Ship Transportation in the CCS Business

— An Overview of Low Temperature/Low Pressure LCO_2 Transportation Methods —

Tomoyuki MURATA*

1. INTRODUCTION

In October 2020, the Japanese government set a target of achieving carbon neutrality by reducing emissions of greenhouse effect gases (GHG) to net zero by the year 2050, and declared in April 2021 that Japan would reduce GHG gases by 46% from the FY 2013 level by FY 2030. This paper focuses on CCS [*1] as one method for reducing carbon dioxide (CO_2), and presents an overview of low temperature/low pressure ship transportation of liquefied carbon dioxide (LCO_2) and JOGMEC's "Guidelines for Setting Common Specifications in the LCO_2 Ship Transportation Value Chain" (hereinafter, Common Guidelines).

2. LOW CARBON TECHNOLOGIES

Technologies for realizing carbon neutrality, that is, low carbon technologies, include the following:

a) Energy saving in existing equipment
b) Renewable energy (solar, wind power, hydropower, geothermal power, etc.)
c) Alternative fuels (hydrogen, ammonia, biomass fuels, SAF (sustainability aviation fuel), biodiesel fuel, e-fuels (synthetic fuels), RPF (refuse-derived paper and plastics densified fuels), etc.
d) CCS/CCUS
e) Nuclear power generation

Intensive research and development are underway in each of these fields. All of these technologies have advantages and disadvantages. However, in terms of both the development period/feasibility and total value-chain cost, d) CCS/CCUS is considered to be the most realistic method for addressing the issue of CO_2 reduction at this time, particularly in industries where discharges of CO_2 are unavoidable and large amounts of CO_2 must be processed.

3. CCS BUSINESS AND LEGAL AND REGULATORY SYSTEMS

3.1 Conventions, Laws and Regulations Related to CCS

- Basel Convention (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal): An international convention that regulates the movement of hazardous substances and other wastes across national boundaries and their disposal. The purpose of the Basel Convention is to prevent environmental pollution and damage to human health. It was ratified 1989, and currently does not include carbon dioxide among its target substances.
- London Convention (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter): Prohibits the disposal of waste (specified items) at sea. Commonly called the London Convention, this convention was ratified in 1972 and took effect in 1975, and was ratified by Japan in 1980. The 1996 Protocol to the Convention strengthened prevention of marine pollution.

  The 1996 Protocol to the Convention was revised in 2009 to allow the export of gases containing carbon dioxide ("CO_2 streams") for sequestration in sub-seabed geological formations under certain conditions. On the condition that the

* Ship Captain, CCS Project Department, Energy Business Unit, Japan Organization for Metals and Energy Security (JOGMEC)

*1 CCS and CCUS are abbreviations for Carbon dioxide Capture and Storage and Carbon dioxide Capture Utilization and Storage, respectively, and are methods for recovering and either storing (CCS) or effectively utilizing (CCUS) CO_2 that otherwise would be discharged into the atmosphere, thereby reducing CO_2 emissions, which are considered to be the cause of global warming. These processes can be broadly divided into three parts: ①Separation and recovery, ②Transportation and ③Effective utilization or storage.

exporting nation and receiving nation have concluded a bilateral agreement, this revision made it possible to export gases containing CO_2.

- Act on the Prevention of Marine Pollution and Maritime Disasters: A Japanese law concerning dumping in the Sea of Japan, which limits sub-seabed sequestration to CO_2 streams with a CO_2 concentration $\geq$ 99 vol% and as the recovery method, only permits chemical absorption by amines.
- Act on Carbon Dioxide Storage Business (so-called CCS Business Act): A Japanese law enacted in May 2024.
- 2025 Revision of the GX Promotion Act, GX-ETS Green Transformation Emissions Trading System: A Japanese law that legally requires companies with annual CO_2 emissions of 100000 t/y-CO_2 or more to participate in the GX-ETS emissions trading system. The anticipated objects of this system are approximately 300 to 400 companies with large CO_2 emissions, beginning with electric power companies, steel makers, chemical companies and the shipping industry.
- EU Emission Trading System (EU-ETS): Application to the shipping sector began in January of 2024.

