ppm
CH_4		HCN	70 ppm
H_2		SO_2	75 ppm
N_2		COS	235 ppm
O_2		NH_3	550 ppm

Table 12: CO_2 Europipe Consortium [23].

4.3.2 CO_2 Compositions Requirements for Shipping

The emerging nature of CO_2 shipping and the absence of standardized guidelines for CO_2 cargo containing impurities present significant challenges. Impurities in the CO_2 stream can affect the system's thermodynamic properties, making the prediction of design parameters under cryogenic conditions difficult.

To address these uncertainties, insights from existing literature and the experience from pipeline transportation can be useful guidance for the development of design parameters and risk assessments necessary to obtain qualifications for concept designs.

Based on ZEP studies, there are two standards for the transportation of CO_2 by ships (Refer to Table 13).

Component	Northern Lights(1) Concentration (ppm mol)	EU(2) Recommendations
Carbon dioxide (CO_2)	Not defined	> 99.7% by volume
Acetaldehyde	$\leq$ 20	Not defined
Amine	$\leq$ 10	Not defined
Ammonia (NH_3)	$\leq$ 10	Not defined
Argon (Ar)	Not defined	< 0.3% by volume
Cadmium (Cd)/Titanium (Ti)	$\leq$ 0.03 (sum)	Not defined
Carbon monoxide (CO)	$\leq$ 100	< 2,000 ppm
Hydrogen (H_2)	$\leq$ 50	<0.3% by volume
Hydrogen sulfide (H_2S)	$\leq$ 9	< 200 ppm
Formaldehyde	$\leq$ 20	Not defined
Mercury (Hg)	$\leq$ 0.03	Not defined
Methane	Not defined	$\leq$ 0.3% by volume
Nitric oxide/nitrogen dioxide (NO_x)	$\leq$ 10	Not defined
Oxygen (O_2)	$\leq$ 10	Not specified as literature inconsistent
Sulfur oxides (SO_x)	$\leq$ 10	Not defined
Water (H_2O)	$\leq$ 30	$\leq$ 50 ppm

Table 13: Two published CO_2 compositions for shipping [14].

Northern Lights published updated LCO_2 quality specifications in February 2024, with stricter specifications on methane, nitrogen, nitrogen oxides, mercury and argon (Refer to Table 14).

Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]
Carbon dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)
Water (H_2O)	ppm-mol	≤ 30
Oxygen (O_2)	ppm-mol	≤ 10
Sulfur oxides (SO_x)	ppm-mol	≤ 10
Nitrogen oxides (NO_x)	ppm-mol	≤ 1.5
Hydrogen sulfide (H_2S)	ppm-mol	≤ 9
Amine	ppm-mol	≤ 10
Ammonia (NH_3)	ppm-mol	≤ 10
Formaldehyde (CH_2O)	ppm-mol	≤ 20
Acetaldehyde (CH_2CHO)	ppm-mol	≤ 20
Mercury (Hg)	ppm-mol	≤ 0.0003
Carbon monoxide (CO)	ppm-mol	≤ 100
Hydrogen (H_2)	ppm-mol	≤ 50
Cadmium (Cd), Thallium (TI)	ppm-mol	Sum ≤ 0.03
Methane (CH_4)	ppm-mol	≤ 100
Nitrogen (N_2)	ppm-mol	≤ 50
Argon (Ar)	ppm-mol	≤ 100
Methanol (CH_3OH)	ppm-mol	≤ 30
Ethanol (C_2H_5OH)	ppm-mol	≤ 1
Total volatile organic compounds (VOC)[2]	ppm-mol	≤ 10
Mono-ethylene glycol (MEG)	ppm-mol	≤ 0.005
Tri-ethylene glycol (TEG)	ppm-mol	Not allowed
BTEX[2]	ppm-mol	≤ 0.5
Ethylene (C_2H_4)	ppm-mol	≤ 0.5
Hydrogen cyanide (HCN)	ppm-mol	≤ 100
Aliphatic hydrocarbons (C_2+)[4]	ppm-mol	$\leq 1{,}100$
Ethane (C_2H_6)	ppm-mol	≤ 75
Solids, particles, dust	ppm-mol	≤ 1

Table: 14: LCO_2 Quality Specifications [24].

