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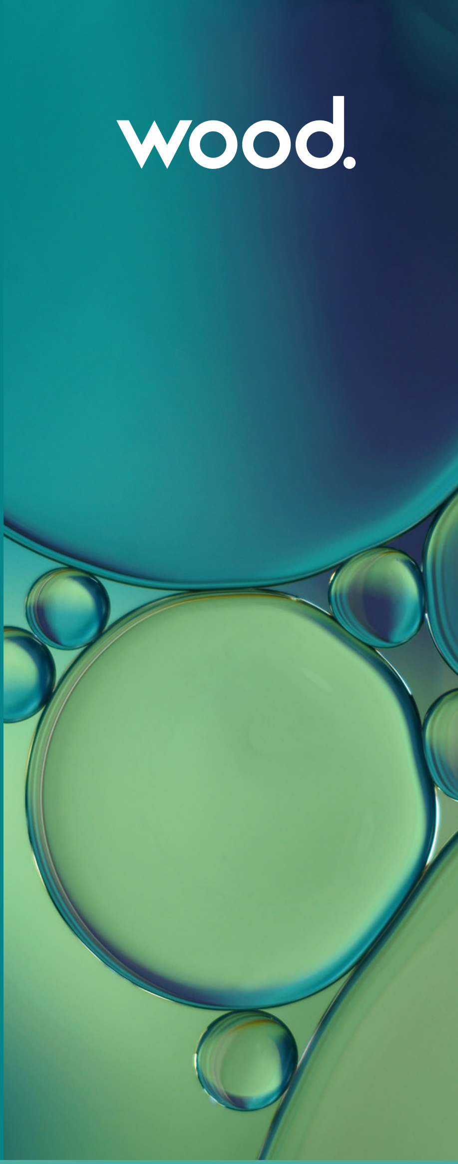
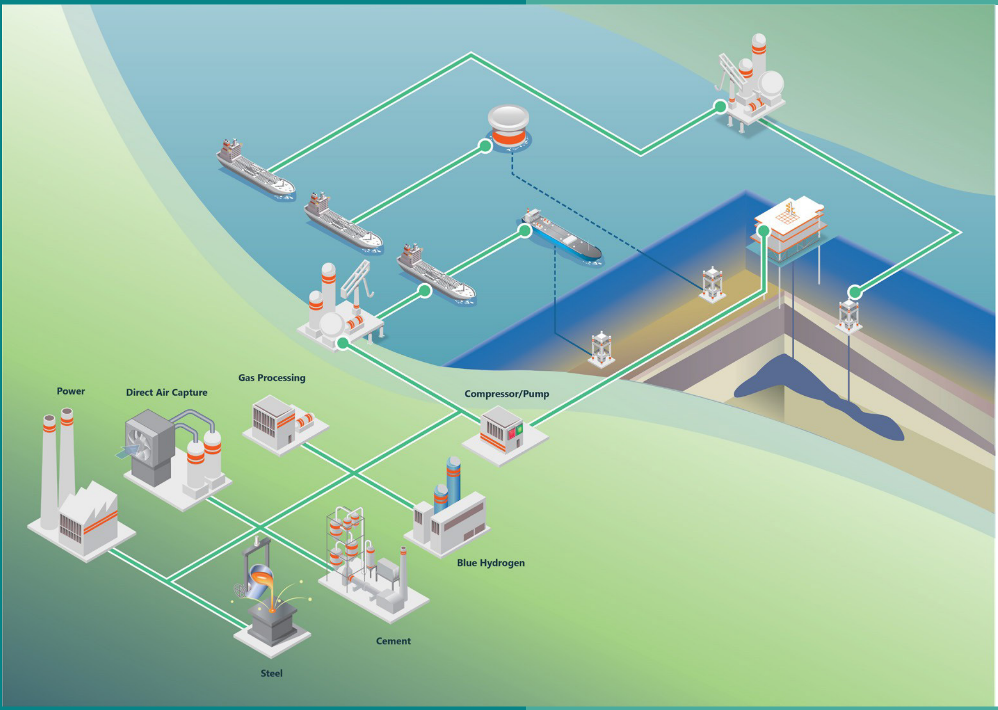
Industry Guidelines for Setting the CO_2 Specification in CCUS Chains

Work Package 9: Ship Transport





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Preface

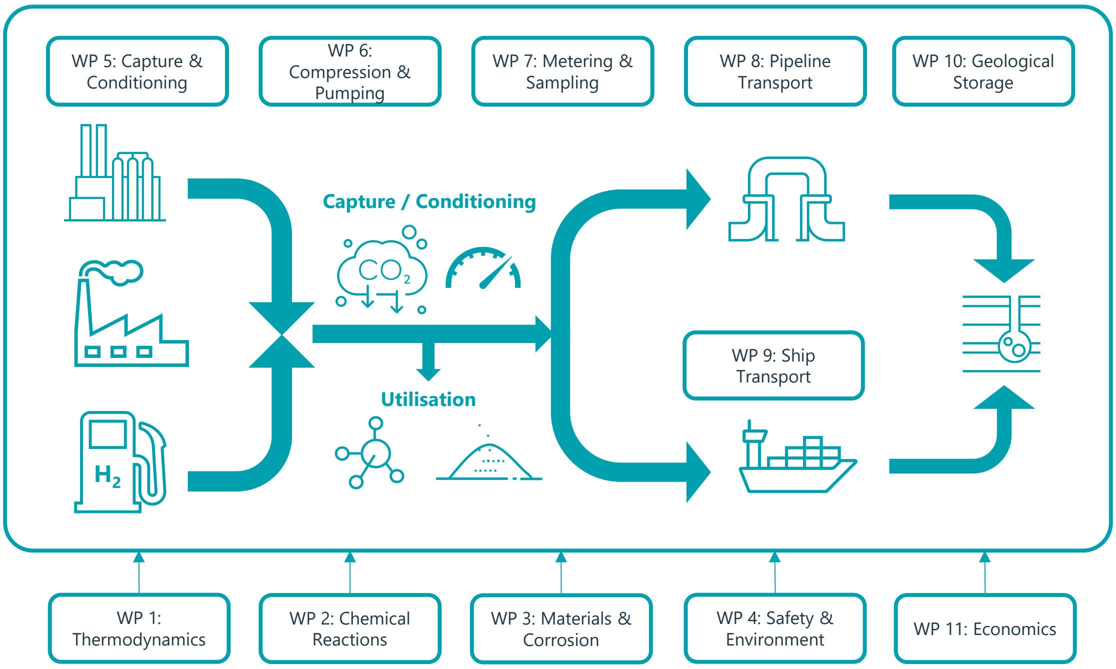
Carbon Capture, Utilisation and Storage (CCUS) is one of the key pathways towards net-zero goals and significant growth is expected in this industry to meet these demands.

The presence of impurities in captured CO_2 impacts the cost and operation of CCUS. A CO_2 Specification represents the maximum allowable level of impurities within a CO_2 stream to ensure safe and cost-effective CCUS chains from capture through to storage.

To support the successful development of CCUS, a Joint Industry Project (JIP) has been formed to provide guidance in setting CO_2 Specifications for CCUS projects.

A series of Work Packages was performed across the CCUS value chain including key areas such as thermodynamics, reaction chemistry and material corrosivity. Each Work Package produced a Guideline report providing current knowledge on the impact of impurities in CCUS.

This report is part of a suite of deliverables and should be read in conjunction with the other Guideline reports which can be downloaded from the Wood website at www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains.



Feedback on the JIP guidelines is welcomed, please get in touch via the link on the above website or directly via CO2SpecJIP@woodplc.com.

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Executive Summary

Objective

The intended objective of this work package was to provide basis and insights for future development of guidelines to set CO_2 specifications for ship transportation.

Conclusion

A literature review was carried out to collect information about the physical effects of impurities present in the CO_2 stream and their implications for shipping, with attention to potential concerns related to the material selection for the cargo containment system, cargo handling operation as well as cargo management.

In the CCUS context, CO_2 is captured from different sources including large-scale combustion of fossil fuels such as gas, oil, or coal-fired power plants, as well as a range of industrial processes. Consequently, the CO_2 stream comprises a range of gaseous pollutants, with varying types and compositions.

The approach to impurities in a CCUS value chain is fundamentally different from other commodity gases such as LPG, LNG, NH_3 which are typically treated to meet specific quality requirements from the end user. As a CO_2 stream in a CCS context can be considered a waste product there will in principle not be an end client requiring specially treated products. Still, the presence of impurities in the CO_2 can have consequences on the value chain which will dictate the requirements of the CO_2 composition.

Impact of impurities in the stream which may be categorised as follow:

- Material Integrity
- Changes in phase behaviour
- Solubility
- Solid formation
- Potential for chemical reactions and acid dropout
- HSE

The IMO International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) currently distinguishes between high purity CO_2 and reclaimed quality CO_2. The cargo compositions are potentially affecting phase transitions (both qualities) and corrosion (reclaimed quality). However, the code does not address the range of impurities and compositions present in a CCUS CO_2 stream.

Currently there are no common practices to evaluate the effect of such impurities present in the CO_2 stream, either with regards to single components or the combined effect of different components. To date, there is limited research and knowledge available to evaluate and quantify the potential impact that impurities have on the CO_2 shipping as part of the CCUS value chain. Further studies are recommended to increase the understanding and support the quantification of these effects. What is known, is that impurities present in carbon dioxide (CO_2) streams can significantly impact CO_2 shipping, the following considers some of these impurities:

- **Non-Condensable Impurities:** These impurities affect the phase behaviour of CO_2 during transport. They include gases that do not condense into a liquid phase at typical transport conditions. Non-condensable impurities can influence temperature, fluid density and operating pressures. Their presence affects the range of operation and safety considerations during shipping [1].
- **Toxic Gases:** When CO_2 is captured from industrial processes or exhaust gases, it may contain other components such as SO_2 (sulphur dioxide) and NOx (nitrogen oxides). These toxic gases can impact the transmission and storage of CO_2. The implications for safety, handling, and environmental risks need thorough examination.

This report aims at providing a basis and insights for future development of guidelines to set CO_2 specifications for ship transportation. The focus is on the effect of impurities and the associated risks with respect to corrosion, cargo handling operation and cargo management as further presented in the following subsections.

However, it is acknowledged that further research and data are required to improve the basis for developing specifications which shall balance the concerns related to corrosion, cargo handling and cargo management with potential commercial impacts. To date, specifications are being developed on project-by-project basis and there are no overarching regulations and further research can lead to modifications to existing specifications.

Material Integrity and Corrosion

Typical liquefied gases are treated to reach a sufficient purity level to meet defined quality targets. In this process, impurities, or contaminants that may cause corrosive environments are removed from the cargo. Consequently, gas carriers are generally designed without any specific corrosion barriers. However, some specific mitigation measures for corrosion are included for some cargoes such as NH_3 where certain materials need to be avoided.

To date, the typical CO_2 carrier designs proposed for CCS value chains are based on the same practice assuming that the CO_2 composition will not cause any challenges with respect to corrosion. In other ship segments such as chemical tankers where corrosion is a concern, barriers such as corrosion resistant material (stainless steel), or coatings are used. Due to the properties of the CO_2 stream, and the pressure and temperature cargo conditions, the use of corrosion barriers for CO_2 carriers needs to be further investigated.

Given the uncertainties related to corrosion barriers on CO_2 carriers, and the risk of corrosive environments generated by the presence of impurities, the industry is investigating suitable CO_2 specifications to mitigate the corrosion risk.

A CO_2 specification needs to consider the individual and combined effect of impurities. The cargo conditions (temperature and pressure) influence the solubility of key components such as water, hence the risk of chemical reactions with SO_X and NO_X creating acid dropouts. A cleaner and dryer CO_2 stream may mitigate the risk of corrosion and the potential for chemical reactions but may come with a premium in terms of liquefaction costs.

To date, publicly available information related to solubility limits and the potential for chemical reactions at the conditions relevant for ship transportation, is limited. There is also limited public data on corrosion rates at such cargo conditions and for different blends of impurities.

To fully understand and quantify the risk of chemical reactions in the CO_2 stream, and the consequences with respect to corrosion and material integrity, more investigations need to be carried out considering different impurities and cargo conditions.

Cargo Handling Operation & Cargo Management

The presence of impurities in the CO_2 stream alters the phase behavior, conditions for dry ice and hydrates formation as well the solubility. These aspects may alter the safe envelope of the cargo handling operation and cargo management. The related uncertainties need to be fully understood and considered when designing and operating the system.

The solubility of different pollutants such as water and non-condensable impurities is affected by the cargo conditions and by the presence of other impurities. Generally, the solubility of one pollutant is reduced at lower temperature and pressure as well as in the presence of other impurities. In addition to corrosion, excessive water content can lead to hydrates formation in the liquid and gas phase. Thus, more stringent dehydration requirements may apply to a low-pressure value chain to prevent the formation of hydrates.

The presence of non-condensable impurities in the stream alters the phase diagram and changes the bubble point increasing the likelihood of two-phase flow. Consequently, the presence of these impurities affects compression requirements. Furthermore, this leads to faster pressure build-up in the cargo tank compared to a pure CO_2 system.

However, it is expected that these impurities are “boiled” from the stream during the liquefaction process and that only a limited amount remain in the CO_2 stream and will be loaded into the ship, reducing the risk implication to the ship operations.

Dry ice formation is regarded as a higher concern for a low-pressure value chain compared to medium pressure as the margin to the triple point is lower. The conditions for dry ice formation are altered by the presence of non-condensable impurities in the stream but the practical implications to cargo operation are not yet fully identified. However, as explained above, it is expected that a low concentration of these impurities will be included in the CO_2 stream loaded to the ship.

Based on this it is not expected that consequences to the cargo handling operation will be governing the specification for the different non-condensable. More stringent dehydration requirements may be expected to reduce risk of chemical reactions leading to corrosion. However, further investigation of the solubility of pollutants other than water and non-condensable impurities may be necessary to draw more solid conclusions and achieve consensus in industry.

Recommendations for Further Work

Due to limited available data on the effect of impurities in CO_2 streams with temperatures and pressures relevant for shipping, only a qualitative evaluation of the potential implications is possible to date.

To reach more solid conclusions and quantify acceptable levels of impurities, further development activities are needed to increase the understanding of the consequences of impurities in the context of ship transport. This may include but not limited to:

- Solubility limits of compounds other than light components, at shipping conditions. Including acids, and products from reactions
- Chemical reactions and acid drop-out at low temperatures (i.e. low-pressure condition)
- Investigation of corrosion rates and identification of potential barriers.

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Abbreviations

Term	Description
BOR	Boil-Off Rate
CCC	Carriage of Cargoes and Containers
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilisation and Storage
EOR	Enhanced Oil Recovery
HP	High-Pressure
HSE	Health, Safety, and Environment
IMO	International Maritime Organization
JIP	Joint Industry Project
LNG	Liquid Natural Gas
LP	Low-Pressure
LPG	Liquid Petroleum Gas
MP	Medium-Pressure
RP	Recommended Practice
SIGTTO	Society of International Gas Tanker and Terminal Operators
SSC	Sulphide Stress Cracking
T_g	Transition glass temperature
VCM	Vinyl Chloride Monomer
VOC	Volatile Organic Compounds
WP	Work Package
ZEP	Zero Emissions Platform
T_{tr}	Triple point temperature
JECFA	Joint FAO/WHO Expert Committee on Food Additives
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
VLE	Vapour Liquid Equilibrium
SO_X	Sulphur Oxides
NO_X	Nitrogen Oxides

1.0 Introduction

1.1 Background

Carbon capture, utilisation and storage (CCUS) will be a key technology to meet the objectives outlined in the Paris and Glasgow agreements. While the CCUS industry and technology is still evolving, a notable challenge lies in establishing connections between capture sources and facilities for either utilization or storage.