3.2 Legal and Regulatory System Related to Ship Transportation of LCO_2

- IGC Code: "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" adopted in the International Maritime Organization.
- ClassNK Rules for the Survey and Construction of Steel Ships: Specifies rules for ships carrying liquefied gases in bulk, Type-C cargo tanks, post-weld heat treatment (PWHT), tank materials, etc.
- Regulations for the Carriage and Storage of Dangerous Goods in Ship: High pressure gas. [*2, *3]
- Port Regulations Act: When handling dangerous goods
- Seaman's Act: Persons responsible for handling hazardous cargoes
- SIGTTO [*4]: Guidelines for Carbon Dioxide Cargo on Gas Carriers

4. ADVANCED EFFORTS FOR COMMERCIALIZATION OF CCS BY JOGMEC

4.1 JOGMEC's Advanced CCS Projects

To prepare the business environment for the start of CCS businesses by the beginning of the 2030s based on Japan's GX Promotion Strategy, JOGMEC is supporting advanced role-model projects, targeting total CO_2 sequestration of approximately 20 million t/y-CO_2 in 9 projects, including 5 in Japan and 4 overseas. Including domestic and international transport, 6 of the 9 projects involve ship transportation.

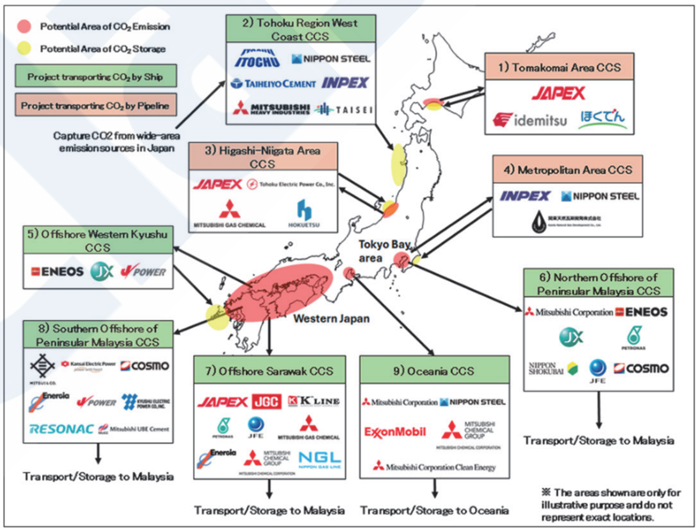

Fig. 1 JOGMEC's advanced CCS projects (Source: https://www.jogmec.go.jp/ccs/advancedsupport_002.html)

[*2] LCO_2 transport ships are not classified as "ships carrying dangerous goods" under Japan's Maritime Traffic Safety Act. The Piloting Law is also interpreted similarly.

[*3] The Act on Preventing Collisions at Sea does not directly describe navigation methods for ships carrying dangerous goods.

[*4] SIGTTO: Society of International Gas Tanker and Terminal Operators, a non-profit non-governmental organization (NGO) https://www.sigtto.org/

As the result of a feasibility study examining the possibility of building a CCS value chain conducted in 2023, the following points were recognized as common issues for realizing CCS.

① Reduction of the cost of utilities such as steam, electric power, etc. necessary for recovery of CO_2

② Strengthening of domestic construction capacity for storage tanks and ships required for CO_2 transportation by ship

③ Acquisition of data for evaluating the possible CO_2 sequestration capacity and injectability, containment capacity and long-term integrity of geological formations for sequestration.

The following sections of this paper focus in particular on ② Ship transportation.

4.2 Means of Mass Transportation of CO_2

The means of mass transportation of CO_2 in CCS can be broadly classified into two types, pipeline transportation and ship transportation.

(1) Pipeline transportation: Pipeline transportation is a fully-established, mature transportation technology for liquids in the modern era, and is also used to transport LPG and LNG, as well as CO_2 for enhanced oil recovery (EOR). After the equipment has been completed, it has the advantage of enabling continuous mass transportation, irrespective of day or night. As disadvantages, location of the production plants, storage facilities and routes connecting them are fixed at the time of construction, and thus are difficult to change after installation. It is also necessary to note the capital expenditure (CAPEX) required for long-distance pipeline construction, the operating expenses (OPEX) associated with maintenance, land use fees and the like, the risk of accidents that may occur in normal temperature/high pressure transportation (for example, leakage from a pipeline passing through a densely populated region) and transportation stoppages.

(2) Ship transportation: On land, transportation of medium temperature/medium pressure LCO_2 is usually performed by tank trucks or gas pressure cylinders. Japan has a record of domestic ship transportation by the ship "Amagi Maru" (medium temperature/medium pressure LCO_2, tank capacity: 365m^3, constructed in 1986), but a low temperature/low pressure ship transportation technology still has not been established.

In ship transportation, the CO_2 shipping point (port) and receiving point (port) can be set and changed easily, and there is also a high degree of freedom in changing transportation routes. In the event of a leakage accident at sea, the danger of asphyxiation is slight because the gas is immediately dispersed in the atmosphere by wind. In terms of the transportation system, redundancy is excellent, as it is possible to continue transportation by a substitute ship even if an accident occurs. It is necessary to note the CAPEX of ship construction (particularly the cost of materials for low-temperature cargo tanks and arranging manufacturing equipment suitable for scaling up the tanks), the OPEX of ship operation and management and fuel costs, requirements for reduced CO_2 emissions from ship engines during transportation, and the difficulty of securing seamen with the qualifications necessary for transportation of liquefied gas.