The presence of non-condensable gases in CO_2 streams significantly impacts energy consumption during compression and liquefaction in the case of low-pressure and low-temperature transportation by ship. As the concentration of inert constituents increases, the energy required for these processes rises proportionally. Different impurities affect energy consumption differently. For example [25]:

- A 1 percent concentration of O_2 increases compression work by approximately 2.5 percent.
- A 1 percent concentration of N_2 results in a 3.5 percent increase.
- A 1 percent concentration of H_2 leads to a 4.5 percent increase.
- A 5 percent concentration of H_2 leads to a 25 percent increase.

Table 15 indicates the CO_2 quality recommendations for ship transport.

Component	Concentration	Limitation	Reason
Water (H_2O)	50 ppm	Design and operational considerations	Freeze-out in heat exchangers
Hydrogen sulfide (H_2S)	200 ppm	Health and safety considerations	Short-term exposure limit
Carbon monoxide (CO)	2,000 ppm	Health and safety considerations	Short-term exposure limit
Methane (CH_4)	< 0.3% v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Nitrogen (N_2)	< 0.3% v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Oxygen (O_2)	Unknown	Literature not consistent	Challenges in the reservoir
Argon (Ar)	< 0.3% v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Hydrogen (H_2)	< 0.3% v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Carbon dioxide (CO_2)	> 99.7% v/v	Balanced with other compounds	Dry ice formation

Table 15: CO_2 quality recommendations for ship transport [25].

4.4 Thermophysical Properties of the CO_2 Stream and Cargo Handling

The development of LCO_2 carriers requires a solid understanding of the behavior of CO_2 as cargo. Carbon dioxide is a non-flammable gas at atmospheric pressure and ambient temperature. As previously mentioned, CO_2 can be liquefied at various pressures between the triple point (5.18 bar(a), -56.6° C for pure CO_2) and critical point (73.8 bar(a), 31.1° C) (Refer to Figure 5). To maximize cargo density, the preferable cryogenic conditions are at low temperature and pressure. However, the composition of the CO_2 stream may affect the thermodynamic properties of the CO_2 stream and impact materials and cargo handling. Table 16 provides an overview of the pysucak and thermodynamic properties and their relevance to CO_2 shipping.