Traditionally, pipelines have been the preferred choice for CO_2 transport, especially for short distances. However, there is a growing interest in ship-based transport, especially for scenarios involving longer trades. Consequently, the further development of CO_2 shipping technology is anticipated to be essential to ensure safe and commercially viable large-scale transportation of CO_2.

Although shipping of liquified CO_2 already takes place, it is a niche market and is exclusively deployed for commercial trade purposes, such as the food and beverage, cleaning, and chemical industries. As for other liquefied gases, liquid CO_2 is transported on ships as a semi-refrigerated cargo under pressure. Maintaining CO_2 in a liquid phase requires pressures higher than the triple point to prevent the transition to a gas or solid phase and the potential for dry ice formation.

In the CCUS context, CO_2 is captured from different sources including large-scale combustion of fossil fuels such as gas, oil, or coal-fired power plants, as well as a range of industrial processes. Consequently, the CO_2 stream comprises a range of gaseous pollutants, with varying types and compositions that may impact different components of the value chain. The presence of impurities influences the CO_2 stream and affects factors such as toxicity, physical properties, phase envelope, and water solubility.

Commercially transported gases such as LPG, LNG and NH_3 are treated and purified to meet quality criteria based on their intended application. Contaminants are removed from the stream also to prevent corrosion issues and limit environmental impacts. Consequently, cargo tanks and cargo handling systems on ships generally designed considering a non-corrosive environment.

Unlike other liquefied gases mentioned above, the quality and purity of a CO_2 stream does not have a commercial value or an industrial function is carbon capture and storage (CCS) is pursued over CCUS. Hence, there may be less incentives for additional treatment and purification of the product prior to transportation. As the ship transport involves a substantial cost element, understanding the role and implications of impurities throughout the CCS chain is crucial. In addition, the CO_2 stream comprises a range of gaseous pollutants, with varying types and compositions which influence liquefaction cost [2]. From this perspective, a preference for less rigid specifications may be viable, reducing the operational and capital costs. However, this must be aligned with the requirements set by each of the components in the value chain, as shown in Figure 1-1.

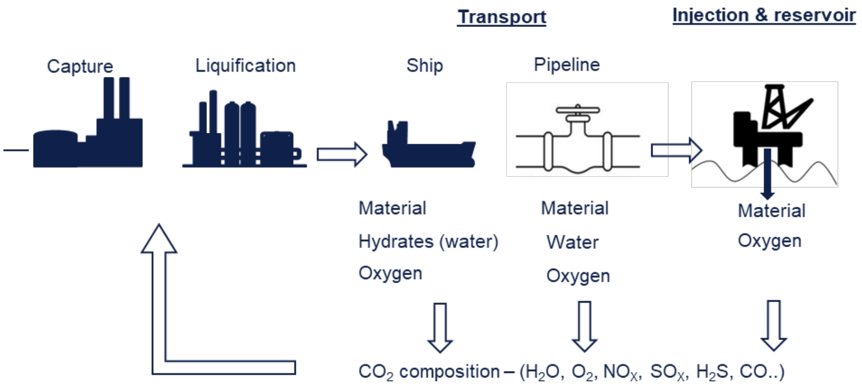


Figure 1-1: Examples of constraints on CO_2 stream composition.

1.2 Scope

A desktop study was carried out to collect information about the physical effects of impurities present in the CO_2 stream and their implication to shipping, highlighting potential concerns related to the material selection for the cargo containment system, loading options, cargo handling operation, and cargo management.

The CCUS value chain can be divided into four main components, Figure 1-2:

1. Production from industrial processes,
2. Capture, conditioning, and liquefaction,
3. Transport and,
4. Storage or alternatively utilization.

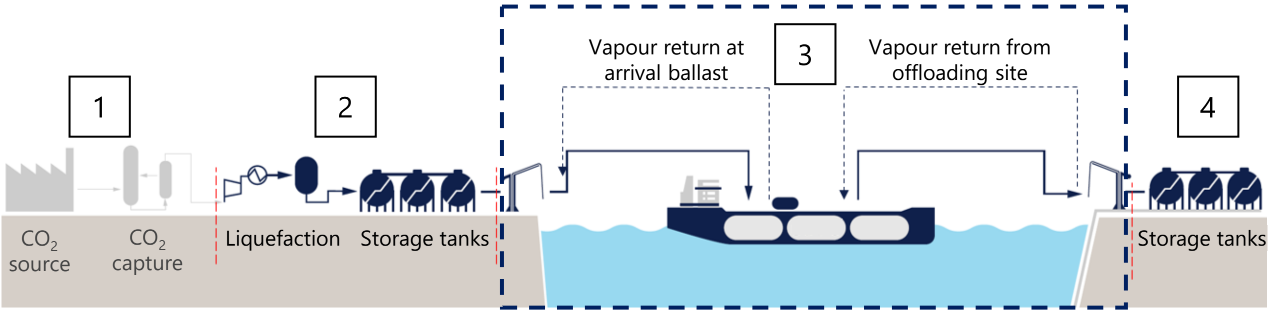


Figure 1-2: Schematic representation of CCS value chain, and battery limit for the study [3].

2.0 Ongoing Research and Development on CO_2 Shipping

A summary of ongoing research and development on CO_2 shipping is given in the following sections.

2.1 DNV CETO JIP (CO_2 Efficient Transport via Ocean)

DNV AS is on behalf of a consortium composed of Equinor Energy AS, Gassco AS, TotalEnergies EP Norge AS and Shell leading a Technology Qualification Programme for a low-pressure CO_2 ship transportation concept. The project is co-funded by Gassnova and Climit Programme.

CETO [3] (CO_2 Efficient Transport via Ocean) aims at reducing the uncertainties related to the design, construction, and operation of a low-pressure ship transport chain and to enhance solutions for ship transport of CO_2 compared to the current practice and commercial scale.

The Technology Qualification comprises several engineering, desktop and experimental activities to gather evidence about the technical feasibility of a low-pressure value chain and technical barriers. These activities include:

- Conceptual design of a conditioning and liquefaction plant and experimental demonstration of the liquefaction at low pressure, in cooperation with Norwegian CCS Research Centre.
- Basic ship concept design of an appropriate and efficient dedicated CO_2 carrier and cargo handling system to accommodate and handle large volumes of CO_2 (~30,000 m^3).
- Design of the cargo containment system and suitable material selection to accommodate the large cargo weight, ensure constructability and operation for design temperature at -55 °C.
- Investigate, by executing experimental activities on a medium-scale pilot plant, the operability of a low-pressure cargo handling system to determine a safe envelope for the operation, observe solid formation including dry ice and hydrates, as well as demonstrate the ability to deal with eventual dry ice formation.
- Simulation tools for assessing cargo handling and operations, interaction with the loading and offloading onshore facilitates and benchmarking of process simulation tools.
- Experimental and modelling work within CO_2 thermodynamics to reduce the uncertainty in software design tools.

The effect of impurities was not the focus of the project, although some of the work packages are tackling some aspects. The experimental test on the operability of a low-pressure cargo handling system includes an investigation of the effect of methane on the cargo transfer and cargo management,

The experimental work performed by Heriot-Watt aims at reducing the uncertainty related to the solubility of typical impurities in liquid CO_2 (including H_2O) at conditions relevant to low temperature CO_2 ship transport. The impurities studied are water, hydrogen, oxygen, nitrogen, methane, CO_2 and argon; and their effects on hydrate formation as well as bubble point are investigated [4].

2.2 CO2LOS

CO2LOS phase II and III have been executed as JIPs and focuses on CO_2 logistics by ship. Two public reports are currently available [5]. The JIP has not had a focus on contaminants or CO_2 product specification.

2.3 CO_2 Safe and Sour JIP

The amount of H_2S allowed in CO_2 pipelines are defined in the recommended practice (RP) DNV-RP-F104 "Design and operation of carbon dioxide pipelines". The recommended practice was not developed with carbon capture, utilisation and storage (CCUS) in mind. There is a belief that the current H_2S level specified is conservative and many potential emitters may not meet the requirements without post-processing of CO_2. Increasing the acceptable level of H_2S in the pipes can potentially enable CCUS projects to receive CO_2 from a higher number of sources/customers with a limited need for processing/cleaning. The joint industry project (JIP) CO_2 Safe & Sour aims to investigate acceptable levels of H_2S in pipelines for CCUS applications and perform an update of the RP based on the findings. The project looks at how increasing acceptable levels of H_2S will affect the risk of Sulphide Stress Cracking (SSC) and corrosion damage in carbon steel pipelines used for CCUS. The project will provide general recommendations for industry wide use and will lead to an update of the DNV-RP-F104 "Design and operation of carbon dioxide pipelines.

2.4 Institute For Energy Technology (IFE) KDC (1, 2, 3, 4) JIP

The implementation of full-scale carbon capture and storage (CCS) will require the transport of large quantities of CO_2. During the last decade, there has been increased attention paid to the possible negative effects of additional components (impurities) that can be present at low concentrations in the captured CO_2. Initially, the focus was on keeping the impurity level low enough to avoid a two-phase situation (gas and liquid CO_2) and to prevent the precipitation of liquid water and hydrate formation. The upper limits for several other components were often set from an HSE perspective in case of an accidental release of CO_2.

The Kjeller Dense Phase CO_2 Corrosion (KDC) project, carried out in three phases from 2012 to 2022, has shown that common impurities could react chemically and create elemental sulphur or a corrosive liquid phase containing sulfuric and nitric acid. The KDC project is now in its fourth phase and aims to provide experimental results that can be used by the CCS industry to prevent negative effects of impurities with respect to chemical reactions, corrosion, and the formation of solids in the CO_2 transportation system. The project will provide a tool for simulating solubilities and chemical reactions in dense phase CO_2 by extending the capabilities of the OLI thermodynamic model.

2.5 IMO and Industry Organizations

IMO’s sub-committee on Carriage of Cargoes and Containers (CCC) is currently working on a revision of the IGC Code. It is expected that the new revision will include updates and amendments of the requirements for the carriage of CO_2, but the details and the extent of amendments is not yet decided.

Several industry organizations are also working on the development of guideline documents for CO_2 shipping. Both the Society of International Gas Tanker and Terminal Operators (SIGTTO) and Zero Emissions Platform (ZEP) are working on guidance documents aimed for CO_2 ship and terminal operators.

It is understood that none of the initiatives will provide extensive information on aspects related to CO_2 composition and impurities.

3.0 Impurities in CO_2 Streams

3.1 CO_2 Stream Composition

In the context of CCUS, CO_2 can be captured from different sources, including large-scale combustion of fossil fuels such as gas, oil, or coal-fired power plants as well as diverse industrial processes such as steel manufacturing, cement manufacturing refineries, and chemical industries.

The different techniques for capturing the CO_2 from combustion power plants are commonly characterized as pre-combustion, post-combustion or oxyfuel processes. Figure 3-1, from Sonke et al. [6], provides an overview of typical sources of CO_2, the associated capture technologies, and the associated compositions.

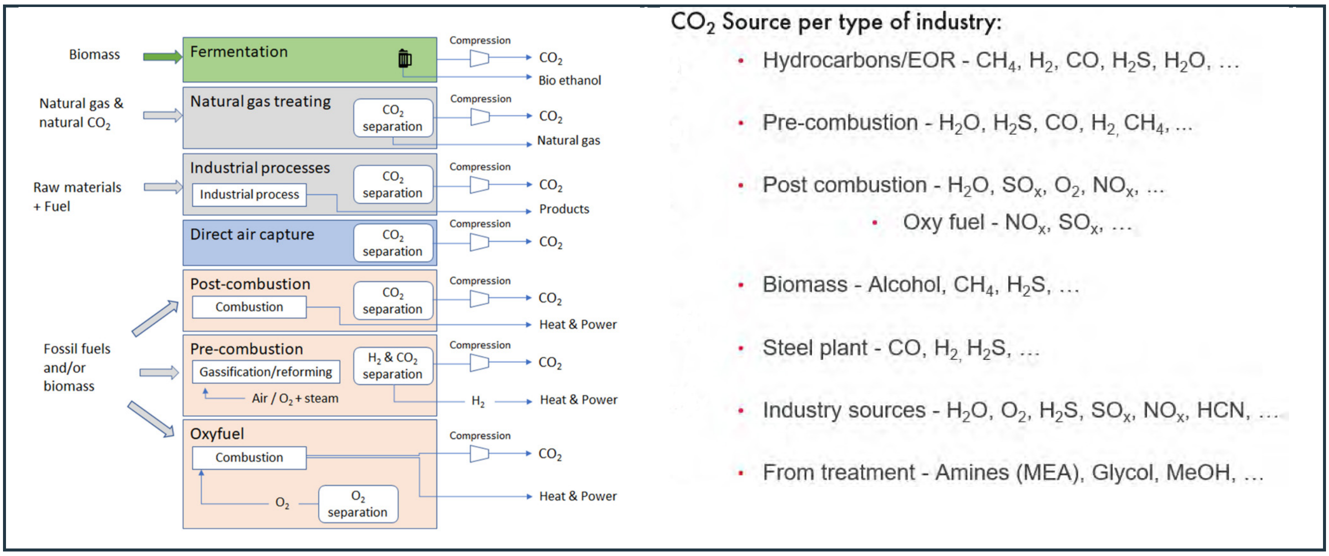


Figure 3-1: Different CO_2 Industries and associated impurities, from Sonke et al. [6].

Table 3-1 from DNV RP-F104 [7] provides an overview of indicative compositions of CO_2 streams. Here, the impurity levels from combustion power plants are evaluated without post-capture processing. For further information on expected impurities from various industries, refer to Section 2, Work Package 5: Capture and Conditioning [8].

Table 3-1: Indicative Compositions of CO_2 Streams Without Post-Capture Processing (Vol%) [7]

	Coal fired power plant			*Gas fired power plants*		
Component	*Post-combustion*	*Pre-combustion*	*Oxy-fuel*	*Post - combustion*	*Pre-combustion*	*Oxy-fuel*
Ar/ N_2/ O_2	0.01	0.03-0.6	3.7	0.01	1.3	4.1
H_2S	0	0.01-0.6	0	0	<0.01	0
H2	0	0.8-2.0	0	0	1	0
SO_2	<0.01	0	0.5	<0.01	0	<0.01
CO	0	0.03-0.4	0	0	0.04	0
NO	<0.01	0	0.01	<0.01	0	<0.01
CH_4+	0	0.01	0	0	2.0	0
Amines	-	-	-	-	-	-
Glycol	-	-	-	-	-	-

These processes may lead to the presence of different chemical compounds in the CO_2 flow, such as CH_4, H_2O, H_2S, SOx, NOx, N_2, O_2, glycol, etc. Table 3-2 provides a non-exhaustive list of the impurities that can be found in the CO_2 stream. In the table the impurities are categorized as:

- non-condensable,
- trace components,
- hydrocarbons,
- volatile organic compounds (VOC),
- heavy metals and process fluid.

Table 3-2: List of Impurities That Can be Expected in Various CO_2 Streams

Classification	Component
Non-condensable	Methane (CH_4)
	Nitrogen (N_2)
	Argon (Ar)
	Carbon monoxide (CO)
	Oxygen (O_2)
	Hydrogen (H_2)
Trace components	Water (H_2O)
	Sulphur oxides (SO_x)
	Nitric oxide (NO)
	Nitrogen oxides (NO_x)
	Hydrogen sulphide (H_2S)
	Carbon disulfide (CS_2)
	COS
	HCN
	HCl
	Ammonia (NH_3)
Heavy metals	Hg
	Cd
	Tl
Hydrocarbons	C_2
	C_3
	C_4-C_{10}
	Ethylene
	Benzene
	Toluene
	Ethyl benzene
	m,o,p xylenes
Process fluid	MEG
	DEG
	TEG
	DME
Volatile organic compound	Formaldehyde
	Acetaldehyde
	Methanol
	Ethanol
	1-propanol
	butanol and isomers
	acetone

Depending on the CO_2 source, light components, which are components that have a high affinity to stay in the gas phase in a CO_2 system such as O_2, Ar, N_2, and CH_4, may be present in the CO_2 stream at high concentrations, i.e., mol% levels. Impurities like NO_X, SO_X, H_2S, and CO are more commonly present at lower concentrations. Other impurities can be present at even lower levels depending on the fuel or feedstock, solvents used in the capturing process.