There are known research results showing that ship transportation is more cost-effective than pipeline transportation when the LCO_2 transportation distance exceeds 200km. In marine transportation, increasing the transportation capacity per voyage by increasing the ship size is preferrable, but there are limitations on the specifications of the tanks for medium temperature/medium pressure transportation (steel material, plate thickness and diameter for high-pressure application), which make it difficult to increase the ship size beyond a certain point. In this regard, low temperature/low pressure transportation is superior, in that the design pressure of the pressure tanks is low, making it possible to increase the tank size. However, the conditions used in low temperature/low pressure transportation (–50°C/0.58MPaG) of LCO_2 are near the triple point (–56.6°C/0.42MPaG) of CO_2, where dry-icing of LCO_2 occurs. To avoid this risk, it is necessary to determine the best balance of transportation safety, the transportation temperature and pressure range, and economic rationality.

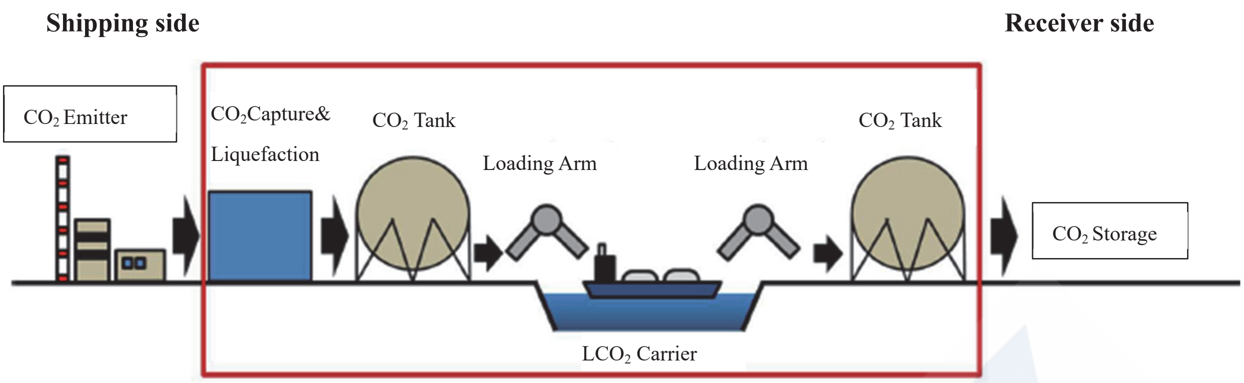

Fig. 2　General flow of CCS by LCO_2 carrier transportation (Source: Common Guidelines, p.3)

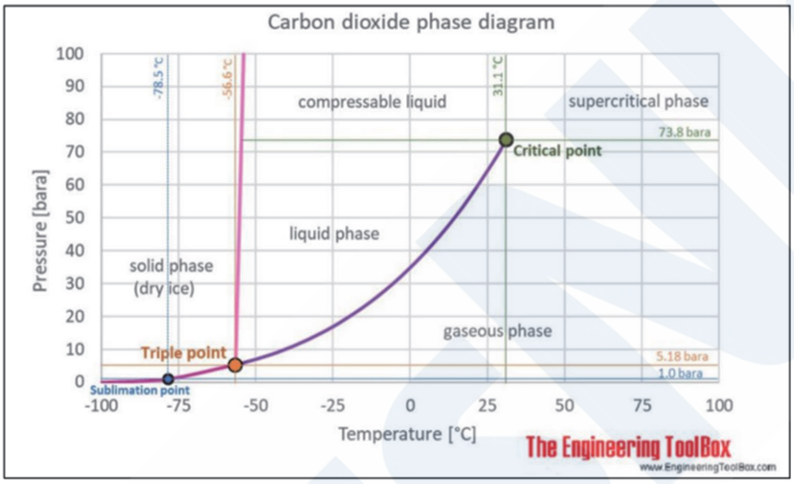

Fig. 3　Phase diagram of LCO_2 (Source: https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html)

4.3　Comparison of Two Types of LCO_2 Transportation by Ship

(1) Medium temperature/medium pressure type

In research on CCS technologies, medium temperature/medium pressure type ship transportation was adopted in almost all the pioneering CCS projects in Europe, and the LCO_2 carrier used in Norway's Northern Lights project, which was the world's first full-scale LCO_2 transportation project, was also a medium temperature/medium pressure type.