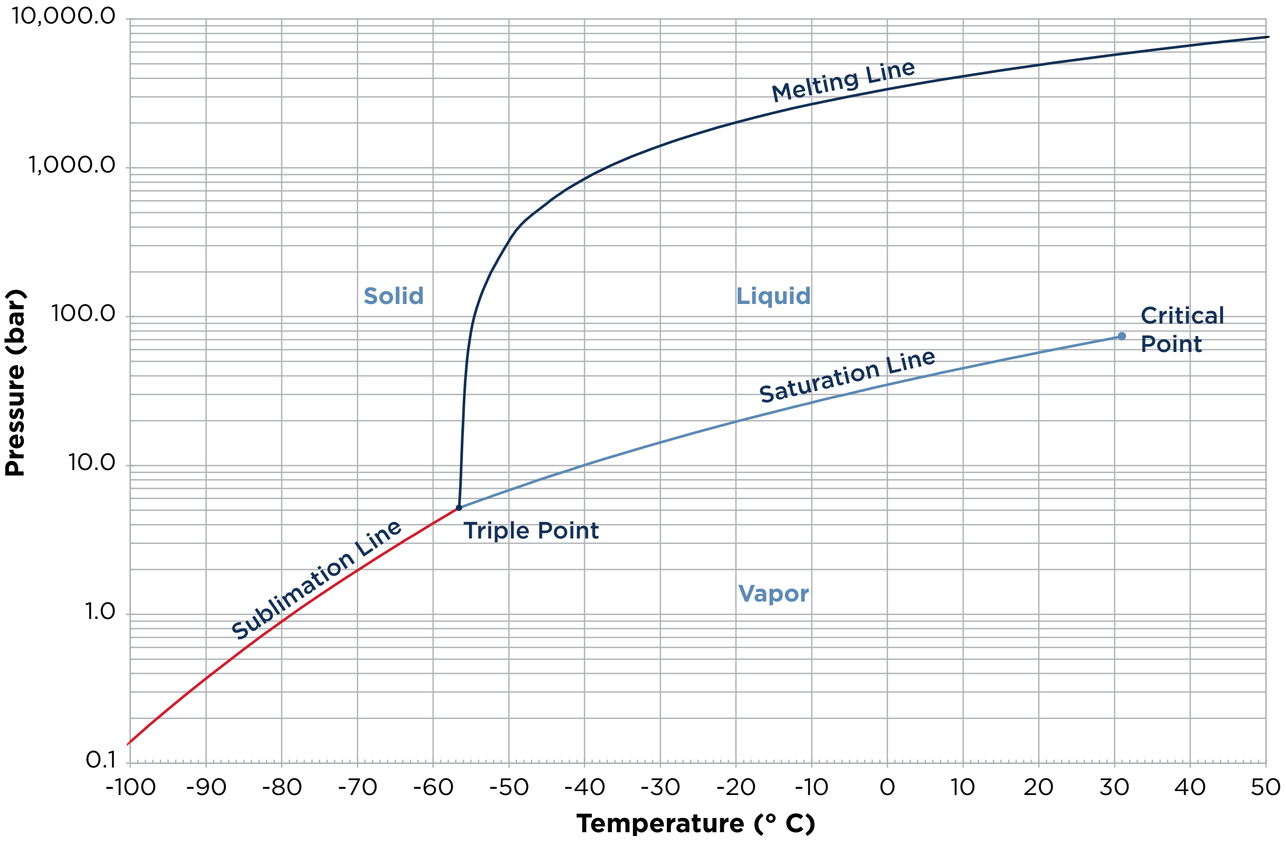

Figure 5: CO_2 phase diagram [26].
© 1999 ChemicaLogic Corporation, Drawn with CO_2 Tab V1.0

Property	Relevance	Remarks	Impurities
Density	Vessel dimensioning, compressor and pump design, carrier stability	Highest near the triple point	N_2, Ar, H_2S
Solubility of water	Risk of corrosion and hydrate formation	Limited experimental data covering shipping conditions	CH_4, N_2, NO_2, SO_2, O_2
Viscosity	Estimation of pressure drop in the system, Design of process equipment	Liquid viscosity data is limited to CO_2 - H_20 systems	H_2O
Phase Equilibria	Water solubility, Phase boundaries, Liquid loading/ unloading, Temperature-pressure characteristics	Minimal presence of impurities can alter phase equilibria significantly	H_2, SO_2, N_2

Table 16: Physical and thermodynamic properties and their relevance to CO_2 shipping [1].

4.4.1 Phase Equilibria of CO_2 Mixtures

A comprehensive understanding of pressure, temperature and composition mechanisms is essential to developing appropriate conditioning, transport and storage procedures, as CO_2 will always need to be processed in liquid forms throughout the shipping transport chain. However, there is a lack of vapor-liquid equilibrium (VLE) data relevant to shipping conditions for binary systems such as CO_2–COS, CO_2–NO, CO_2–amines, CO_2–SO_2 and even more for tertiary systems. This challenge is getting more complicated based on the variable compositions of CO_2 from different emitters and the absence of a common standard CO_2 composition.

Depending on the impurities, the phase boundaries widen and the pressure requirement for single-phase containment changes. For pipeline transportation, impurities increase the critical temperature and pressure and influence the operating region. The two-phase region is not economical or the preferred region of operation.

The presence of non-condensable gases affects the phase behavior of CO_2. The following non-condensable gases might be present in CO_2: H_2, argon (Ar), N_2, O_2 and methane (CH_4). These non-condensable gases have an extremely low tendency to interact with other materials but will dilute CO_2 making phase change more complex than the normal coexistence of pure CO_2 and LCO_2 at constant pressure and temperature. Their presence also increases the pressure requirements for the condensation of CO_2.

For pipeline transportation, these non-condensable impurities affect the transport and injection capacity by increasing the critical pressure, consequently causing supercritical transport conditions with higher pressures and higher costs.

For shipping transportation, predicting and managing the behavior of LCO_2 under these conditions is even more critical. Table 17 below shows VLE data on shipping conditions for binary and ternary systems of different impurities.

System	Sources	Points	Temperature (K)	Pressure (MPa)	CO_2 concentrations (mol%)
CO_2 - N_2	34	> 700	208 to 303	0.6 to 21.4	0.15 to 0.99
CO_2 - O_2	8	> 292	218 to 298	0.9 to 14.7	0.15 to 0.99
CO_2 - Ar	4	~ 200	233 to 299	1.5 to 14	0.25 to 0.99
CO_2 - H_2S	8	> 270	248 to 365	1 to 8.9	0.01 to 0.97
CO_2 - CO	3	106	223 to 293	0.8 to 14.2	0.2 to 0.99
CO_2 - H_2	8	> 400	218 to 303	0.9 to 172	0.07 to 0.99
CO_2 - N_2 - O_2	3	80	218 to 273	5.1 to 13	0 to 0.93
CO_2 - CO - H_2	1	36	233 to 283	2 to 20	0.17 to 0.98
CO_2 - CH_4 - N_2	2	> 100	220 to 293	6 to 10	0.27 to 0.99
CO_2 - CH_4 - H_2S	1	16	222 to 239	2.1 to 4.8	0.024 to 0.78
CO_2 - CH_4 - H_2O	5	> 132	245 to 423	0.1 to 100	0.001 to 0.83

Table 17: VLE data for CCUS-relevant systems at shipping conditions [1].