For CCUS projects, CO_2 composition and associated threats can be distinguished by the purity of the CO_2 stream and classified by the single or multiple sources as described in [6].

1. **Single source CO_2 stream:** CO_2 streams originating from one source. There is significant experience with the injection of CO_2 from oil and gas production used for Enhanced Oil Recovery (EOR). This is a CO_2 source

that typically contains impurities that do not trigger chemical interactions between impurities. Experience has shown that there are relatively few operational problems, provided the fluid is kept relatively pure, the water content is controlled and O_2 ingress is avoided.

2. **Mixed source CO_2 stream:** The source of CO_2 can originate from a range of industrial sources (emitters). The impurities include those present in the gas source (e.g. H_2O, NO_X, SO_X, O_2, CO, H_2, etc.), as well as those present from the cleaning process (e.g. glycol, amines), or other project specific impurities (e.g. NH_3, methanol, glycol, etc.).

The composition of the CO_2 stream after the capturing plant may change further downstream due to:

- Compression and conditioning — i.e. by changing pressure and temperature conditions and thereby modifying solubility limits of the impurities in the CO_2 streams;
- Further purification — i.e. by an intended removal of one or more impurities;
- Reactions between impurities present in the stream;
- Reactions of impurities with the surroundings, e.g., pipeline walls or formation water.

Impurities may be introduced from the processes of cargo tank cleaning/purging, in the case of interchangeable use of the vessel for different cargoes. Usually, nitrogen is used as inter purging gas and, therefore, could be found as a trace in the cargo tanks.

3.2 Effect of Impurities

3.2.1 General

In a CCUS value chain, the CO_2 concentration will typical be greater than 98%, hence, it is expected that impurities will be present but in low concentrations. Despite the low concentration levels, impurities can potentially affect the behavior of the CO_2 stream and impact operation. Their effects are potentially important and impurity limits in the CO_2 specification need to be defined based on the implication caused by a single compound and in combination with other components.

Even at ppm levels, impurities may affect the behavior of the CO_2 stream. Thus, it is important to know the concentration of the different impurities in the CO_2 stream to be able to accurately predict the thermodynamic behaviour and assess the associated risks. In addition, there are uncertainties to how the impurities may affect the material integrity, including corrosion, cracking, pitting and embrittlement. The solubility of impurities, including water, varies with the temperature and pressure, therefore, the potential for drop-out of a separated liquid or solid phase need also to be evaluated for the different temperature and pressure conditions. Also, depending on the impurities, chemical reactions between the different impurities may take place, resulting in acid formation.

A summary of the implications added by main impurities related to corrosion, reactions, and physical behaviour, solubility is given in Table 3-3. These aspects are further explained in from Section 3.2.2 to Section 3.2.7.

Table 3-3: Implication of Corrosion and Physical Behaviour

Component	Comment
Water	The water solubility in the CO_2 stream depends on the actual operating conditions and the composition of the stream. This will determine the maximum allowable water without drop-out of water. Water can react with NO_X, SO_X, and H_2S producing strong acids which is corrosive. There is also a risk of hydrate formation.
H_2S	There are various risks related to H_2S. Toxicity in case of accidental release. May react with other compounds and form sulphuric acid, nitric acid and elemental sulphur. The acids have a high potential for corrosion and the elemental sulphur may lead to clogging. In addition, H_2S may lead to sulphide stress cracking if present along with a water phase.
SO_X	The result of fossil fuel combustion. The concern is cross chemical reactions and the formation of sulphuric/nitric acid causing drop out of an aqueous sulphuric acid phase. Sulphuric and nitric acid is corrosive to metals.
NO_X	
CO	The level of CO will normally be governed by its toxicity in case of accidental release of the gas. Risk for CO-CO_2 cracking if a free water phase is formed.
O_2	Oxygen enhances the formation of elemental sulphur and sulphuric/nitric acid if SO_X/NO_X are present.
N_2	Commonly classified as non-condensable. The concentration will be limited by the amount of non-condensable that can be dissolved in the liquid phase at the given condition. The accumulation of non-condensable in the conditioning stage may limit the amount of captured CO_2 that is entering the ship. These impurities will change the bubble point of the stream and can lead to a two-phase flow as well as affect boil-off.
CH_4	
Ar	
H_2	
Amine	Amines may react with and degrade several non-metallic materials.

3.2.2 Material Integrity

For a full assessment of impurity impact on materials, refer to Work Package 3: Materials & Corrosion [9]. Selection of suitable metallic material is essential to ensure integrity for all operating scenarios, including upsets. In general, the use of low alloy steel will reduce the cost compared to corrosion-resistant steel. In this case, it is relevant to consider degradation mechanisms and the implications of the impurities. Such mechanisms can be summarised as:

- General and localised corrosion due to the formation of an acidic water phase caused by SO_X, NO_X, CO_2 and O_2
- Environmental cracking due to the presence of H_2S, H_2 and chloride for low alloy steel and corrosion resistant alloys
- Pitting and stress corrosion cracking of corrosion-resistant alloys due to the presence of O_2 and chloride
- Liquid embrittlement due to the presence of mercury

Low alloy steels will corrode rapidly if an acidic water phase forms due to the presence of SO_X, NO_X, CO_2 and O_2, therefore, can low alloy steels only be used if the fluid is 'dry'. Relevant corrosion-resistant alloy candidate materials are stainless steel such as 316L, 22Cr and 25Cr. These are less prone to corrosion and provide a mitigation against degradation mechanisms. However, an assessment should be made related to the presence of other impurities and other mitigation elements that may be introduced for CO_2 application as described in Section 6.2.1.

Nickel steels are not resistant to all concentrations of H_2S and application of corrosion allowance is required. The presence of H_2S may cause cracking of low alloy steel and corrosion-resistant alloys. ISO-15156 gives material requirements (hardness, utilisation, chemical composition etc.) and safe application limits for (partial pressure of H_2S, temperature, chloride content) materials in an H_2S and chloride-containing environment for the candidate material. Candidate materials are low alloy steel and corrosion-resistant alloys, provided they meet the requirements and design limitations as specified in ISO-15156.

Non-metallic materials (polymers) are also exposed to CO_2 and their suitability and integrity may be affected by the stream composition. Such material can be used in seals, hoses, flexible pipes etc. As for metallic materials, these can undergo a degradation mechanism that can be accelerated by the presence of impurities. The main mechanisms, also discussed in Work Package 3: Materials and Corrosion Section 3.2.4 [9] are:

- Chemical degradation by reaction with components in the stream,
- Chemical degradation by diffusion of stream components into the polymers,
- Permeation through the polymer causing leakage,
- Rapid gas decompression,
- Low temperature embrittlement and cracking.

The degradation rate induced by the first three items is increased by temperature and pressure. Hence, the low temperature and low-pressure conditions for CO_2 transport mitigate such risks.

On the other hand, low temperature embrittlement is a concern, and the polymers need to be designed and qualified for low temperatures (i.e. -50 °C).

In addition to the product condition, the compatibility of non-metallic material with the possible impurities in the stream shall be evaluated. It is recommended to qualify the materials in accordance with recognised standards such as NORSOK M710 for sealing material, API 17J and API 17K for flexible and bonded pipe respectively.

NORSOK M710 indicate the qualification of non-metalling materials in sour service and a limiting value shall be agreed upon. Among the other compounds, SO_X, NO_X may contribute to the degradation of types of non-metallic materials. The presence of CH_4 shall be limited if "non-polar" elastomers are planned as it leads to swelling while H_2 may permeate through the polymer and lead to leakage. Amine may react with and degrade several non-metallic materials and a limiting value shall be provided.

3.2.3 Changes in Phase Behaviour

Depending on the physical and chemical nature of the impurities will induce diverse phase equilibria, resulting in a unique phase envelope for a specific composition. The presence of non-condensable impurities such as oxygen, nitrogen, argon, and methane, which cannot be liquefied at ambient temperature will affect the density. This will be the case even if the impurities are at the ppm level. Certain impurities can cause drop out of additional undesirable liquid phases if the system operates at low pressure. These liquid phases can appear at normal operating temperatures and can lead to corrosion mechanisms. Hence, there is a need to accurately predict the thermodynamic behaviour of the CO_2 specification that will be transported in the CCS network [10] [11].

An example of the impact of the concentration of different impurities has on the CO_2 phase diagram can be seen in Figure 3-2. Here, the phase envelope for three different CO_2 compositions given in Table 3-4 from the White Rose CCS Project [12] is presented. This is a qualitative example of the physical effect of the impurities on the phase envelope and does not necessarily reflect actual compositions seen in the industry. The example illustrates how the presence of impurities in the CO_2 affects the phase envelope; the larger the fraction of impurities, the greater the range of pressures and temperatures at which the fluid can be in the two-phase region [12].

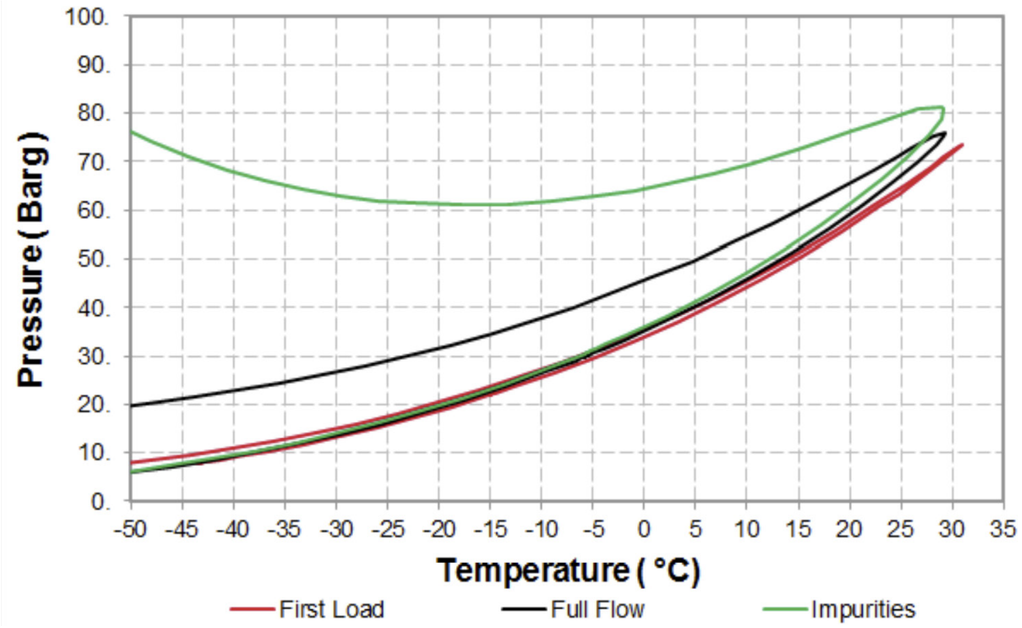


Figure 3-2: Phase envelope for three CO_2 streams with different fluid compositions [12].

Table 3-4: Fluid Composition [12]

Component	First Load (mol%)	Full Flow – Generic (mol%)	Impurities – Sensitivity (mol%)
Carbon-Dioxide	99.700	97.400	96.000
Argon	0.068	0.599	0.411
Nitrogen	0.226	1.995	1.371
Oxygen	0.001	0.001	0.001
Water	0.005	0.005	0.005
Hydrogen	0.000	0.000	2.000
Hydrogen-Sulphide	0.000	0.000	0.002
Carbon-Monoxide	0.000	0.000	0.200
Methane	0.000	0.000	0.010
Total	100.000	100.000	100.000

3.2.4 Solid Formation

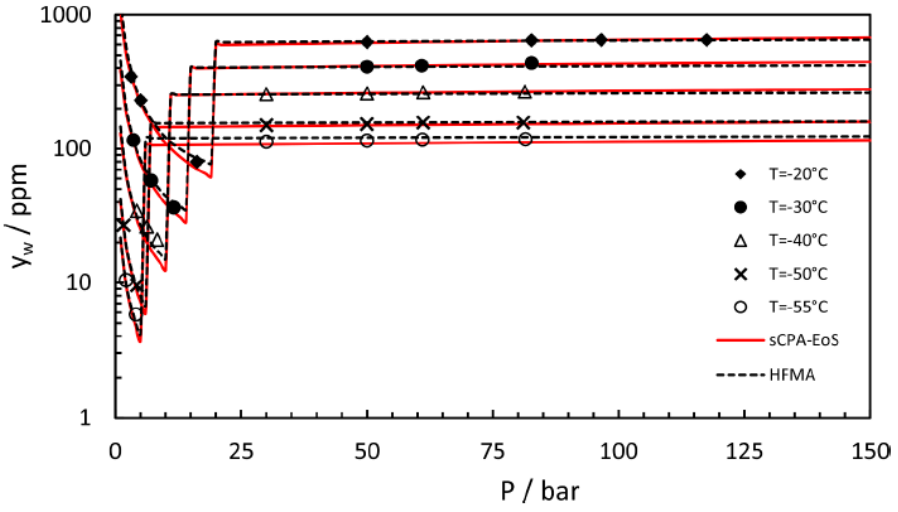
Knowledge of the water content in CO_2 is critical for safe transport, loading and offloading operations. Hydrates can form in both the liquid and vapour phases, and it is important to evaluate the hydrate curve based on the operating pressure and temperature range. Changes to the initial pressure and temperature can move the fluid into conditions where there is a risk for hydrate formation. Condensation of water may result in corrosion, ice and gas hydrate formation and blockage, so the fluid system should meet certain dehydration requirements. Even for pure carbon dioxide, these requirements are not well defined.

There is limited published experimental data for low water content gases, particularly at low temperatures, close to the carbon dioxide triple point (T_{tr}=-56.56 °C). Generating reliable experimental data for systems at these conditions is challenging due to the requirements for establishing equilibrium and accurately measuring water content at levels down to a few ppm [4]. Additional water content measurements in equilibrium with hydrates can be found in Chapoy et al. [13], however these conditions (dense phase) are not representative of shipping applications. For guidance on hydrate prediction modelling, refer to Work Package 1: Thermodynamics [14].

systems Note that these high levels of impurities are more relevant to pipeline transport. For an example of water dehydration requirements to avoid hydrates for impure CO_2 streams for LP and MP refrigerated, refer to Section 9.6.2, Work Package 5: Capture & Conditioning [8].

From the measurements presented in Burgass et al. [4], Figure 3-3 illustrates the water content in the stream at which hydrates will form for given pressure and temperature conditions. Looking at the different isotherms, the lower the temperature, the lower the water content leading to hydrate formation. For temperatures in the range from -55 to -20 °C hydrates will not form in the liquid region for pure CO_2, if the moisture content is below 110 ppm (average water content in the liquid CO_2 region at -55 °C is 116 ppm). In the vapour region, water content needs to be as low as 6 ppm to avoid any hydrate formation (Figure 3-3).

It is expected that uncertainty in the measurements (6 ppm) will not lead to significant drying costs. Consequences would be also minimal as only 6 ppm water would be able to form hydrates.