The reasons for adopting the medium temperature/medium pressure type in European projects are as follows.

① Because the Technology Readiness Level (TRL) of the medium temperature/medium pressure type was high (already an established technology with a track record of long-term use).

Since Michael Faraday and Humphry Davy succeeded in liquefying gases for the first time in the world in 1823, CO_2 has been used in various fields. For example, it is used in carbonated beverages, beer and sparkling wine, as a shield gas in arc welding, as a feedstock in the chemical industry and as a fire-extinguishing agent. In recent years, it has also been used in agriculture (as an environment for greenhouse cultivation), as a repair agent for punctured tires and in CO_2 lasers. In Japan, CO_2 is contained in green-colored cylinders (Fig. 4) under the provisions of the High Pressure Gas Safety Act. Fire-extinguishing equipment using CO_2 (or halogens or other suffocating gases) is sometimes installed where water fire-extinguishing is not suitable, such as in multistory parking buildings and electrical rooms. In some cases, large-scale LCO_2 tank equipment (Fig. 5) is provided for use in fire-fighting on ships where car fires are a risk, such as large ferries and dedicated car carriers. Work to replenish these stationary-type tanks is normally performed by transportation from the CO_2 production plant by tank truck (medium temperature/medium pressure) and filling using a flexible hose.

② Because the transportation distances of projects in the EU region are short.

When the transportation distance is short, the boil off gas (BOG) generated as a result of heat transfer into the tank during transportation of a liquefied gas is slight. This means that heat transfer can be suppressed simply by providing heat insulation, without costly reliquefying equipment or chilling equipment that require installation space, and pressure-keeping transportation is possible without exceeding the working pressure of the tank. Of course, the tank design pressure must be set taking into account the pressure rise during transportation. Therefore, as points to note, it may be necessary to either use a high grade steel material, such as high Ni steel or increase the tank wall thickness if carbon steel is to be used, or there may be limitations on the maximum diameter of the tank.

③ Because the risk of dry-icing is low.

Since the phenomenon of a phase transition of liquid LCO_2 to solid dry ice occurs when the liquid temperature/pressure decreases to the triple point or below, a transportation temperature/pressure condition far from the triple point has the merit of a relatively low risk of dry-icing.

Fig. 4 Liquefied CO_2 gas cylinders (the small cylinder is a normal temperature/high pressure type)

(Source: Website of Shinko AirTech, Ltd., https://shinko-airtech.com/gasliquid_CO2.html)

Fig. 5 Marine CO2 fire-extinguishing system (–17°C/2.1MPa)

(Sources: Website of Air Water Safety Service Inc., https://awb.co.jp/service/vessel/)

(2) Low temperature/low pressure type

When considering large-volume transportation and large-volume sequestration of CO_2 in the CCS business in Japan in the future, sequestration in overseas countries is a promising option. While this will require large-scale LCO_2 carriers capable of long-distance, large-volume transportation, it can perhaps be said that low temperature/low pressure transportation is the most rational choice under those conditions. The relevant Common Guidelines set the lowest working temperature of LCO_2 tanks at –50°C and the lowest design temperature at –55°C. As the temperature of the LCO_2 decreases, its density increases and the transported mass also increases. However, as specified in the IGC Code, "6.4 Requirements for metallic materials," a response to higher-level design conditions is required if the design temperature of marine cargo tanks is set lower than –55°C. Therefore, the above-mentioned set value was adopted in order to avoid cost increases due to the increased difficulty of design and manufacture, and to secure a margin of safety from the triple point (–56.6°C), where there is a risk of dry-icing.

In comparison with the aforementioned medium temperature/medium pressure type, the low temperature/low pressure type has the following weaknesses: ①The Technology Readiness Level (TRL) is "6-7: Demonstration stage," which is inferior to the medium temperature/medium pressure type, ②A reliquefying or chilling device for treating BOG is essential due to long distances of transportation to overseas sequestration sites, ③The risk of dry-icing is high because the liquid temperature and pressure are near the triple point, and ④The land-side CAPEX is high because the capacity of the shipping/receiving facilities must be larger than the amount of LCO_2 transported in per voyage.