Figure 6 illustrates the effect of impurities on pressure-temperature phase equilibria.

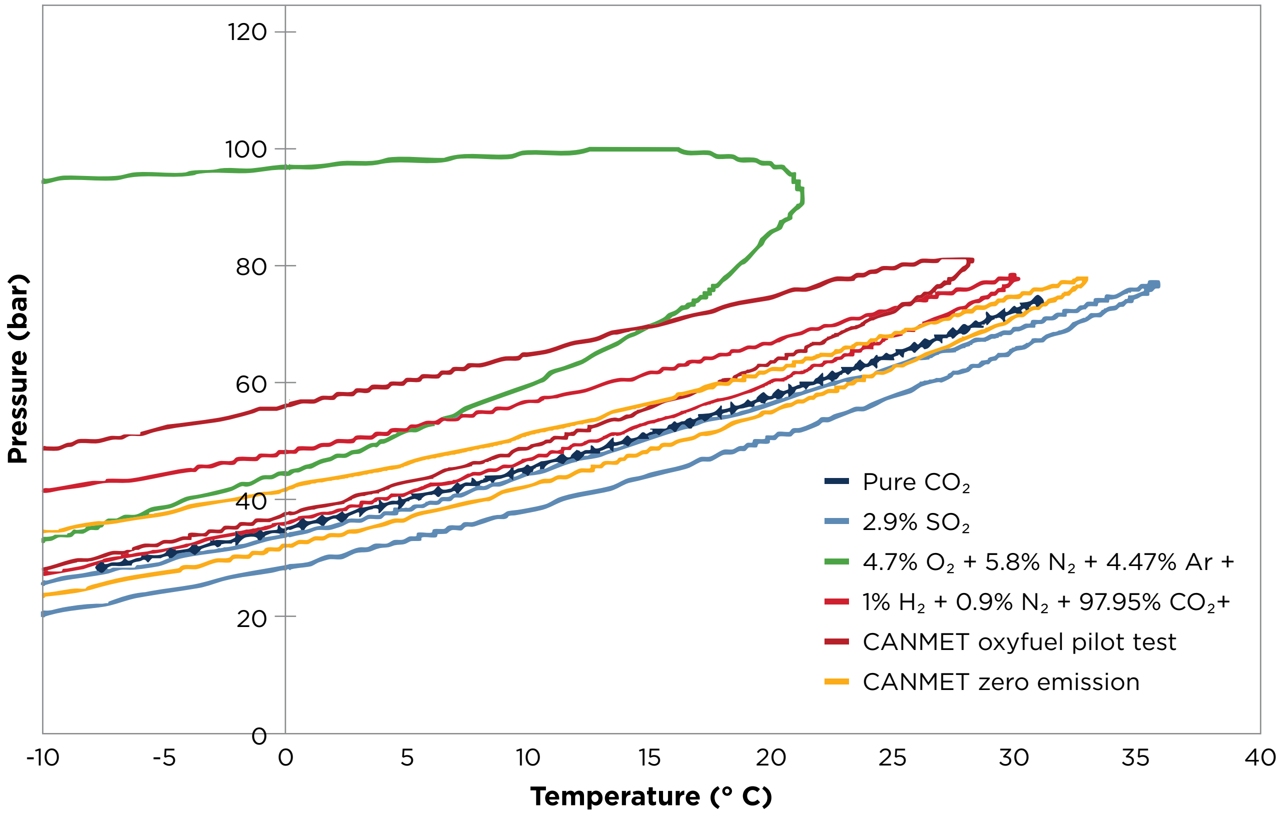

Figure 6: Calculated phase boundaries for mixtures of CO_2 [1].

Different impurities have varying effects on the CO_2 phase envelope. Vapor pressure can increase by as high as 30 percent due to incondensable impurities such as H_2, O_2 and N_2, even at concentrations below 0.5 mol percent. In contrast, SO_2 affects the phase envelope differently. A mixture of 98 mol percent CO_2 and 2 mol percent H_2 exhibits bubble-point pressures of 6.12 MPa and 6.24 MPa at 253 K and 263 K, respectively, higher than the bubble-point pressure of pure CO_2. The effect of impurities on bubble-point pressures at cryogenic temperatures is summarized in Table 18.