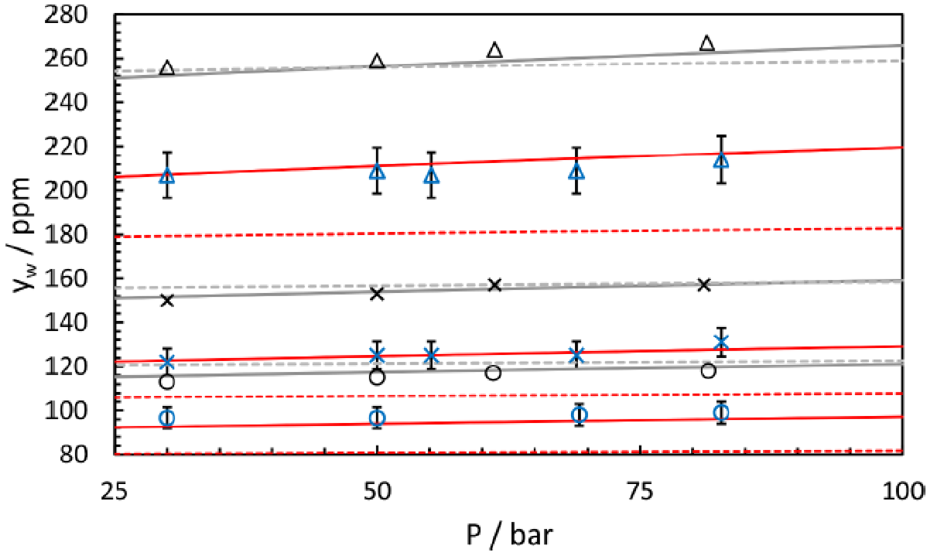


Plot showing experimental water content data and predictions for the water content of CO_2 in equilibrium with hydrates. (♦): T=-20°C; (●): T=-30°C; (△): T=-40°C; (X): T=-50°C; (O): T=-55°C; Red curves: predictions using CPA-EoS; Dashed black lines: predictions using MFHEA.

Figure 3-3: Experimental water content data and predictions for pure CO_2 **[4]**.

The impact of impurities on hydrate formation was also investigated. Figure 3-4 shows that 5% CH_4 reduces the water content by about 18% in the liquid region (compared to pure CO_2), and 3% N_2 reduces the water content by about 11% in the liquid region. In the vapour region, the impact of impurities is negligible.

Note that these high levels of impurities are more relevant to pipeline transport than the lower levels that would be found in ship transport. For an example of water dehydration requirements to avoid hydrates for impure CO_2 streams for LP and MP refrigerated transport, refer to Section 9.6.2, Work Package 5: Capture & Conditioning [8].



T≤-40◦C / Plot showing experimental water content data and predictions for the water content of LIQUID 95 mol % CO_2 + 5mol% CH4 in equilibrium with hydrates. Pure CO_2: (△): T=-40◦C; (X): T=-50◦C; (O): T=-55◦C; Pure CO_2: Grey curves: predictions using CPA-EoS; Dashed grey lines: predictions using HFMA. 95 mol% CO_2 + 5 mol% CH_4: (△): T=-40◦C; (X): T=-50◦C; (O): T=-55◦C; 95 mol% CO_2 + 5 mol% CH_4: Red curves: predictions using CPA-EoS; Red dashed lines: predictions using MFHEA.

Figure 3-4: Experimental water content data and predictions with 5% CH_4 **[4]**.

In addition to hydrate formation, other components can react and form solids that can accumulate and cause clogging of the system. Ammonia (NH_3) can react with CO_2 and water and form solid urea (ammonium carbonate), [6]. Amine may also react with CO_2 and water and form solid particles, but the risk is lower than for NH_3.

Trædal et al [15] investigates the liquefaction of CO_2 at low-pressure condition, focused on dry ice formation during such processes. The experiment demonstrates the feasibility of liquefaction for pure CO_2 and CO_2/N_2 mixtures, but also provides an indication of the possibility of dry ice formation during such process and effect of the impurities on dry ice formation. The results indicate that a N_2 concentration in the range of 3.0% mol was necessary to increase the pressure at which dry ice was formed (from 5.4 bara for pure CO_2 to 6-6.5 bara with impurities). To date, equivalent experiments have been conducted for other mixtures but have not yet been published.

An upcoming publication from Delić et al. (SINTEF) demonstrates liquefaction for CO_2 down to -55 °C conditions with water present in the CO_2. Hydrates were formed during some of the experiments.

Although not directly related to ship transport, these references provide useful information about the effect of impurities on the physical behaviour of the stream. The current literature review did not identify publicly available information dedicated to the shipping component of the value chain.

3.2.5 Solubility Limit of Impurities

In general, the solubility of impurities in CO_2 increases with increased pressure or temperature. However, the solubility of one single component is dependent on the type and amount of other impurities in the liquid CO_2. The concentration of non-condensables is limited by the solubility of the component in the CO_2 liquid at the pressure and temperature conditions in the ship tank. Hydrocarbons and other VOCs pose the risk of forming an additional liquid phase, based on the solubility limit of the impurity. The heavier the hydrocarbon, the less soluble it is in liquid CO_2. These components do not pose a material integrity risk but may pose multiphase flow risks and/or reduction of the amount of CO_2 in the tank. Water also poses a risk of dropping out as a secondary liquid phase.

Water is a key compound and condensation of water may result in corrosion and hydrate formation; hence, the fluid system should meet certain dehydration requirements. Burgass et al [4] indicated that at low-pressure, the water solubility is reduced, and higher dehydration requirements shall be met. The presence of glycols, i.e., MEG or TEG, together with H_2O aggravates the risk for liquid drop-out and the formation of an aqueous phase. The primary risk is in the CO_2 gas-dominated range, with a potential for liquid-liquid de-mixing under shipping conditions. Experiments of Mono-Ethylene Glycol (MEG) in CO_2 have been performed by Miguens et al. [16] at temperatures of 0 and 20 °C from 10 to 50 bar. The solubility of carbon dioxide was also calculated using the CPA-EoS. The result from the experiment is compared to the calculated solubility curves in Figure 3-5. Here, the sudden increase in concentration is due to the phase transition from gaseous to liquid CO_2.

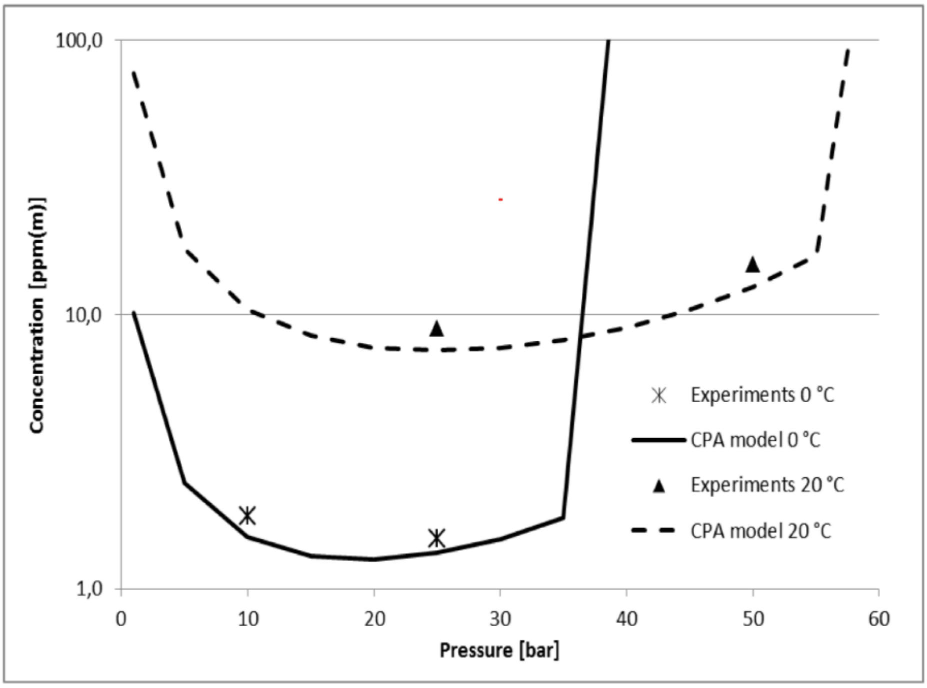


Figure 3-5: Solubility limits of MEG in pure CO_2. [16].

The solubility of non-condensable impurities such as N_2, O_2, CH_4 and Ar was investigated through a testing campaign by Franklin Okoro et al [17]. Attention is given to the solubility limits at low temperature condition and in the range from -45 to 0 °C. The use of equilibrium cells and proper mixing ensures ideal conditions for the measurements. The bubble point pressure was measured for different temperatures and concentrations of the impurities. The measurements indicate for all the isotherms, the higher the concentration, the higher the increase in the bubble point. Reducing the temperature, will all also increase the bubble point. Nitrogen was found to be the compound to most influence the bubble point (5% mol).

For further discussion on impurities solubilities, refer to Section 6.0, Work Package 2: Reaction Chemistry [18].

3.2.6 Potential for Chemical Reactions

When water is present in the fluid it will react with CO_2 and form carbonic acid (H_2CO_3), a dibasic acid that easily decomposes at a certain temperature and pressure [11]. Testing has shown that for a pure H_2O-CO_2 system with a high H_2O concentration, where the water was present as a separate aqueous phase saturated with CO_2, the corrosion rate varied from 2 to 24 mm/y However, in systems where the water was fully dissolved in the CO_2

phase the corrosion rate was less than 0.002 mm/yr [19].

If NO_X (NO, NO_2), SO_X (SO_2, SO_3) H_2S, O_2 and water are present acids can form, according to the reaction shown in Figure 3-6. Both H_2SO_4 and HNO_3 are strong acids while H_2SO_3 is a weak acid. Depending on the amount and the solubility of the reaction product, drop-out of liquid acid can occur which is a corrosive phase [6].

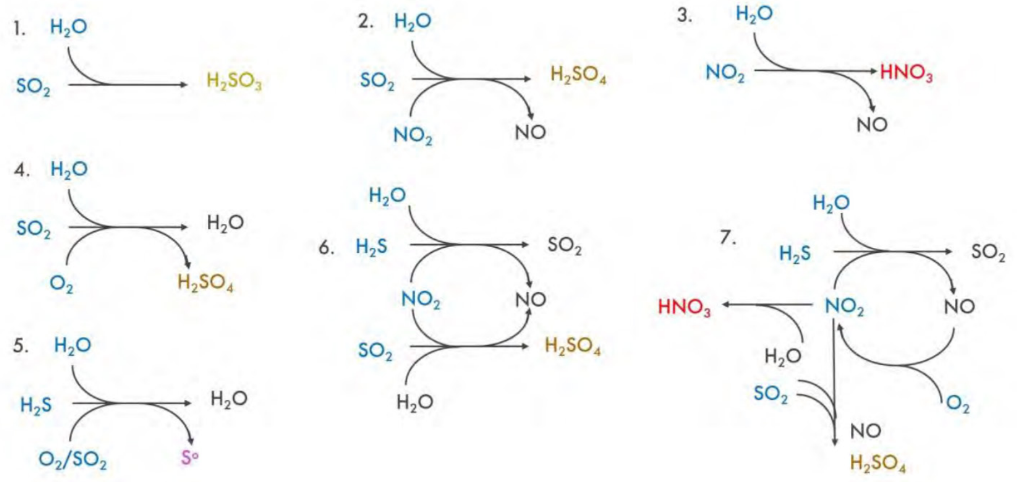


Figure 3-6: Most likely chemical reactions between a range of impurities (H_2O, SO_2, NO_2, H_2S and O_2) from J. Sonke et al. [6].

Sonke et al. [6] summarises tests performed to identify the threshold at which the corrosive phases are formed. In Table 3-5, tests with ship transport conditions are shown, and periods of validation typically cover around 50 h exposure. Fuller details of this work is discussed in Section 4.4, Work Package 3: Materials and Corrosion [9].

Table 3-5: Excerpt of Limits for the Formation of a Separate Phase in CO_2 [ppm-mol] at Ship Transportation Conditions

Condition	Phase	Impurity [ppm-mol]					Comment
		H_2O	SO_2	H_2S	O_2	NO_2	
-25 °C 20 bar	liquid	10	Total 60		10	-	No reactions or acid formation was observed with H_2S + SO_2 at a total of 60 ppm-mol
-23 °C 20 bar	liquid	30	10	5	10	1.5	Some reactions, but no liquid drop-out observed. At 2.5 ppm-mol NO_2 acids were formed, and reaction product drop-out has been observed.

As presented in Section 2.4, IFE is conducting a testing campaign on the acid reaction to identify CO_2 transport specifications that ensure material integrity [20, 21]. The campaign focuses on the possibility of chemical reactions and acid drop-out at pipeline conditions, i.e. 100 bar and 25 °C. Although these conditions are not representative of the shipping conditions discussed in this report, it is worth noting that different concentrations of impurities at a given pressure and temperature condition can result in chemical reactions, drop-out and eventually formation of an acid-liquid phase.

For further discussion on reaction chemistry, refer to Section 6.0, Work Package 2: Reaction Chemistry [18].

3.2.7 HSE

The HSE risks related to CO_2 are defined by the concentration and duration of exposure to CO_2. A CO_2 concentration between 1 to 3% leads to a decrease of blood pH and an increase in respiration. Above 3%, the breathing rate increases exponentially and hearing loss or visual disturbance may occur. When CO_2 concentrations exceeds 5%, symptoms increase in severity. Unconsciousness can occur minutes after concentrations reaching 10-15%. At concentrations reaching 30% CO_2 death occurs within a few minutes [22].

The presence of impurities in the CO_2 stream can also lead to concerns related to health and toxicity. Toxic compounds like CO, H_2S, NO_X, and SO_X can be noxious to people in the case of accidental emissions to the environment. H_2S is extremely toxic at low concentrations, thus, the acceptable level of H_2S is normally governed by the toxicity in cases of accidental release. Components like H_2S, H_2 and CO are flammable, however, CO_2 is not [7].

4.0 Publicly Available CO_2 Specifications for Ship-based Transport

This section summarises publicly available CO_2 stream specifications for ship-based transport. Section 9.4 of Work Package 5: Capture and Conditioning [8] reviews these specifications from the perspective of liquefaction, noting where impurities may challenge the liquefaction process. Sections 9.7.1 and 9.7.2 of the Work Package 5 report discuss the requirements in CO2 specifications for LP and MP transport and the need for additional research in these areas.

4.1 CO_2 Specifications for CCS

4.1.1 Longship CO_2 Specification

As part of the Longship project, Northern Lights will be the first cross-border, open-source CO_2 transport and storage infrastructure network transporting captured CO_2 from across Europe with ships and storing it permanently in a reservoir via pipelines in the northern North Sea. Northern Lights is a joint venture between Equinor, Shell, and TotalEnergies. The superseded 2021 CO_2 specification is given in Table 4-1 [23, 24]. The Northern Lights ships are loaded with CO_2 at conditions between 13-15 barg and -30.5 and -26.5 °C. Currently, the reservoir has a capacity to store 1.5 million tonnes of CO_2 per year.