On the other hand, the advantages of the low temperature/low pressure type are as follows:

a) Transportation efficiency is good because the density of LCO_2 at –50°C (1.15kg/L) is more than 10% larger than the density at –20°C (1.03kg/L).

b) It is possible to use low-temperature carbon steel, which is relatively inexpensive in comparison with high Ni steel, because the design pressure of the cargo tanks is lower than that of the medium temperature/medium pressure type; in addition, light weight, a larger loading capacity and lower costs can also be expected because a thinner plate thickness or larger tank diameter can be used. (Explanations of steel plate thickness limits and post-weld heat treatment are omitted here.)

c) If the ship is as large as possible, this means that the number of ships or number voyages required for the amount of LCO_2 necessary in the project can be reduced and rationalized, and a reduction of the total transportation cost of CAPEX and OPEX can be expected.

d) Reducing the number of ships is advantageous for easing the shortage of shipbuilding capacity in Japan's domestic shipbuilding industry, and is also an advantage for easing the shortage of seamen because fewer seamen are needed to crew the reduced number of ships.

Japan's New Energy and Industrial Technology Development Organization (NEDO) carried out a study on long-distance, large-volume ship transportation of LCO_2 and discovered that the low temperature/low pressure type is superior. Using the demonstration test ship "EXCOOL" (996G/T, commissioned in 2023), which was constructed for large-volume, long-distance transportation tests of LCO_2 under the low temperature/low pressure condition (–50°C, 0.58MPaG) as a CCUS R&D and Demonstration Project from 2021, NEDO has been conducting demonstration tests of various cargo-handling and ship transportation conditions.

Demonstration test ship "EXCOOL"
Length overall: 72.0 m
Breadth overall: 12.50 m
Full load draught: 4.55 m
Gross tonnage: 996 G/T
Cargo tanks: 725 m^3 x 2
Design enables transportation of LCO_2 under conditions from medium temperature/medium pressure to low temperature/low pressure.
Cruising speed: 12.0 kts
Engine output: 1,471 kW
Navigation area: Short sea(non-international)
LPG combination carrier specification

Fig. 6 "EXCOOL [*5]" demonstration test ship

(Source: Website of Nippon Gas Line Co. Ltd., NEWS 2023.12, https://ngl.co.jp/news/)

[*5] The origin of the ship name "EXCOOL" is an idea premised on the themes of "CCS is a countermeasure for prevention of global warming" and "a ship that transports LCO_2 at a cryogenic temperature of –50°C." Analyzing "LCO_2," which means liquefied CO_2 (carbon dioxide) into its component letters, we discover LCOO, which can be converted to COOL as an anagram. Affixing EX to COOL, we have the portmanteau word "EXCOOL," with the double meanings of "CCS to cool the Earth" and "LCO_2 at –50°C is extremely cool." To express global environment-friendliness and its Japanese nature, "EXCOOL" is written in Japanese in soft hiragana characters as "えくすくぅる." (The ship's name was devised by the author of this paper.)

4.4 Features of European CCS Projects

The form of CCS frequently seen in CCS projects in Europe is transmission of CO_2 collected from the factories of multiple emitters by pipeline to a facility at the loading port, where the CO_2 is stored in payout tanks after aggregation and liquefaction, loading on LCO_2 carriers at medium temperature/medium pressure, transportation to destinations within the EU region, and offloading to receiving tanks at the sequestration facility, where it is pressurized/heated to a supercritical state and finally injected into a geological formation deep below the sea bottom. This process assumes that transnational transportation between two countries in the EU or an EU country and non-EU country is performed based on application of the London Protocol (i.e., a bilateral agreement).

In Europe, small-scale marine transportation of CO_2 was commercialized from several years ago. Ships and barges are used to transport food-quality CO_2 from producing plants to distribution terminals on the coast. The size of the ships currently in use is between 1,000 and 1,500m^3, and the transport pressure is in the range of 14 to 20barA, which is classified as medium temperature/medium pressure.

The following presents several examples of research on LCO_2 ships in Europe and projects that are currently underway.

(1) ZEP [*6] Report: Achieving a European market for CO_2 transport by ship

This report positions ship transportation in Europe as follows: "The European Commission aims to store at least 50 million tonnes of CO_2 by 2030. Shipping will play a crucial role in Europe for the development of carbon capture and storage. 1 million tonnes of CO_2 can be transported per year by a 20,000 tonne cargo liquefied ship with a one-week round trip. 26 storage projects identified could use shipping to transport CO_2. European policymakers should support the development of CO_2 transport by ship for industrial decarbonisation. (Report, p.7)."

(2) ZEP Report: Guidance for CO_2 transport by ship 2022

According to the Executive Summary of the Report, it was determined that "For CCS projects aiming at transporting CO_2 by ship, interoperability could be important in order to optimise the development of CO_2 infrastructure . . . .There is a need for some degree of standardisation on CO_2 specifications (composition, pressures, temperatures, etc.), ship design and specifications (e.g. referring to loading and off-loading). (Report, p.7)"

(3) SINTEF [*7] Report

In 2021, SINTEF conducted a detailed comparative study on medium temperature/medium pressure type and low temperature/low pressure type transportation of LCO_2, and finally concluded that large-volume shipping of CO_2 at a pressure of 7barG and liquid temperature of –46°C achieves the largest cost reduction (approx. 30%). (Also confirmed from the original SINTEF paper.)