Mixture	Vapor pressure	Mixture	Vapor pressure
100% CO_2	0.67 MPa	CO_2 mixture — 0.05 mol% O_2	0.69 MPa
CO_2 mixture — 0.05 mol% N_2	0.7 MPa	CO_2 mixture — 0.05 mol% H_2	1.03 MPa
CO_2 mixture — 0.1 mol% N_2	0.73 MPa	CO_2 mixture — 0.05 mol% CO	0.7 MPa
CO_2 mixture — 0.05 mol% N_2	0.97 MPa	CO_2 mixture — 0.05 mol% Ar	0.68 MPa

Table 18: Effect of impurities on equilibrium pressure of CO_2 at 223 K [1].

4.4.2 Solubility in CO_2 and Challenges

When water dissolves in CO_2, it forms carbonic acid, which is a highly corrosive substance. The water content of supercritical CO_2 is temperature-dependent. While pure CO_2 with dissolved water below the saturation limit does not corrode carbon steel in operating conditions, it may form hydrates, which can cause blockages in the system. Hydrate formation becomes more problematic at higher operating pressures. A drop in pressure can cause water to separate from the CO_2, leading to the formation of carbonic acid and creating a corrosive environment. This makes temperature and pressure fluctuations a critical consideration for the design and operation of cargo containment systems.

The solubility of water in CO_2 increases with pressure and temperature (Refer to Figures 7 and 8).

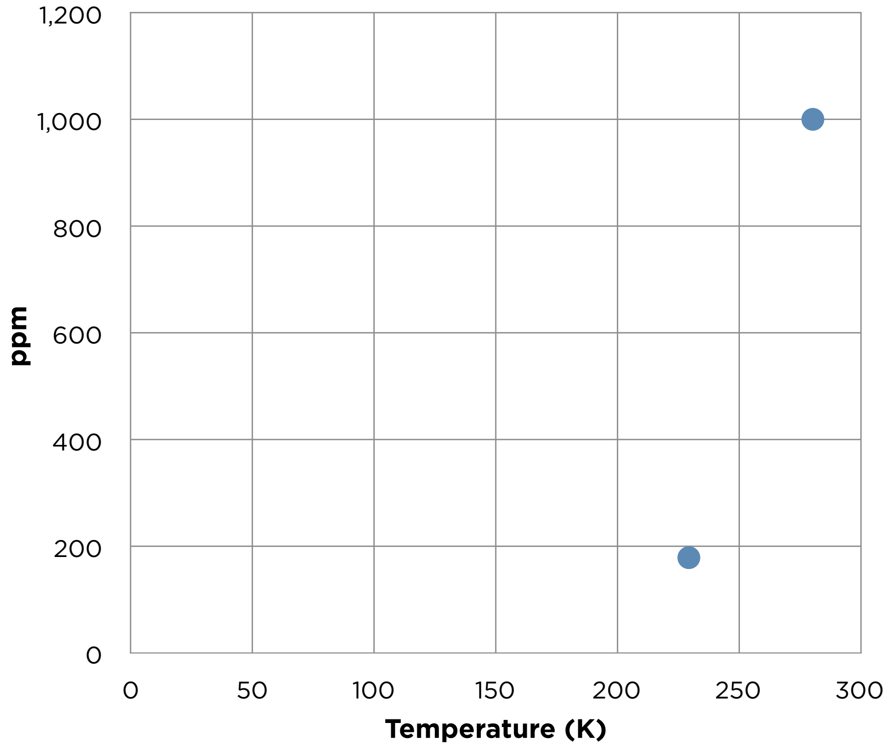

Figure 7: Solubility of water in Liquid CO_2 [17].