Table 4-1: 2021 Longship CO_2 Specification [24]

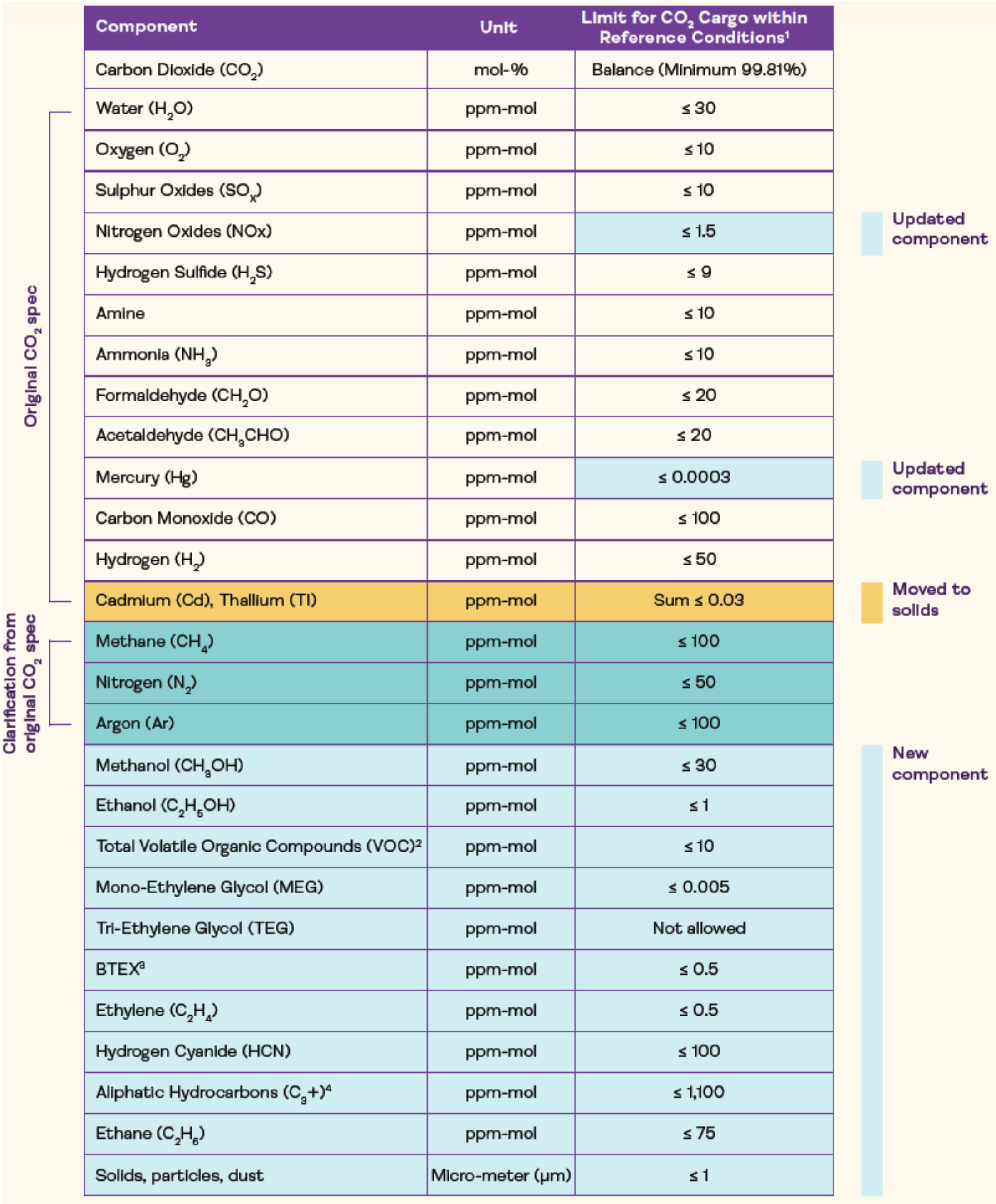
Component	Concentration (ppm-mol)
Water (H_2O)	≤ 30
Oxygen (O_2)	≤ 10
Sulphur oxides (SO_X)	≤ 10
Nitric oxide/Nitrogen dioxide (NO_X)	≤ 10
Hydrogen sulphide (H_2S)	≤ 9
Carbon monoxide (CO)	≤ 100
Amine	≤ 10
Ammonia (NH_3)	≤ 10
Hydrogen (H_2)	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury (Hg)	≤ 0.03
Cadmium (Cd), Thallium (Tl)	Sum ≤ 0.03
Non-condensable gases are components that, when pure, will be in gaseous at 15 barg and -26 °C. The content of non-condensable gasses will be limited by the actual solubility of the liquid CO_2 in the interim storage tanks at the capture plants.	

On February the 15th 2024, Northern Lights published an updated set of liquid CO_2 quality specifications for their infrastructure [25]. The specification was discussed in a dedicated webinar on February the 21st 2024 available on the Northern Lights' website [26].

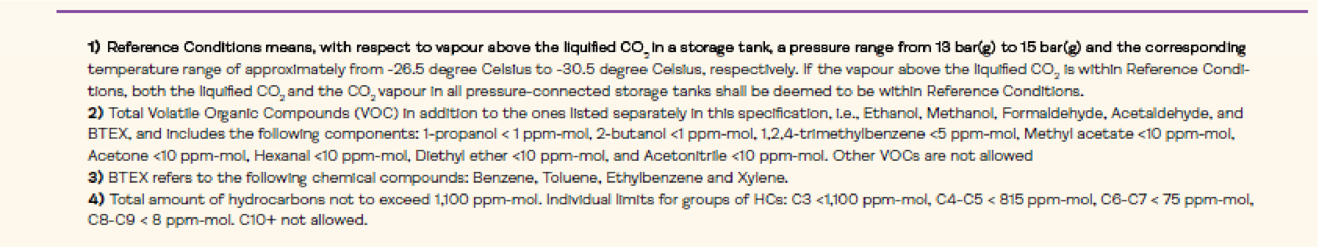
The updated specifications are claimed to be based on insights to the potential risks and implications to material integrity, operability, health, safety, and environment considerations. Furthermore, feedback from emitters covering a wide range of industries was considered to ensure that the specification can be met by customers. Consequently, to accommodate the wide range of industries, the specification had to be expanded, although becoming more restrictive for some of the components.

Based on the research work carried out by Northern Lights, the updated specification includes a clearer definition of non-condensable. The limit for NO_X was reduced from 10 ppm-mol to 1.5 ppm-mol which was found to be the most efficient way to limit the risk for cross reaction and acid formation. Further research and knowledge may allow for some of the limits to be revisited.

Table 4-2: 2024 Northern Lights Liquid CO_2 Updated Specifications [25]



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
Sulphur Oxides (SO_x)	ppm-mol	≤ 10
Nitrogen Oxides (NOx)	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_3CHO)	ppm-mol	≤ 20
Mercury (Hg)	ppm-mol	≤ 0.0003
Carbon Monoxide (CO)	ppm-mol	≤ 100
Hydrogen (H_2)	ppm-mol	≤ 50
Cadmium (Cd), Thallium (Tl)	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[3]	ppm-mol	≤ 0.5
Ethylene (C_2H_4)	ppm-mol	≤ 0.5
Hydrogen Cyanide (HCN)	ppm-mol	≤ 100
Aliphatic Hydrocarbons (C_3+)[4]	ppm-mol	≤ 1,100
Ethane (C_2H_6)	ppm-mol	≤ 75
Solids, particles, dust	Micro-meter (µm)	≤ 1



1) Reference Conditions means, with respect to vapour above the liquified CO_2 in a storage tank, a pressure range from 13 bar(g) to 15 bar(g) and the corresponding temperature range of approximately from -26.5 degree Celsius to -30.5 degree Celsius, respectively. If the vapour above the liquified CO_2 is within Reference Conditions, both the liquified CO_2 and the CO_2 vapour in all pressure-connected storage tanks shall be deemed to be within Reference Conditions.
2) Total Volatile Organic Compounds (VOC) in addition to the ones listed separately in this specification, i.e., Ethanol, Methanol, Formaldehyde, Acetaldehyde, and BTEX, and includes the following components: 1-propanol < 1 ppm-mol, 2-butanol <1 ppm-mol, 1,2,4-trimethylbenzene <5 ppm-mol, Methyl acetate <10 ppm-mol, Acetone <10 ppm-mol, Hexanal <10 ppm-mol, Diethyl ether <10 ppm-mol, and Acetonitrile <10 ppm-mol. Other VOCs are not allowed
3) BTEX refers to the following chemical compounds: Benzene, Toluene, Ethylbenzene and Xylene.
4) Total amount of hydrocarbons not to exceed 1,100 ppm-mol. Individual limits for groups of HCs: C3 <1,100 ppm-mol, C4-C5 < 815 ppm-mol, C6-C7 < 75 ppm-mol, C8-C9 < 8 ppm-mol. C10+ not allowed.

4.1.2 Aramis CO_2 Specification

Aramis, a collaboration between TotalEnergies, Shell, EBN, and Gasunie, involves both ship and pipeline transportation. Aramis have two specifications, one for ship conditions and one for pipeline conditions. The Aramis specification is shown in Table 4-3 [27]. The plan is to start operations with at least 5 Mt/year of carbon dioxide transported to storage locations under the North Sea.

Table 4-3: Aramis CO_2 Specification [27]

Class	Component	Constraint	Unit	Limit Ship condition	Limit Pipeline condition
	Carbon dioxide (CO_2)	larger than	mol%	balance	95
	Water (H_2O)	less than	ppm-mol	30	70$^{(1)}$
Inerts	Nitrogen (N_2)	less than	mol%	-	2.4
	Oxygen (O_2)	less than	ppm-mol	10	40
	Hydrogen (H_2)	less than	ppm-mol	500	7500
	Argon (Ar)	less than	mol%	-	0.4
	Methane (CH_4)	less than	mol%	-	1
	Carbon Monoxide (CO)	less than	ppm-mol	1 200	750
	$O_2+N_2+H_2+Ar+CH_4+CO$	sum less than	ppm-mol	2 000	40000
	Nitrogen oxides (NO_X)	sum less than	ppm-mol	1.5	2.5$^{(4)}$
Sulphur	Sulphur oxides (SO_X)	sum less than	ppm-mol	10	-
	Hydrogen Sulphide (H_2S)	less than	ppm-mol	5	5
	Carbonyl Sulphide (COS)	less than	ppm-mol	-	-$^{(1)}$
	Dimethyl Sulphide (DMS)	less than	ppm-mol	-	-$^{(1)}$
	$H_2S+COS+SO_X+DMS$	sum less than	ppm-mol	-	20
VOCs	Amine	less than	ppm-mol	10	1
	Formaldehyde	less than	ppm-mol	20	-
	Acetaldehyde	less than	ppm-mol	20	-$^{(1)}$
	Aldehydes	sum less than	ppm-mol	-	10
	Carboxylic acids & amides	sum less than	ppm-mol	-	1
	Phosphorus-containing compounds	sum less than	ppm-mol	-	1

Class	Component	Constraint	Unit	Limit Ship condition	Limit Pipeline condition
VOCs	Ammonia (NH_3)	less than	ppm-mol	10	3
	Ethylene (C_2H_4)	sum less than	ppm-mol	-	-(1)
	H-Cyanide (HCN)	less than	ppm-mol	-	2
	Total volatile organic compounds (excl. MeOH, EtOH, aldehydes)	sum less than	ppm-mol	10	10
	Methanol (CH3OH)	less than	ppm-mol	40	620
	Ethanol (C2H5OH)	less than	ppm-mol	20	20
Heavies	Glycols (TEG)	sum less than	ppm-mol	-	Follow dew-point specification
	C2+ (aliphatic hydrocarbons)	sum less than	ppm-mol	-	1200
	Aromatic Hydrocarbons	sum less than	ppm-mol	-	0.1
Metal	Mercury (Hg)	less than	ppb-mol	30	-
	Cadmium (Cd) + Thallium (Tl)	sum less than	ppb-mol	30	-
Dew point	Dew point (any liquid phase)	sum less than	°C (@ 20 bar)	-	-10(2)
Solids	Full removal cut-off diameter	Less than	micron	1(3)	1(3)

(1) There are some specific limits when transporting via OCAP infrastructure that can be obtained from OCAP B.V. (www.ocap.nl)

(2) Measured or predicted using CPA equation of state.

(3) This is the entry solids / dust specification for the envisaged Aramis stores. In order to achieve this Aramis will request Aramis emitters to install dust removal facilities with a cut-off diameter of 10 micron as a minimum. Furthermore, Aramis is planning to locate filters with cut-off diameter of 1 micron at optimal locations at the envisaged compressor and terminal stations.

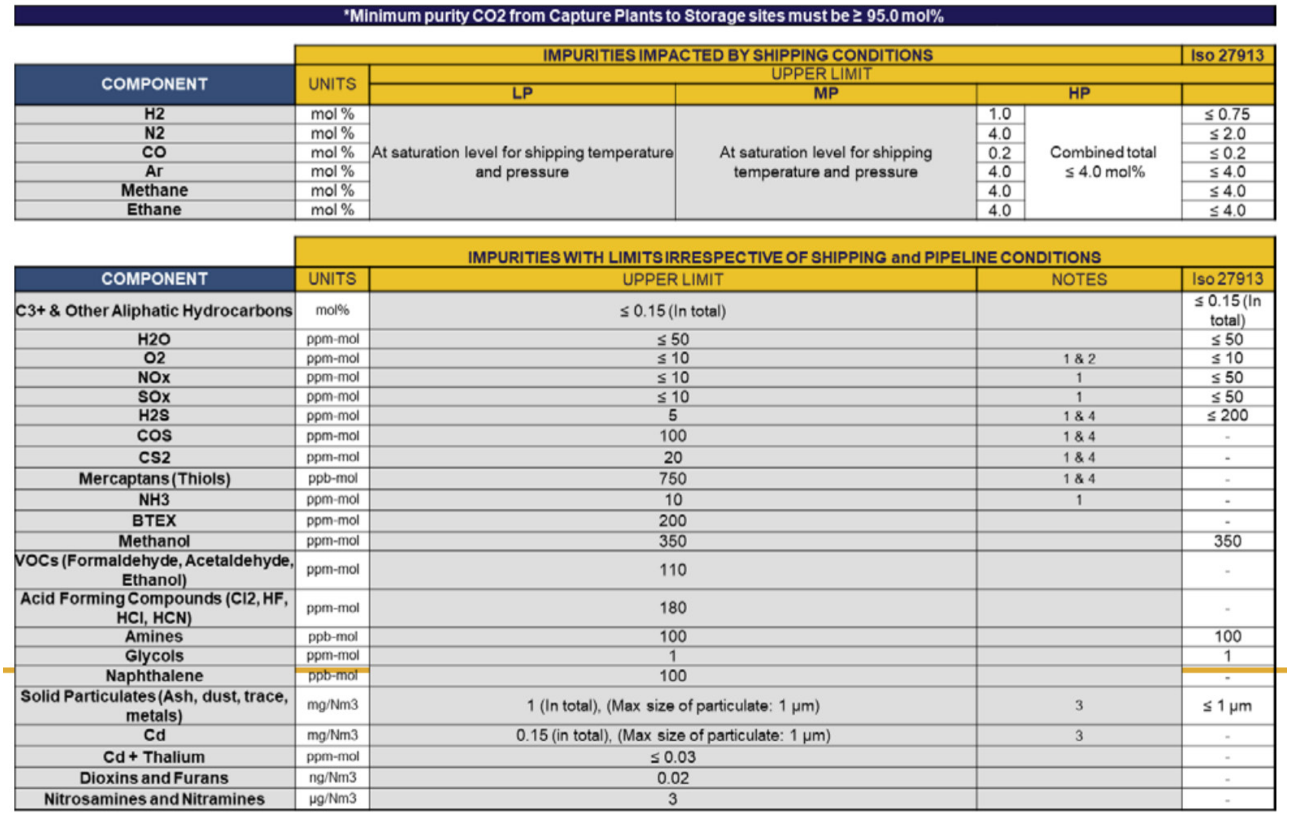
(4) Specification more stringent than Porthos CO_2 specification v3.1 at 5 ppm-mol. The limit is set based on testing similar to those described in section A.4 in ISO TR 27921 at seabed conditions.

A number of impurities are included in the overview without a specific limit to their content. Emitters agree to inform Aramis in case these components are expected in the CO_2 product at levels above 1 ppm-mol. Aramis will then conduct a risk assessment study to understand the maximum amount that can be tolerated. If the aforementioned CO_2 stream, includes components that are not included in the Aramis CO_2 specification and that can adversely affect Aramis, its personnel or the Aramis Transport System (e.g. as a result of liquid formation, corrosion or toxicity (HSE)), then Aramis shall in relation to each such component in consultation with customer, but at Aramis' sole discretion establish an upper concentration limit. The aggregate of these components and related concentration limits, as established from time to time shall constitute the CO_2 specification. The risk assessment for impurities in a CO_2 collection hub system and in particular the interaction of impurities from different sources is an ongoing field of research. A good summary of today's understanding is the 2020 issue of ISO TR 27921. Evolving insights may result in a re-visit of the risks associated with a particular impurity or combination of impurities. Aramis plans to actively manage these risks and hereby reserves the right to adjust the specification, if the existing level will adversely affect Aramis, people working on the project, or the envisaged Aramis Transport System.