> A July 2021 SINTEF paper entitled "At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 Barg Shipping" concludes that 7barg /-46C is the optimal condition for large volume shipping due to the lower vessel cost(~30%)
> Source: https://www.mdpi.com/1996-1073/14/18/5635/pdf

Fig. 7 ZEP Guidance for CO_2 transport by ship 2022 (p.14)

(4) Northern Lights projections

In a report by the Northern Lights Project on a full-chain economic assessment using market-based ship CAPEX costs, the project concluded that low temperature/low pressure transportation gives the lowest cost in transportation by large-volume LCO_2 ships with capacities of more than 20000m^3.

[*6] ZEP: Abbreviation of Zero Emissions Platform, a European Technology and Innovation Platform (ETIP) under the European Strategic Energy Technology Plan (SET-Plan) of the European Commission; ZEP was established as the technical advisor to the European Commission on the development of CCS and CCU.

[*7] SINTEF: Abbreviation for The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, an independent research organization which was established in 1950 and is headquartered in Trondheim, Norway. It carries out research and development projects on a contract basis.

5.1.1.2 Recent Northern Lights projections

The Northern Lights project has provided information advising that their full chain economic evaluation using market-based ship CAPEX costs indicates that

Vessel cargo size	Lowest end-to-end costs
Up to 15,000m³	Medium pressure ((~15 barg) and at -30°C) gives lowest cost
15,000-20,000 m³	Evaluation inconclusive. Either medium or low pressure may be lower cost depending on finer details of the project
Above 20,000 m³	Low pressure ((~7 barg) and at -50°C). gives lowest cost

Figure 6: Cryogenic ship cargo size at different pressure and temperature

The reason for the two cryogenic operating conditions relates to the mass of steel required. In the smaller vessels the steel required to contain a pressure of 15 barg is acceptable. In a larger vessel the mass of steel required to contain 15barg becomes uneconomic despite the greater energy requirement to cool the liquified gas to -50°C.

Fig. 8　ZEP Guidance for CO_2 transport by ships 2022, p.15

(5) Examples of European LCO_2 Ships

Northern Lights / The Longship CCS project

Project outline: Transportation of CO_2 recovered from customers in Norway, Denmark and the Netherlands to a receiving terminal located in Oygarden in western Norway. Will transport at least 400,000tonnes/year from each location for injection in a reservoir 2,600 meters below the sea bottom via a pipeline.

Northern Pioneer
Length overall: 130 m
Breadth overall: 21.2 m
Draught: 7.5 m
Gross tonnage: 8,035 G/T
LCO_2 capacity: 7.500 m³/2 tanks
Transported LCO_2: Medium temperature/medium pressure, 18 barG
LNG-fueled ship with ship bottom air lubrication system
Equipped with rotor sail
Constructed by Dalian Shipbuilding Industry Co., Ltd., China
Classified by DNV
Phase I will include 4 sister ships

Fig. 9　From the website of Kawasaki Kisen Kaisha, Ltd. (“K” Line), news release, Nov. 26, 2024
(https://www.kline.co.jp/ja/news/liquefied_gas/liquefied_gas-20241126.html)

Greensand Future Project

Project outline: Planned to transport 400,000t/y from the Port of Esbjerg, Denmark to Nini West Platform (depleted oil field in the Danish North Sea).

Carbon Destroyer 1: Launched 14 May 2025 as the first large LCO_2 ship built in the EU.

Carbon Destroyer 1 ready to launch (Greensand Future)

Carbon Destroyer 1
Length overall: 149.95 m
Breadth overall: 15.9 m
Draught: 8.6 m
The design incorporates a total of 8 LCO_2 tanks in 2 rows x 4 tanks, based on the hull of a multi-purpose bulker (hold capacity: 14,000 m^3)
LCO_2 capacity: Approx. 5,000 m^3
Transport LCO_2: Medium temperature/medium pressure

Fig. 10 From an article in the Maritime Observer dated 14 May 2025
(https://maritime-executive.com/article/video-carbon-destroyer-1-eu-s-first-co2-carrier-for-ccs-is-launched)

5. GUIDELINES FOR SETTING COMMON SPECIFICATIONS IN THE LCO_2 SHIP TRANSPORTATION VALUE CHAIN (COMMON GUIDELINES)

5.1 Formulation of the Common Guidelines

In order to achieve optimum efficiency not only in the ship transportation portion of the Advanced CCS Project, but in the value chain as a whole, repeated discussions and studies were carried out in JGOMEC's Council for Discussion on Common Specifications in LCO_2 Ship Transportation Value Chain (hereinafter, Common Guidelines Council) in cooperation with the Ministry of Economy, Trade and Industry (METI), and on 30 May 2025, JOGMEC issued "Guidelines for Setting Common Specifications in the LCO_2 Ship Transportation Value Chain [*8]" (Common Guidelines) for use in the Advanced CCS Support Project and as reference when studying CCS projects where ship transportation of CO_2 is to be performed in the future.