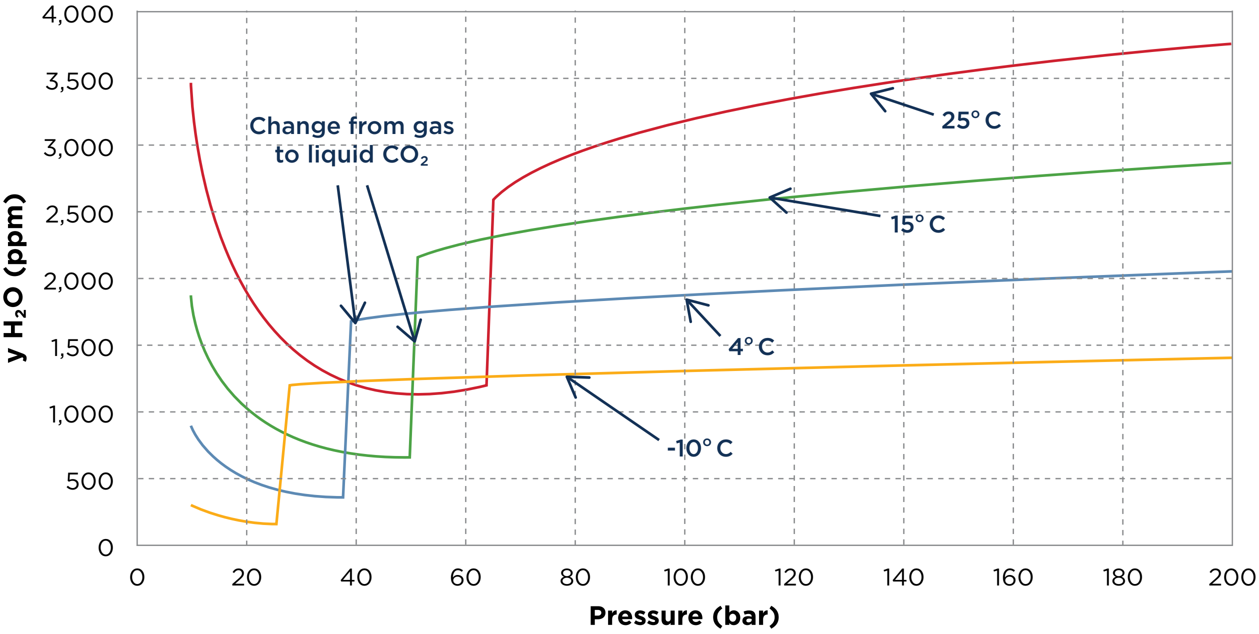

Figure 8: Solubility of water in CO_2 [27].
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When LCO_2 carries more water than gaseous CO_2, the solubility of water in CO_2 abruptly changes during the phase transition of CO_2. The presence of impurities affects the phase behavior of CO_2 and makes it more corrosive. The solubility of water in CO_2 decreases in the presence of impurities such as NO_2 and SO_2 and, to some extent, in the presence of CH_4, N_2 or O_2. In contrast, the presence of a small amount of H_2S increases water solubility, and a low water level allows higher concentrations of H_2S without inducing corrosive effects.

The presence of free water aggravates the formation of solid crystalline hydrate and increases corrosion due to the reaction of water with acidic gases such as SO_x and NO_x.

Hydrates are typically formed by low-soluble gases such as CO_2, CH_4 and H_2S above the freezing point of water, and at high pressure. Hydrates can form even without the presence of free water.

To mitigate any risks, the desired water limit in CO_2 should vary from 40 ppm (conservative) to 500 ppm or higher to avoid free water formation. Under normal operating conditions, water's solubility is 1,500 ppm; therefore, dense phase CO_2 containing 500 ppm of water does not pose a high risk of free water formation.

Impurities such as H_2S and SO_x, when present at high concentrations, may release elemental sulfur that may deposit or block passages if the temperature exceeds 673 K at compressor discharge. In addition, H_2S may also cause brittleness. Reactive impurities like H_2S, O_2, SO_x, NO_x, etc., are corrosive to metallic components and can damage non-metallic seals.

4.4.3 Density of CO_2 and Challenges

The density of CO_2 varies significantly across its phases and is higher near the triple-point. For reference, CO_2 at ambient conditions has a density of approximately 1.8 kg/m^3, while in the liquid phase (close to -50° C and 7 bar(a)), it reaches approximately 1,100 kg/m^3 and increases when reducing the pressure due to the lower equilibrium temperature (Refer to Figures 9 and 10).