4.1.3 Greensand Project

Project Greensand is developed by INEOS Energy, Wintershall Dea and Nordsøfonden and transporting CO_2 via ships and pipelines. The CO_2 specification for this project is shown in Table 4-4 [28].

Table 4-4: CO_2 Specification Defined for the Greensand Project [28]



*Minimum purity CO2 from Capture Plants to Storage sites must be ≥ 95.0 mol%

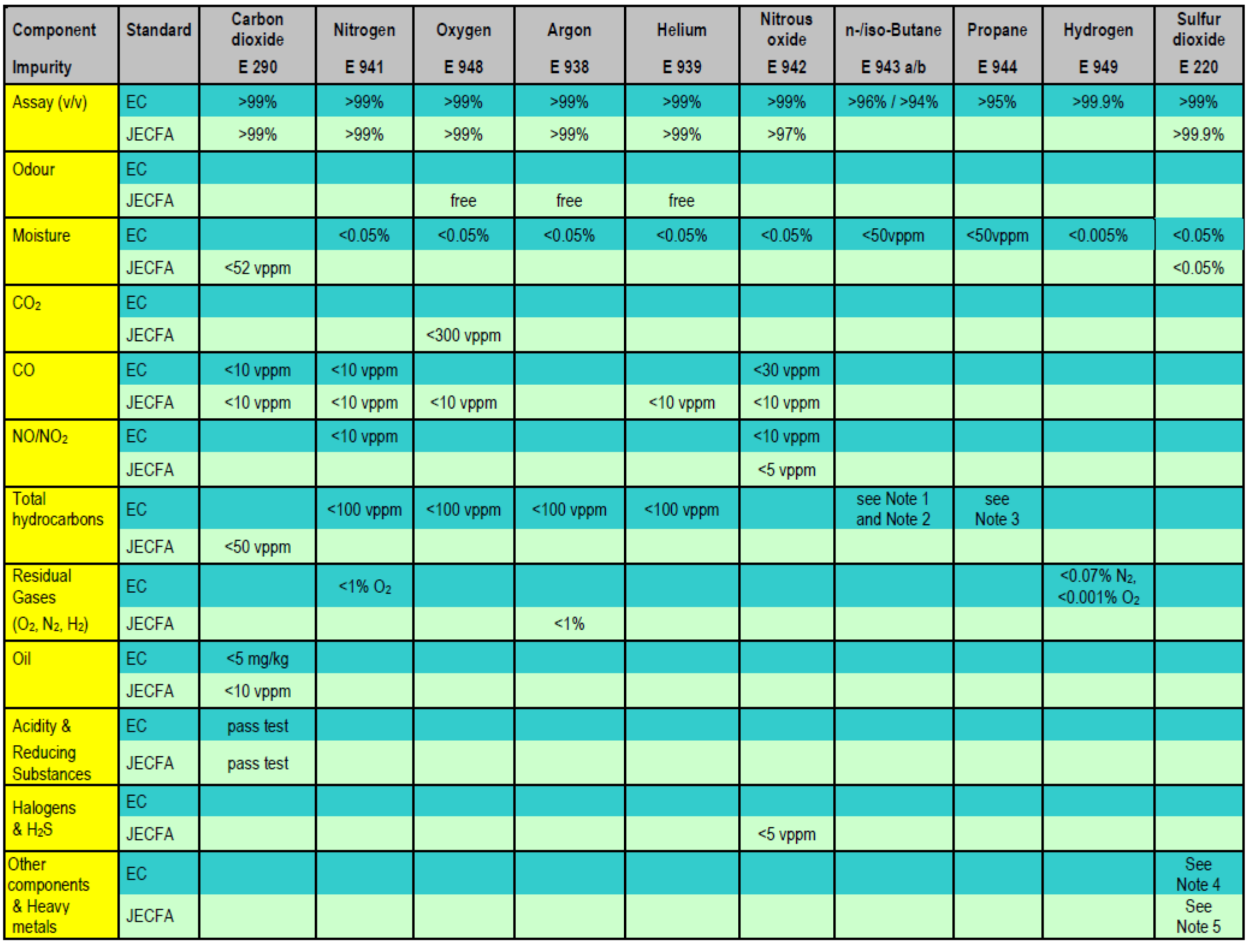
COMPONENT	UNITS	IMPURITIES IMPACTED BY SHIPPING CONDITIONS				Iso 27913
		UPPER LIMIT				
		LP	MP	HP		
H2	mol %	At saturation level for shipping temperature and pressure	At saturation level for shipping temperature and pressure	1.0	Combined total ≤ 4.0 mol%	≤ 0.75
N2	mol %			4.0		≤ 2.0
CO	mol %			0.2		≤ 0.2
Ar	mol %			4.0		≤ 4.0
Methane	mol %			4.0		≤ 4.0
Ethane	mol %			4.0		≤ 4.0

COMPONENT	UNITS	IMPURITIES WITH LIMITS IRRESPECTIVE OF SHIPPING and PIPELINE CONDITIONS		
		UPPER LIMIT	NOTES	Iso 27913
C3+ & Other Aliphatic Hydrocarbons	mol%	≤ 0.15 (In total)		≤ 0.15 (In total)
H2O	ppm-mol	≤ 50		≤ 50
O2	ppm-mol	≤ 10	1 & 2	≤ 10
NOx	ppm-mol	≤ 10	1	≤ 50
SOx	ppm-mol	≤ 10	1	≤ 50
H2S	ppm-mol	5	1 & 4	≤ 200
COS	ppm-mol	100	1 & 4	-
CS2	ppm-mol	20	1 & 4	-
Mercaptans (Thiols)	ppb-mol	750	1 & 4	-
NH3	ppm-mol	10	1	-
BTEX	ppm-mol	200		-
Methanol	ppm-mol	350		350
VOCs (Formaldehyde, Acetaldehyde, Ethanol)	ppm-mol	110		-
Acid Forming Compounds (Cl2, HF, HCl, HCN)	ppm-mol	180		-
Amines	ppb-mol	100		100
Glycols	ppm-mol	1		1
Naphthalene	ppb-mol	100		-
Solid Particulates (Ash, dust, trace, metals)	mg/Nm3	1 (In total), (Max size of particulate: 1 µm)	3	≤ 1 µm
Cd	mg/Nm3	0.15 (in total), (Max size of particulate: 1 µm)	3	-
Cd + Thalium	ppm-mol	≤ 0.03		-
Dioxins and Furans	ng/Nm3	0.02		-
Nitrosamines and Nitramines	µg/Nm3	3		-

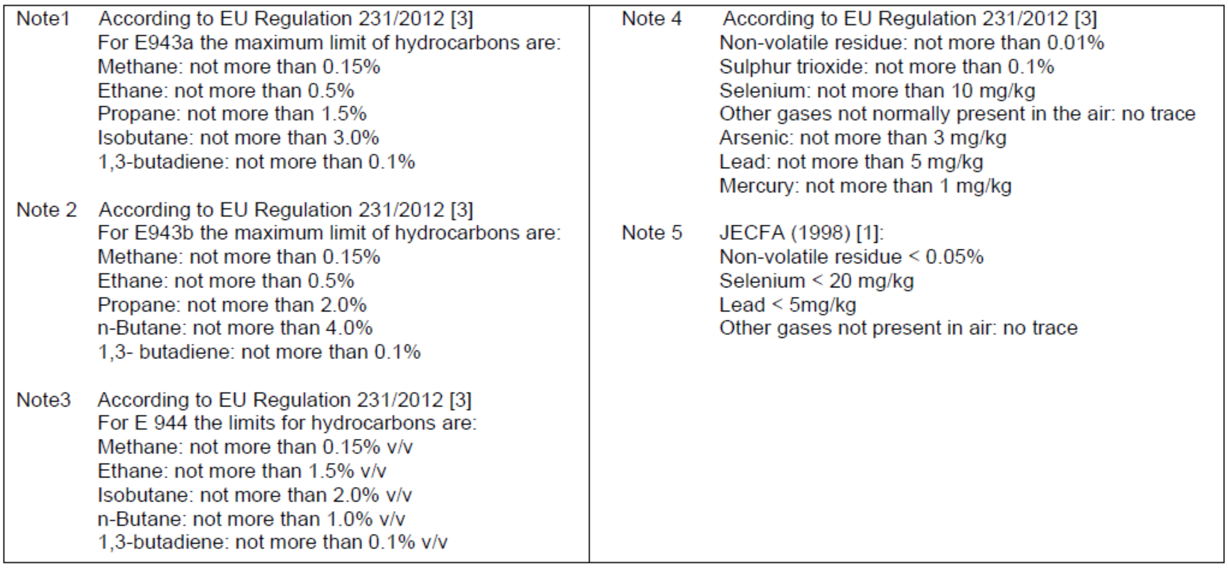
4.2 CO_2 Specifications for CCU

The minimum specifications for food additive gases from the Joint FAO/WHO Expert Committee on Food Additives (JECFA) and the European Union (EU) legislation are listed in Table 4-5 [29].

Table 4-5: Summary of Current Food Additives Gases Specifications in EU Legislation and JECFA [29]



Component Impurity	Standard	Carbon dioxide E 290	Nitrogen E 941	Oxygen E 948	Argon E 938	Helium E 939	Nitrous oxide E 942	n-/iso-Butane E 943 a/b	Propane E 944	Hydrogen E 949	Sulfur dioxide E 220
Assay (v/v)	EC	>99%	>99%	>99%	>99%	>99%	>99%	>96% / >94%	>95%	>99.9%	>99%
	JECFA	>99%	>99%	>99%	>99%	>99%	>97%				>99.9%
Odour	EC										
	JECFA			free	free	free					
Moisture	EC		<0.05%	<0.05%	<0.05%	<0.05%	<0.05%	<50vppm	<50vppm	<0.005%	<0.05%
	JECFA	<52 vppm									<0.05%
CO_2	EC										
	JECFA			<300 vppm							
CO	EC	<10 vppm	<10 vppm				<30 vppm				
	JECFA	<10 vppm	<10 vppm	<10 vppm		<10 vppm	<10 vppm				
NO/NO_2	EC		<10 vppm				<10 vppm				
	JECFA						<5 vppm				
Total hydrocarbons	EC		<100 vppm	<100 vppm	<100 vppm	<100 vppm		see Note 1 and Note 2	see Note 3		
	JECFA	<50 vppm									
Residual Gases (O_2, N_2, H_2)	EC		<1% O_2							<0.07% N_2, <0.001% O_2	
	JECFA				<1%						
Oil	EC	<5 mg/kg									
	JECFA	<10 vppm									
Acidity & Reducing Substances	EC	pass test									
	JECFA	pass test									
Halogens & H_2S	EC										
	JECFA						<5 vppm				
Other components & Heavy metals	EC										See Note 4
	JECFA										See Note 5



Note1 According to EU Regulation 231/2012 [3]
For E943a the maximum limit of hydrocarbons are:
Methane: not more than 0.15%
Ethane: not more than 0.5%
Propane: not more than 1.5%
Isobutane: not more than 3.0%
1,3-butadiene: not more than 0.1%

Note 2 According to EU Regulation 231/2012 [3]
For E943b the maximum limit of hydrocarbons are:
Methane: not more than 0.15%
Ethane: not more than 0.5%
Propane: not more than 2.0%
n-Butane: not more than 4.0%
1,3- butadiene: not more than 0.1%

Note3 According to EU Regulation 231/2012 [3]
For E 944 the limits for hydrocarbons are:
Methane: not more than 0.15% v/v
Ethane: not more than 1.5% v/v
Isobutane: not more than 2.0% v/v
n-Butane: not more than 1.0% v/v
1,3-butadiene: not more than 0.1% v/v

Note 4 According to EU Regulation 231/2012 [3]
Non-volatile residue: not more than 0.01%
Sulphur trioxide: not more than 0.1%
Selenium: not more than 10 mg/kg
Other gases not normally present in the air: no trace
Arsenic: not more than 3 mg/kg
Lead: not more than 5 mg/kg
Mercury: not more than 1 mg/kg

Note 5 JECFA (1998) [1]:
Non-volatile residue < 0.05%
Selenium < 20 mg/kg
Lead < 5mg/kg
Other gases not present in air: no trace

5.0 Current Practice for Ship-based Transportation of Liquefied Gases and Related Specifications

5.1 Introduction

Bulk transportation of liquefied gases by ships is integral to the global energy and chemical supply chain, including vital commodities such as Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), ammonia, ethylene, propylene, vinyl chloride monomer, and others. These products are valued for applications in power generation, heating, transportation, industrial processes, petrochemical industry, etc, and exhibit diverse purity and quality requirements based on their intended use.

The IMO International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code, [30]) serves as the primary international technical standard for the design and construction of gas carriers. Chapter 19 of the Code outlines the approved liquefied gases for bulk carriage on gas carriers. Gas carriers are normally designed to accommodate the different purity and quality grades of the cargo, with design considerations addressing potential hazards such as flammability, toxicity, corrosivity, low temperature, etc. The physical properties of the cargo, including cargo density, temperature, and pressure conditions during storage and transportation, are the basis for design, material selection and dimensioning of the cargo containment systems. To ensure safe cargo operations, the Code prescribes operating requirements, providing operators with essential information about cargo properties and system operation.

For the most common liquefied gases, it is generally assumed, in addition to proper design requirements, that impurities or contaminants causing a corrosive environment are adequately removed before loading to the ship. This assumption means that the potential for degradation of containment system performance and integrity due to corrosion is normally not accounted for in the design.

5.2 Types of Containment System

Figure 5-1 shows the most common types of containment systems which are used for storage and transport of liquefied gases in bulk, as defined in the IGC Code [30]. The tank types are categorized depending on the shape and construction of the tank, the documentation approach, and the safety philosophy.

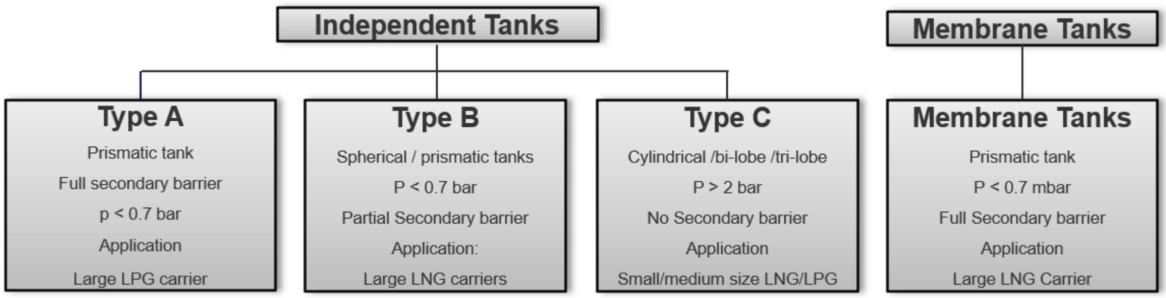


Figure 5-1: Illustration of different types of containment system.

Independent tanks are self-supporting tanks which do not form part of the ship's hull. They are further divided into Types A, B, and C, as follows:

- **Independent tanks type A** are tanks which are primarily designed by use of classical ship-structural analysis in accordance with recognized standards. The tanks are normally a prismatic shape and are operated at atmospheric pressure conditions. The insulation is fitted on the tank external surfaces to prevent excessive boil-off of cargo. A full secondary barrier is required to protect the hull structure from low temperature exposure in case of leakage of cargo from the tank. The tank type is commonly used for larger fully refrigerated LPG carriers. The cargo hold boundaries are made of low temperature steels and serve as a secondary barrier for the tanks. Recently Type A tanks have also been built for carriage of LNG. In this case, the hull structure is insulated and protected by a separate secondary barrier in case of leakage of cargo from tank. As the cargo is carried at atmospheric pressure, this tank type is not considered applicable for carriage of CO_2.