In conducting its study on setting common specifications for the LCO_2 ship transportation value chain, the Common Guidelines Council carried out the study and compiled the results on the premise that low temperature/low pressure LCO_2 transportation is the optimum method for realizing long-distance, large-volume ship transportation.

5.2 Large Low Temperature/Low Pressure LCO_2 Carriers [*9]

5.2.1 Common Specifications

The conditions in CCS ship transportation in Japan are decisively different from those in European projects. Japanese CCS projects assume quite long transportation distances to overseas sequestration sites, with a one-way transportation distance of approximately 2,300 to 5,000 nautical miles and the number of voyage days of 6 to 16. For this reason, there are areas where large ships and cost reduction by large-volume transportation are necessary.

(1) Basic ship type

① Length overall: Less than 235m

This is the result of a survey of the participants in the Common Guidelines Council regarding the maximum ship length that can be received, based on the limitations of quays, etc.

[*8] The Common Guidelines state to the effect that "Although ①Securing the possibility of interoperability and shared used of shipping and receiving facilities, ②Securing an efficient supply chain and ③Reducing transportation costs are expected in ship transportation of LCO_2 preconditioned on ensuring safety, these Guidelines do not specify standards/criteria that include regulatory provisions or have binding force on the CCS business concepts of individual operators." (From Common Guidelines, p.2)

[*9] In the Common Guidelines, in addition to specification for large ships, specifications were also formulated for medium-sized (23,000 m^3 type) and small coastal ships (5,000 m^3 type) for use in hubs and clusters or domestic transportation. However, due to space limitations, the explanations of those types will be omitted in this paper.

② Draught: Not more than 11.5m

This is the result of “a survey of the draught limits of quays where new construction of cargo-handling piers is assumed at existing berth which are expected to be used in shipping/receiving of LCO_2, and the water depth, navigation rules, tides, etc. of the planned navigation routes,” planned by the Council participants.

③ Cargo capacity: 50,000m^3

The result of a trial calculation of the maximum cargo was 50,000 m^3 with a total of 6 tanks, assuming construction of tanks using low-temperature carbon steel, which can be loaded under the above-mentioned hull conditions and navigation conditions.

④ Tank design temperature/pressure and working temperature/pressure range

Design temperature: –55°C, design pressure: 0.8MPaG

Working temperature: –50°C to –44°C, working pressure: 0.58MPaG to 0.76MPaG (values assuming pure LCO_2)

(2) Cargo-handling equipment

① Cargo-handling time: 16 to 20 hours

In many cases, the harbour master places restrictions on nighttime port entry/departure and the cargo-handling time of ships carrying dangerous goods specified in the Act on Port Regulation. Therefore, it is necessary to carry out a study with the aim of optimizing the cargo-handling cycle, considering port entry/departure time and the allowable cargo-handling time in each case.

② Flow velocity: 2m/s to 5m/s

If the flow velocity of the LCO_2 in the piping is increased, it is thought that the risk of dry-icing will also increase. Although this issue has been researched by many experts, particularly in Europe, the maximum flow velocity for safe cargo-handling of low temperature/low pressure LCO_2 still has not been determined. As an actual result, in cargo-handling of LCO_2 on NEDO’s demonstration test ship “EXCOOL,” a transfer test between the ship and land-based facilities was carried out based on a piping flow velocity of 2m/s [*10]. Accordingly, in these Guidelines, the flow velocity is examined with 2m/s as a starting point from the viewpoint of securing safety. While it goes without saying, when the flow velocity is low, a larger number of piping will be needed to cover the scheduled cargo-handling volume and time. Furthermore, since the designs of shipyards in other countries show maximum piping flow velocities in the range of 4 to 8m/s, if Japanese shipyards cannot offer designs with a flow velocity at least on a similar level, their competitiveness will fall behind in the future.

③ Number and arrangement of manifold piping on ship

The piping diameter is assumed to be DN200 to DN400. Since the flow rate (flow volume) decreases when the pipe diameter is reduced, it is necessary to allow a longer cargo-handling time or increase the number of pipes. Moreover, use of general-purpose products and cost reduction can be expected by standardizing the pipe diameters of LPG ships and LNG ships, which are current liquefied gas carriers.