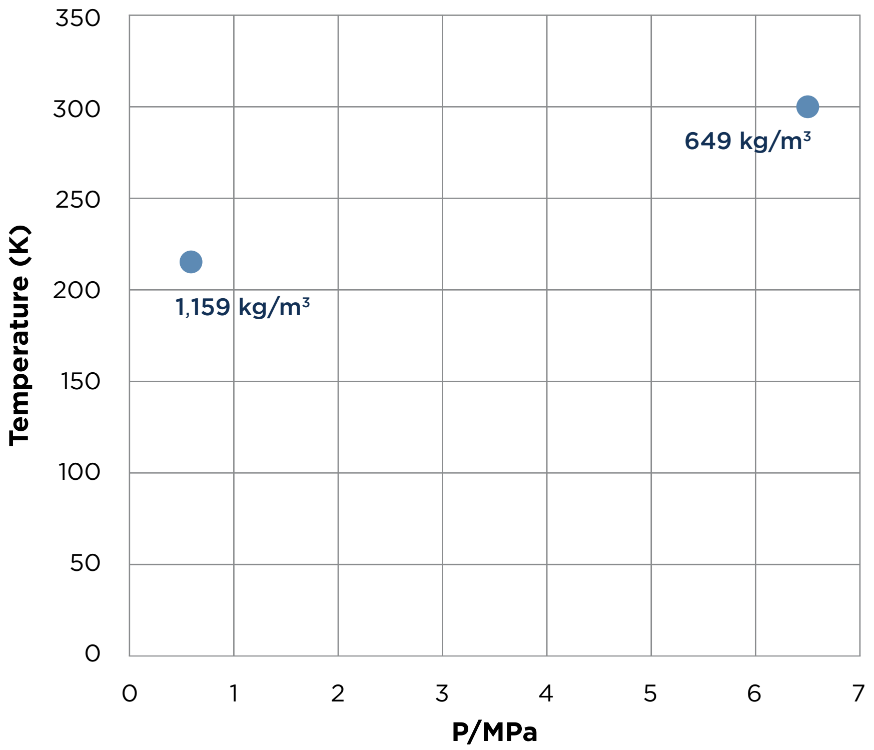

Figure 9: Liquid and saturation liquid densities of CO_2 [1].

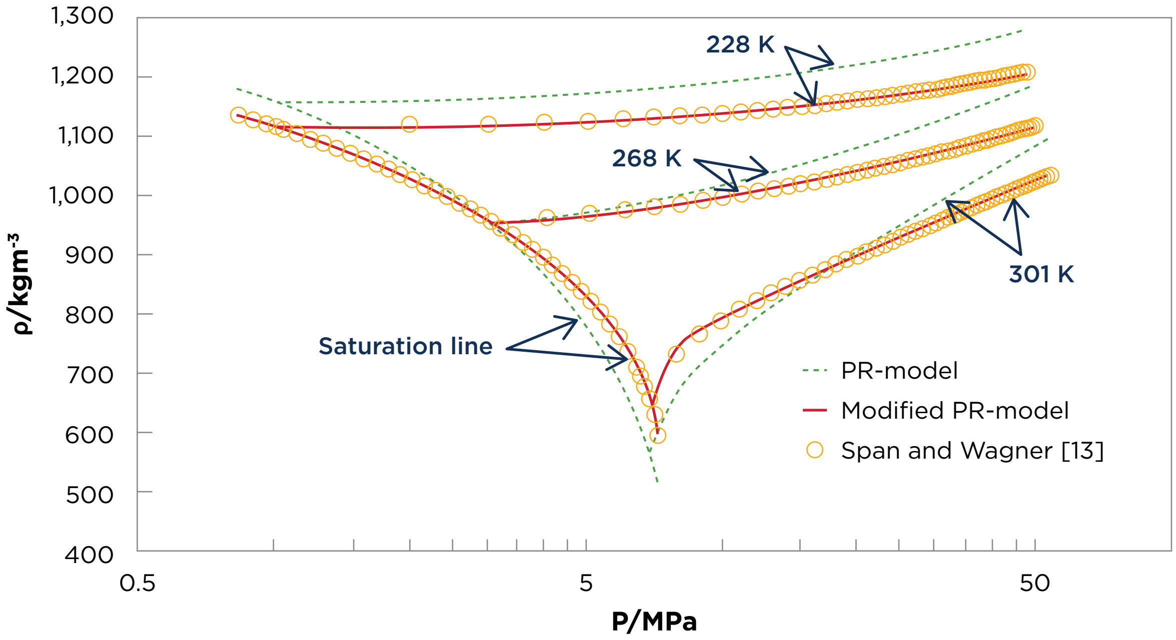

Figure 10: Liquid and saturated liquid densities of CO_2 [1].

Density is sensitive to impurities and moderately sensitive to pressure. The molar volume of most impurities is higher than that of CO_2, reducing the density of the mixture. Non-condensable impurities increase the pressure requirement. The density of saturated LCO_2 is inversely related to the pressure.