- **Independent tanks type B** are tanks which are designed using model tests, refined analytical tools and analysis methods to determine stress levels, fatigue life and crack propagation characteristics. The comprehensive documentation scope is assumed to justify the replacement of a full secondary barrier with a partial secondary barrier with a small leak protection system. The most common type B tank design is the spherical tank used for large LNG carriers. Prismatic tanks are also built for carriage of LNG. The tanks are operated at atmospheric pressure conditions and are hence not considered applicable for carriage of CO_2.
- **Independent tanks type C** are pressure vessels designed based on standard pressure vessel criteria modified to include fracture mechanics and crack propagation criteria. The tanks are designed to a minimum design vapour pressure to ensure that the dynamic stresses are sufficiently low such that the probability for structural failures and leakages through the primary barrier is extremely low and can be neglected. Hence, this tank type does not require a secondary barrier. Independent tank type C are either a conventional cylindrical shape or bi-lobe or multi-lobe types. The tank type is common on smaller gas carriers and is used for all types of refrigerated or pressurised liquefied gases, including LNG, LPG, ammonia, ethylene and CO_2.
- **Membrane tanks** are, according to IGC Code, defined as a non-self-supporting tank that consists of a thin liquid and gastight layer (membrane) supported through insulation by the adjacent hull structure. The tank type requires a full secondary barrier in case of leakage of cargo through the primary barrier. The tanks are normally a prismatic shape and are operated at atmospheric pressure conditions. The tank type is commonly used for larger LNG carriers but are also applied for refrigerated ethylene carriers. The tank type is not considered applicable for CO_2 carriage.

5.3 Material Selection for Gas Carrier Application

Material selection for the cargo containment system and cargo handling for gas carriers in general is mainly driven by design temperature and strength properties. For some cargoes like NH_3 certain materials need to be avoided as further described in Section 5.4.3.

Materials for cargo containment systems are specified in the IGC Code [30] and the Classification Rules of the Classification Societies.

The IGC Code groups applicable low temperature materials depending on the design temperature.

Low temperature carbon manganese steels are specified for design temperatures between 0 and -55 °C. The material yield strength is generally limited to 410 MPa. These materials are typically used for cargo containment systems on LPG carriers and on existing CO_2 carriers.

For design temperatures from -55 to -165 °C nickel alloy steels, aluminium, austenitic stainless steel, and austenitic high manganese steels are specified. Nickel alloy steels are normally used for ethylene (5% Ni) and LNG (9% Ni), while stainless steel, aluminium and austenitic high manganese steels are used for LNG.

5.4 Bulk Transportation of Liquefied Gases

5.4.1 Liquefied Natural Gas (LNG)

Liquefied Natural Gas (LNG) is one of the most common liquefied gases which is transported by sea in large volumes and over large distances. Comprising primarily of methane (>80%), with a smaller amount of ethane and some other heavier hydrocarbon fractions, the gas is purified and cooled down to liquid form at atmospheric pressure prior to storage and transport.

Throughout the treatment and liquefication process, impurities, and contaminants such as solids, water, carbon dioxide, hydrogen sulphide, mercury and higher density hydrocarbons, are removed. This purification ensures that the distributed gas meets quality targets (e.g., energy density/heating values). It also ensures that the cargo maintains its non-corrosive and non-toxic properties, limiting environmental impacts and preventing corrosion or other damages to the containment system of the ship.

LNG carriers are designed to carry different grades of LNG at cryogenic temperatures and atmospheric pressure conditions. The cargo tanks and cargo handling systems are designed for cryogenic temperatures down to -163 °C, and is typically made of stainless steel, 9% nickel alloy steel or aluminium, depending on the type of containment system. A minimum design cargo density value of 500 kg/m^3 ensures that the ship can accommodate the cargo density ranges relevant to LNG.

5.4.2 Liquefied Petroleum Gas (LPG)

Liquefied Petroleum Gas (LPG) typically consists of propane or butane or a mixture of the two gases, with possible fractions of propylene, butylene, and other hydrocarbon gases. LPG is liquefied and transported either in pressurised condition at ambient temperature, or in refrigerated condition at intermediate or near atmospheric pressure.

LPG is used for heating, cooking, as automotive fuel, as a refrigerant, in the production of chemical products etc. The composition and characteristics of LPG vary depending on the manufacturing process and the gas mixture. LPG gases are regarded as flammable products but considered generally non-toxic and non-corrosive.

LPG carriers are normally multi-gas vessels, and the design cargo density, temperature, and vapour pressure of the cargo containment system are specified depending on the product range, mixtures, and the cargo storage condition. Some LPG carriers are also designed to carry ammonia and higher density cargoes such as vinyl chloride monomer (VCM).

Caution should be taken when the cargo mixtures contain high concentrations of butadiene, as the mixture potentially becomes a toxic and reactive product.

Semi or fully refrigerated LPG carriers typically have a design temperature of -48 °C, corresponding to the temperature of liquid propylene at atmospheric pressure. However, recent market entry of LPG with high ethane or methane content reduces the cargo temperatures and may require design temperatures lower than what is common for the current LPG fleet. LPG with high ethane or methane content may also affect the efficiency of the reliquefication plant.

5.4.3 Anhydrous Ammonia (NH_3)

Anhydrous Ammonia (NH_3) is an industrial chemical with a wide range of application areas. The product is normally transported in liquid form under conditions similar to LPG. Ammonia is categorized into different grades based on its purity and application. It typically contains small fractions of water and oil, as well as carbon monoxide, carbon dioxide and other particles. The specified grades are as follows:

- Metallurgical grade ~ > 99.998 % ammonia
- Refrigeration grade ~ 99.98 – 99.995 % ammonia
- Commercial grade ~ 99.5 – 99.6 % ammonia

The metallurgical and refrigeration grades are the purest grades of ammonia and have a strict water content (33-150 ppm) and contaminant requirements. These grades are used in applications where a high level of purity is required, such as laboratory work, metallurgical industry and in use as refrigerant in refrigeration systems.

The major share of produced ammonia is of commercial grade and is predominantly used in the agriculture industry to produce fertilisers. A similar grade is also considered applicable for the use of ammonia as an alternative fuel in for the decarbonisation of the transportation sector. Commercial grade ammonia contains a modest amount of water (5000 ppm).

Anhydrous ammonia is toxic and corrosive to certain materials such as mercury, copper, and zinc. In addition, certain materials, including high strength carbon steels and nickel steels, are also susceptible to stress corrosion cracking. Commercial grade ammonia, with its small amount of water content, is considered to be favourable with regard to risk of stress corrosion cracking.

Gas carriers used for carriage of ammonia are normally LPG carriers subject to special materials and cargo composition requirements to prevent corrosion and stress corrosion cracking. First, materials known to be corrosive to ammonia such as mercury, copper and copper-bearing alloys, and zinc are not accepted in the cargo containment systems and in equipment normally in contact with the cargo. Containment systems made of carbon manganese steel have limitations to the specified minimum yield strength (<355 MPa) and actual yield strength (<440 MPa) to reduce risk of stress corrosion cracking. In addition, one of the following design or operational requirements needs to be fulfilled:

- Specified minimum tensile strength < 410 N/mm^2
- Post-weld stress relief heat treatment
- Ammonia carried at temperature close to the boiling point of -33 °C, but in any case, not above -20 °C.
- Ammonia shall contain not less than 0.1% w/w water.

Containment systems constructed with nickel alloy steels containing more than 5% nickel are not accepted for ammonia carriage. Nickel alloy steels with nickel content less than <5% are acceptable only if ammonia is carried at temperature close to the boiling point.

Recommendations are also given in the IGC Code regarding reduction of oxygen content in cargo tanks prior to filling of ammonia to reduce crack corrosion cracking.

5.4.4 Other Liquefied Gases

Ethylene is widely used in the petrochemical industry which typically requires a high level of purity. The product is normally liquefied and transported in refrigerated condition at near atmospheric pressure. Typically, the ethylene content is more than 99.5% or higher, and there are strict requirements to contaminants such as ethane, methane, nitrogen, carbon dioxide, carbon monoxide, acetylene etc. Ethylene is assumed to be a flammable, but a non-toxic and non-corrosive product.

As ethylene normally has strict tolerances to contamination, it is very important to ensure proper cleaning of the cargo containment system, piping, etc, prior to loading, particularly if the previous cargo has been ammonia or other similar cargoes. Only minor residuals of ammonia may bring the cargo off specification.

Several products such as ethylene oxide and propylene oxide have strict requirements for cleaning of cargo tanks and cargo handling systems to avoid the potential for traces of previous cargoes causing a dangerous reaction of the cargo.

Ships carrying methyl-acetylene-propadiene mixtures have composition requirements to ensure sufficient stabilization of the cargo. This relates to the relative ratio of methyl acetylene to propadiene as well as the concentration of hydrocarbon diluents such as propane, butane, etc.

Transport of carbon dioxide by ships is currently limited to a dedicated fleet of vessels serving small scale industrial and specialist gas users, including food and beverage markets. The product is liquefied and transported under pressure and at semi-refrigerated conditions, normally referred to as medium pressure condition. The IGC Code distinguishes between high purity CO_2 (Ch.17.21) and reclaimed quality CO_2 (Ch.17.22), considering cargo compositions potentially affecting phase transitions (both qualities) and corrosion (reclaimed quality).

The Code does not define the boundary between the two qualities, but the specifications of the cargo currently shipped today are generally regarded as high-quality CO_2 with strict requirements on impurities and contaminants.

The given distinction may need to be revised in the context of impurity levels and quality related to CCS and CCU applications.

5.4.5 Off Specification Cargoes

For the most traded liquefied gases, including LNG, LPG etc, the handling of off specification cargoes is often a commercial matter to be agreed between buyer and seller of the product. Off-specification can be related to pressure/temperature conditions, compositions, and the potential for contamination from previous cargoes, and are often reflected in discount of cargo. As examples, discounts typically assumed for the first cargoes after change of grade (e.g. ammonia), or after drydocking.

5.5 Gas Carriers Operations

5.5.1 Loading and Offloading

During the loading operations, the liquid product is transferred from the onshore storage tanks at the terminal to the ship tanks. The transfer occurs through cargo lines, cargo hoses or marine loading arms. Despite efforts to minimize heat ingress through design, there is a potential for boiling and two-phase flow of cargo during transfer. Two phase-flow is not uncommon in LNG/LPG operations, and procedures are established to ensure proper flow of cargo.

Loading operation can be conducted with or without vapor return to shore. The use of vapor return lines ensures pressure balance between the onshore tanks and ship tanks, balancing the displaced gas, the boiloff caused by heat ingress, and the vapor flash caused by cooldown of cargo tank structure.

If vapor return is not performed, a vaporizer may need to be used to compensate pressure reduction in the onshore tank. On the other hand, the increasing vapor in the ship tank may be handled by a reliquefication plant.

During the offloading operations, the liquid gas is pumped from the ship tank to the onshore storage. Simultaneously, the vapor from the onshore tank is displaced to the ship tank to maintain the pressure at a certain level.

5.5.2 Cargo Pressure and Temperature Control during Voyage

As stated in the IGC Code, Chapter 7, the cargo tanks pressure and temperature shall be controlled at all times to be within the design range. The Code lists alternative means for cargo management, including pressure accumulation, and reliquefication.

For Type C tanks, cargo boil off can normally be handled by pressure accumulation. According to the IGC Code §7.5, the containment system insulation, design pressure or both shall be adequate to provide for a suitable margin for the operating time and temperatures involved.

There are different practices for assessing suitable margins against pressure build up, but a minimum of twice the time for the longest planned voyage have often been used as basis for design. The tank pressure upon arrival at the offloading point will depend on the initial loading temperature, ambient temperatures (air/sea), the loading level, and duration of the voyage. The pressure build-up rate is normally higher during ballast voyage due to cargo heel.

Gas carriers carrying cargo at atmospheric pressure and many semi-refrigerated LPG carriers are also equipped with reliquefication plants to maintain cargo conditions. The reliquefication system is designed to recover evaporated gas by reliquefication, and then return the liquefied gas back to the cargo tanks.

Most LNG carriers use their own cargo vapour as fuel and do not normally need an additional reliquefication plant onboard.

6.0 Considerations on Shipping of CO_2 streams

6.1 CO_2 Transport Conditions

Liquified CO_2 shipping is currently a niche market which is exclusively employed for commercial trade purposes such as the food and beverage, cleaning, and chemical industries. As for other liquefied gases such as propane and butane, CO_2 is currently transported on ships as a semi-refrigerated liquid under pressure at conditions which often are referred to as medium-pressure.

For the medium-pressure condition, the CO_2 is transported in liquid state at pressures ranging from 15 to 18 barg and at temperatures ranging from -21 to -26 °C. The ships ordered for the Northern Lights project, with a cargo capacity of 7500 m^3, are designed for this temperature and pressure regime.

When transporting larger volumes of CO_2, other pressure conditions are being investigated with the intention of increasing the transportation capacity at viable costs. Ship concepts targeting both low and high-pressure conditions are being evaluated by industry.

At low-pressure conditions, the CO_2 is foreseen to be transported at pressures in range of 6 to 10 barg with corresponding liquid temperatures in the range of -40 to -49 °C. The lower pressure may allow for the utilization of larger cargo tanks and enhanced flexibility in the ship arrangement. This, in combination with an increased liquid product mass density, accommodates for an increased cargo capacity per ship and hence potentially contributing to an overall reduction in transport cost.

High pressure concepts assume CO_2 condition at near ambient temperature and with a correspondingly higher pressure (higher pressure than for medium and low-pressure transport). The pressure and temperature conditions are closer to the conditions in the permanent storage reservoirs, implying that the overall refrigeration and heating demand for the value chain is lower.

A summary of the typical cargo temperatures and pressures is given in Table 6-1 for the different pressure conditions while Figure 6-1 provides a visual reference compared to Vapor Liquid Equilibrium (VLE) curve for pure CO_2.

Table 6-1: Cargo Pressure and Temperature for Ship Transportation of Liquid CO_2

Condition	Pressure	Temperature
Low Pressure	6 to 10 barg	-40 to -50 °C
Medium Pressure	13 to 18 barg	-21 to -30 °C
High Pressure	34 to 44 barg	-0 to 10 °C

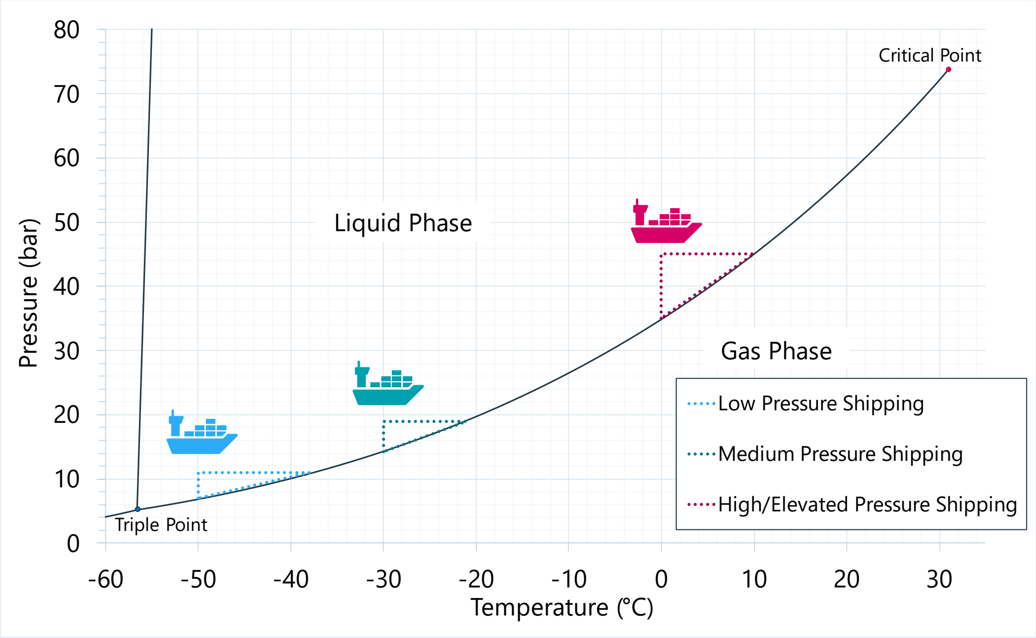


Figure 6-1: VLE curve for pure CO_2 and representative ship transport conditions.