Lower-density LCO_2 reduces a ship's volumetric efficiency, and a higher pressure limits tank size and increases the wall thickness.

5 CONCLUSION AND KEY TAKEAWAYS

The increasing demand for CO_2 transportation highlights the critical role of LCO_2 carriers in supporting the global carbon value chain. While pipelines remain a well-established option, shipping offers unique advantages, especially for remote and geographically dispersed emitters. This publication highlights several critical considerations for the design and operation of LCO_2 carriers based on the current understanding of this topic and ABS' work with major shipyards to grant AIPs for LCO_2 carrier designs of various sizes.

1. Design and Operational Considerations:
    a. The design trend is to transport CO_2 at lower pressures closer to the triple point using larger tanks and an increased total capacity.
    b. Operational pressures for LCO_2 carriers are typically maintained within the 6 to 10 bar(g) range and away from the triple point to ensure safety and efficiency while avoiding dry ice formation.
    c. Type C tanks, with their robust designs, are the preferred option, but material selection must account for the low-temperature and high-pressure operating conditions.
2. Impact of CO_2 Composition:
    a. Carbon dioxide composition plays an important role in designing these vessels and associated systems. Most designs consider reasonably pure CO_2.
    b. The presence of impurities significantly influences thermophysical properties, corrosion potential and cargo handling systems. Variations in CO_2 sources and capture technologies, the solvents or absorbents, and the downstream clean-up technology require flexibility in design specifications.
    c. Non-condensable gases, such as H_2 and N_2, increase pressure and energy requirements, while reactive impurities like SO_x and H_2S demand careful material selection to mitigate corrosion and operational risks.
4. Research Gaps
    a. A lack of comprehensive VLE data for shipping conditions complicates the prediction of CO_2 phase behavior, particularly with mixtures containing impurities.
    b. Further research is needed to investigate the quantitative impact of impurities in the CO_2 mixture on shipboard transportation. Without proven data, one safe approach during the design stages is to use appropriate simulation tools and equations of state to predict phase changes for a safe cargo operation and choose suitable materials.

In conclusion, while the transportation of LCO_2 presents unique challenges, it also offers a great opportunity to enable the large-scale deployment of CCUS technologies. Addressing the technical, operational and safety challenges highlighted in this publication will be critical to achieving global climate goals.

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6.1 ABS Publications

ABS *Rules for Building and Classing Marine Vessel, January 2023.*

ABS *Requirements for Onboard Carbon Capture and Storage, December 2022.*

ABS *Requirements for Liquefied Carbon Dioxide Carriers, January 2024.*

ABS *Setting the Course to Low Carbon Shipping – Zero Carbon Outlook, June 2022.*

ABS *Sustainability Publication: Carbon Capture, Utilization and Storage, August 2021.*

6.2 ISO Documents

ISO/TR 27921:2020	Carbon dioxide capture, transportation, and geological storage – Cross Cutting Issues – CO_2 stream composition

CONTACT INFORMATION

NORTH AMERICA REGION
1701 City Plaza Dr.
Spring, Texas 77389, USA
Tel: +1-281-877-6000
Email: ABS-Amer@eagle.org

SOUTH AMERICA REGION
Rua Acre, nº 15 - 11º floor, Centro
Rio de Janeiro 20081-000, Brazil
Tel: +55 21 2276-3535
Email: ABSRio@eagle.org

EUROPE REGION
111 Old Broad Street
London EC2N 1AP, UK
Tel: +44-20-7247-3255
Email: ABS-Eur@eagle.org

AFRICA AND MIDDLE EAST REGION
Al Joud Center, 1st floor, Suite # 111
Sheikh Zayed Road
P.O. Box 24860, Dubai, UAE
Tel: +971 4 330 6000
Email: ABSDubai@eagle.org

GREATER CHINA REGION
World Trade Tower, 29F, Room 2906
500 Guangdong Road, Huangpu District,
Shanghai, China 200000
Tel: +86 21 23270888
Email: ABSGreaterChina@eagle.org

NORTH PACIFIC REGION
11th Floor, Kyobo Life Insurance Bldg.
7, Chungjang-daero, Jung-Gu
Busan 48939, Republic of Korea
Tel: +82 51 460 4197
Email: ABSNorthPacific@eagle.org

SOUTH PACIFIC REGION
438 Alexandra Road
#08-00 Alexandra Point, Singapore 119958
Tel: +65 6276 8700
Email: ABS-Pac@eagle.org