The cargo conditions have direct implications to other components of the value chain, including liquefaction, cargo handling operation, choice of material for containment system and cargo handling system, boil off management and insulation.

Section 6.2 and Section 6.3 describe how the cargo condition and impurities can affect the ship and operations.

6.2 Material Selection for CO_2 Applications

6.2.1 Metallic Materials

The selection of materials for the cargo containment system and cargo handling in typical CO_2 carriers designs currently being developed are mainly driven by design temperatures and strength properties.

Materials for cargo containment systems are specified in the IGC Code [30] and the Classification Rules of the Classification Society as presented in Section 5.3 of this report. The materials typically used for refrigerated gases like CO_2 are low temperature carbon-manganese steels which are generally not regarded as corrosion resistant in environments with a presence of water and certain other impurities included the CO_2 stream.

The cargo tanks on board the CO_2 carriers operating in commercial trades are built of conventional carbon-manganese steel incompliance with the IGC Code. The size of the cargo tanks is typically limited by the material strength.

To accommodate the foreseen transportation volumes in the CCUS value chain, it is anticipated that larger tanks need to be built, and the material strength is an important parameter to meet the desired size.

For medium and low-pressure cargo conditions, materials are required to provide a combination of low-temperature performance and strength. The industry is looking towards extra high strength carbon-manganese steel with strength properties exceeding the limits defined in the IGC. Hence, these steels need qualification activities to document their suitability for gas carrier applications. Nickel alloys steels (3.5% Ni, 5% Ni, 9% Ni) are suitable for low-temperature applications but provide limited strength advantage and may be considered too expensive for CCS / SSC applications.

For high-pressure application, the low temperature performance of the material is less important, which may open for the use of more standard pressure vessel materials.

Due to the limited mechanical properties and costs, stainless steels are not regarded as the best option for the large-scale CO_2 transport, although they may exhibit improved corrosion resistance compared to conventional carbon-manganese alloys.

For the cargo handling system in a low-pressure and temperature application (i.e. -55 °C) various grades of Stainless Steel such as 304, 304L, 316 and 316L as well as specially treated carbon manganese steel would in principle be suitable for the cargo piping.

For further information on materials refer to Work Package 3: Materials & Corrosion [9].

6.2.2 Non-Metallic Materials

Polymer seals shall be compatible with the product specification and temperature rating. CO_2 may cause deterioration of O-rings, seals, gaskets and valve seats. There are several types of materials which are chemically suitable for dry CO_2 cargoes containing very little impurities such as SO_X, NO_X, O_2, H_2S and H_2O. However, the low temperature application may limit material options. The use of non-metallic materials is also discussed in Section 3.2.4, Work Package 3: Materials and Corrosion [9].

Ansaloni et al. [31] summarised a non-exhaustive list of polymers that have been identified in the CCS value chain, including the component these polymer materials can typically be found in, as seen in Table 6-2. It is shown that that there are limited options for polymers applicable for shipping conditions.

Table 6-2: From Ansaloni et al. [31] a Non-Exhaustive List of Polymers That May be Found in the CO_2 Transport Chain, with their Typical Glass Transition Temperatures (T_g)

Polymer	Acronym	T_g(°C)	Type of Component
Elastomers			
Ethylene-propylene diene monomer	EPDM	-54	Sealants, gaskets
Chlorosulphonate polyethylene rubber	CSM	-55	Sealants, gaskets
Fluoroelastomers	FKM, FFKM, FEPM	-15 to 3	Sealants, gaskets
Nitrile butadiene rubber	NBR	-38 to -2 (3)	Sealants, gaskets
Styrene butadiene rubber	SBR	-65 to -50 (4)	Sealants, gaskets
Ethylene vinyl acetate rubber	EVM	-25 to 0 (5)	Sealants, gaskets
Chloroprene rubber	CR	-45	Sealants, gaskets
Isoprene rubber	IR	-70	Sealants, gaskets
Engineering Thermoplastics			
Polypropylene	PP	-25 to 0 (1)	Tubes, pipes
High density polyethylene (usually PE100)	HDPE	-135 to -115	Tubes, pipes, tanks, vessels
Polyamides (Nylon, e.g. PA11 or PA12)	PA	40 to 60	Tubes, pipes, tanks, vessels
Polytetrafluoroethylene	PTFE	See (2)	Tubes, pipes, sealants, gaskets
Polyvinylidene difluoride	PVDF	-35	Tubes, pipes, sealants, gaskets
Polyethertherketone	PEEK	145	Higher temperature valves

Notes:
(1) Depending on tacticity;
(2) the T_g of PTFE is subject to scientific debate; however, PFTFE is typically tough even at low temperatures
(3) depending on the acrylonitrile content;
(4) depending on the production process (polymerisation in solution or emulsion);
(5) depending on the copolymer composition (amount of ethylene versus vinyl acetate).

The chemical compatibility of some polymeric materials with impurities commonly present in a CO_2 stream can be seen in Table 6-3 [31]. The data is combined from a selection of materials suppliers. Green indicates good compatibility with the concentrated chemical; orange indicates poor compatibility with the concentrated chemical and red indicates that significant interactions with the concentrated chemical are expected and therefore this combination could be unsuitable. The sources were chosen arbitrarily from commercially available literature, and the results must be considered as indicative rather than absolute.

Table 6-3: Typical Stability of Some Polymer Materials with Respect to Various Contaminants [31]

Component	Conc (mol%)	HDPE	PP	PA12	PTFE	PVDF	Fluoro-elastomer	EPDM	NBR	SBR	IR	CR
CH_4	100	🟩	🟩	-	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
CO	100	🟩	🟩	-	🟩	🟩	🟩	🟧	🟩	🟩	🟧	🟧
H_2	100	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟩
H_2S gas (dry)	100	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟥	🟩	🟧	🟧
NH_3 gas	100	🟩	🟩	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩
Water	100	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧
SO_x												
SO_2	100	🟩	🟩	-	🟩	🟧	🟩	🟩	🟥	🟥	🟥	🟧
SO_3	100	🟥	🟥	-	🟧	🟥	-	-	🟥	🟥	🟧	🟥
NO_x												
N_2O	100	🟩	🟩	-	🟩	-	🟩	🟩	🟩	🟩	🟩	🟩
NO_2	100	🟩	🟩	-	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Amines												
Butylamine	100	🟩	🟥	-	🟩	🟧	🟩	🟥	🟩	🟥	🟥	🟥
Dibutylamine	100	-	-	-	🟩	-	-	-	-	🟥	🟥	🟥
Diethylamine	100	🟧	🟩	-	🟩	🟥	🟧	🟩	🟥	🟥	🟧	🟥
Diethylenamine	100	-	🟧	-	🟩	-	-	🟩	🟩	-	-	-
Diethylenetriamine	100	🟥	🟥	-	🟩	-	-	-	-	-	-	-
Dimethylamine	100	-	🟩	-	🟩	🟥	🟥	🟧	🟥	🟥	🟥	🟥
Monoethanolamine	100	-	-	-	🟩	-	-	🟩	🟥	🟧	🟧	🟥
Triethanolamine	100	🟧	🟩	-	🟩	🟧	🟧	🟩	🟩	🟧	🟥	🟧
Triethylamine	100	🟧	🟥	-	🟩	-	🟩	🟩	🟥	-	🟧	🟩
Methylamine	100	🟥	🟧	-	🟩	🟧	🟩	🟩	🟧	🟧	🟧	🟩
Aldehydes												
Acetaldehyde	100	🟧	🟧	🟩	🟩	🟥	🟧	🟩	🟥	🟧	🟧	🟧
Acetaldehyde	40	🟩	🟩	🟩	🟩	-	🟧	🟩	🟥	-	-	-
Formaldehyde	35	🟩	🟩	🟧	🟩	🟧	🟩	🟩	🟧	🟧	🟧	🟧
Formaldehyde	50	-	🟩	-	🟩	-	🟧	🟩	-	🟧	-	-
Note: An increase in temperature is typically corresponding to a decrease in stability (higher diffusion, higher reaction kinetics). However, the effect of temperature on stability can be significantly different, and each case should be carefully investigated depending on the specific need.												

6.3 Implication of Impurities on Design and Operation of CO_2 Carriers

6.3.1 Material Integrity and Corrosion

To date, the typical CO_2 carrier designs proposed for CCS value chains are typically designed without specific corrosion barriers. This assumes that the CO_2 composition will not cause any challenges with respect to corrosion. However, the CO_2 stream can lead to a corrosive environment depending on the presence of impurities, see Section 3.0.

As explained in Section 3.2.5 the solubility of the different impurities in the CO_2 stream is affected by the cargo conditions. Water is regarded as a key impurity when it comes to the risk of corrosion and chemical reactions. The solubility of water in CO_2 is affected by the presence of other impurities but is generally reduced by the temperature.

Consequently, it is expected that a low-pressure value chain will have a more stringent dehydration requirement to avoid condensation and therefore generation of a corrosive environment in the presence of other impurities such has SO_X and NO_X. However, to date, there is no publicly available literature illustrating the solubility of H_2S, SO_X, NO_X and the potential for chemical reactions at pressure and temperatures relevant for the three shipping conditions.

In other ship segments such as chemical tankers where corrosion is a concern, barriers such as corrosion resistant material (stainless steel), or coatings are used. However, it shall be noted that the cargo is at different pressure and temperature conditions compared to CO_2.

To reduce the risk of corrosion, the use of stainless steel to line the bottom of the tanks, where the liquid dropout will accumulate, could be further investigated. In addition, the secondary liquid phase can also be drained. A rubber liner and a paint coating to protect the materials is used in chemical carriers. However, there is limited experience with the use of such barriers in a low-temperature application and the possible impact that CO_2 may have on the coating.

6.3.2 Cargo Handling and Cargo Management

Loading and offloading in CO_2 can be performed as for conventional gas carriers and with or without the use of vapor return, Section 5.5. Vapour return is used as a means to control the pressure in the tanks during cargo transfer, controlling pressure increase in the receiving tank and to avoid that cargo pressure is reduced with risk of dry ice formation. It is also possible that the cargo transfer is interrupted due to the insufficient pump head.

As an alternative to vapour return, own cargo vapour must be generated through vaporisers to balance the pressure reduction during the offloading operation. On the other hand, a reliquefication plant is needed to handle increasing pressure in the receiving tank. These operations are common for LPG carriers but may add novelty elements for CO_2 carriers as there is no experience with the installation and operation of a reliquefication plant on board CO_2 ships.

Considering the presence of impurities in the CO_2 stream, the vapor return can be regarded as a possible means to impact the mix of different impurities and specifications.

In the case that offloading facilities have been accepting cargo from different sources, it is likely that the vapor displaced back to the ship during offloading will contain a different blend of impurities compared to what was initially present in the cargo tank.

At the end of the ballast voyage, the ship connects to an export terminal to load CO_2, the vapor from the cargo tank is displaced back to the onshore tank and eventually reaches the liquefaction plant. Considering that the ship is potentially carrying vapor originated from a different source, it is possible that the emitters will receive components via vapour return that were not originally present in their liquid product. Consequently, emitters will have to handle liquid products not necessarily corresponding to their own liquid product.

As presented in the webinar (see Section 4.1.1), Northern Lights basis is open vapor return across all customers, and the compliance with liquid CO_2 specification is key for ensuring vapor return compliance for the different CO_2 sources.

Furthermore, during the ballast voyage, when the ship is loaded with a smaller amount of liquid CO_2, the impurities accumulating in liquid and vapor phases have higher concentrations than in the loaded voyage. This increases the risk of possible chemical reactions, which may be enhanced by the additional impurities loaded via vapor return.

The presence of impurities in the CO_2 stream alters the phase envelope, see Section 3.2.3. The larger the fraction of impurities, the greater the range of pressures and temperatures at which the fluid can be in the two-phase region. Two phase-flow is however not uncommon for traditional gas carrier operation and can be addressed through design and prediction of the thermodynamic behaviour of the stream.

The experimental campaign by Franklin Okoro et al [17] summarised in Section 3.2.5 provides data on the effect of non-condensable impurities on the bubble point and their solubility. The concentrations of non-condensable dissolved in the liquid phase is reduced by lower temperature and pressure. Consequently, it is expected that during the liquefaction process, these impurities will separate from the stream limiting the amount that is dissolved in the CO_2 stream after liquefaction. Hence the level of non-condensable loaded to the ship is presumably lower in a low-pressure value chain compared to medium-pressure and high-pressure.

Presence of non-condensable will affect the bubble point of the CO_2 stream and potentially increase the rate of pressure build-up. This needs to be considered when evaluating means for cargo management.

The current fleet of CO_2 carriers are using pressure accumulation as the main means of boil off management.

The selection of suitable cargo management options depends on the cargo condition (i.e., low, medium, high pressure), the tank design, the insulation performance, transit distance, etc. The low-pressure solutions are generally more prone to heat ingress due to lower cargo temperatures.

However, as the concentration of non-condensable depends on the condition at the end of the liquefaction process, a lower concentration of non-condensable is likely to be loaded for a low and medium pressure condition compared to high-pressure.

On the other hand, a low-pressure tank is typically designed with a narrow margin of pressure operation, hence it is important to have a sound approach when designing for pressure accumulation.

In addition, the literature focuses on binary systems and the review did not identify references illustrating the solubility limits of other impurities at shipping conditions such as trace components, acids, and products from reactions.

6.3.3 Solid Formations

In a low-pressure value chain, where the margin to the triple point is reduced compared to a medium pressure solution, the possibility of ice formation is regarded as a threat to the reliability to the cargo handling operation. For pure CO_2, the triple point is well defined, but the presence of impurities affects the phase behavior, as well as the triple point.

Trædal et al [15] shows that presence of non-condensable, depending on the element and concentration, has implication to the conditions for dry ice formation during the liquefaction process. However, as noted above, the concentration of non-condensable in the stream is limited by the pressure and temperature at the end of the liquefaction process. The amount of non-condensable stated in the published specification are anticipated to have limited impact on the triple point and dry-ice formation during cargo handling. However, there is limited supporting evidence for this claim.

Hydrate formation is determining dehydration requirements, as described [4]. These are expected to be less stringent than what imposed by corrosion but shall be also considered in the design phase and possible damages to vaporiser.

6.4 Combined Gas Carrier and Back-haul Cargo

Most of the concepts for liquid CO_2 carriers are designed and optimized for one cargo only. A dedicated LCO_2 carrier will be transporting liquid cargo one way while returning without payload. Hence, some industry players have been looking into alternative cargo for the return voyage, which may be attractive especially for longer distances.

Accommodating different cargo influences design and operations: it will add more severe specifications to the ship as it must be designed for the most stringent parameters dictated by each cargo and requires cargo tank preparation when accommodating cargo changes.

ZEP/CCSA Shipping Workgroup Report [32] describes possible combinations for back-haul cargo including LPG/NH_3 and LNG. Differences in density, transport temperature and pressure and requirement to purging/warm up/cooldown of the cargo containment system makes the concept of back-haul cargo challenging.

6.5 Off-Specification Management

The approach to impurities in a CCUS value chain is fundamentally different from other commodity gases such has LPG, LNG, NH_3 which are typically treated to meet specific quality requirements from the end user. For these gases, the handling of off specification cargoes is often a commercial matter to be agreed between buyer and seller of the product.

In the context of CCUS, there will be in principle no end client end and the quality of the product is related to the risk of corrosion and to operations.

Quality control of the cargo before it is loaded is a means to limit the likelihood that off specification cargo is loaded onto the ship. Corrosion coupons can also be used to evaluate whether the cargo can harm the system.

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