The cargo volumes and cargo-handling times for one voyage required in CCS projects vary widely, and pipe diameter, flow velocity and number of piping which satisfy those requirements also differ. In case the LCO_2 carrier to be used is substituted due to a change in ship allocation, etc., it is possible to respond by using a reducer, even when the manifold diameter is different by one step, but adoption of common specifications for piping arrangements as far as possible may be more efficient. A basic example of the layout of the manifold liquid piping and vapor piping is presented, in which the vapor piping is located in the center so that it is possible to respond even if the number and arrangement of liquid piping is different at the terminals of the shipping port and the receiving port, or the port and starboard docking side of the ship are reversed.

④ Loading arm

The equipment weight of loading arms for LCO_2 is greater than that of loading arms for LPG and LNG because the thickness must be increased to withstand pressure. When the number of loading arms increases due to the relationship of the cargo-handling time and flow rate, the total equipment weight of the loading arms will also increase. Therefore, it is necessary to note that the weight-bearing capacity of the berth and space for installation must be secured.

In installation of the loading arm piping, common specifications should be adopted as much as possible to enable trouble-free connection to the ship’s manifold. For loading arms as well, in order to allow connection even if the type and number of piping

[*10] In a report on recent demonstration tests by Nippon Gas Line, a demonstration of shipboard CO_2 handling of LCO_2 between tanks was carried out using the two cargo tanks installed on the ship (“EXCOOL”), and transfer tests were conducted at flow velocities of 4 m/s and higher.
https://ngl.co.jp/wordpress/wp-content/uploads/2025/06/20250630 船上高流速 PR-和文.pdf

are different from those of the ship, the Guidelines present an example in which the vapor piping is arranged in the center of the manifold line, as in the manifold of the ship, and the liquid piping is arranged symmetrically before and after it, thereby achieving high compatibility in connection of the piping with the ship.

5.2.2 Types of Impurities and Their Effects

The types and concentrations of impurities contained in transported LCO_2 cargoes differ depending on the CO_2 discharge source, separation/recovery method, pretreatment for liquefaction, etc. As in the case of dry-icing risk due to the flow velocity, in ship transportation of LCO_2, the items to be noted are the existence and concentration of impurities. The conceivable problems that may occur when impurities are contained in LCO_2 can be broadly divided into ①Vapour pressure rise due to non-condensable components, ②Formation of corrosive substances and ③Components with adverse effects on human health and the environment.

At present, the list of types of impurities and allowable concentrations in LCO_2 cargoes published by Northern Lights (medium temperature/medium pressure LCO_2) shown in Table 1 is generally used as reference.

Table 1 Northern Lights table of allowable concentrations of impurities

Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]
Carbon dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)
Water (H_2O)	ppm-mol	≤ 30
Oxygen (O_2)	ppm-mol	≤ 10
Sulfur oxides (SO_x)	ppm-mol	≤ 10
Nitrogen oxides (NO_x)	ppm-mol	≤ 1.5
Hydrogen sulfide (H_2S)	ppm-mol	≤ 9
Amine	ppm-mol	≤ 10
Ammonia (NH_3)	ppm-mol	≤ 10
Formaldehyde (CH_2O)	ppm-mol	≤ 20
Acetaldehyde (CH_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[2]	ppm-mol	≤ 0.5
Ethylene (C_2H_4)	ppm-mol	≤ 0.5
Hydrogen cyanide (HCN)	ppm-mol	≤ 100
Aliphatic hydrocarbons (C_2+)[4]	ppm-mol	≤ 1,100
Ethane (C_2H_6)	ppm-mol	≤ 75
Solids, particles, dust	ppm-mol	≤ 1

Table: 14: LCO_2 Quality Specifications [24].

https://ww2.eagle.org/content/dam/eagle/publications/knowledgecenter/CO2 Impurities and LCO2 Carrier Design-Practical Considerations.pdf（Page20）

Research on impurities by experts and research groups in countries around the world has a long history, and diligent efforts are underway even now. Nevertheless, additional time and costs will be required in order to investigate the effects of the many individual impurities that exist by concentration, and to investigate and reach conclusions regarding the phenomena in a state where multiple impurities are combined.

As noted above, the types of impurities and the content of their effects can be classified in the following three types.

(1) Non-condensable components

These are components that exist in a gaseous state, even in LCO_2, because their molecular weights and boiling temperatures are lower than those of CO_2, and include hydrogen (H_2), nitrogen (N_2), argon (Ar), carbon monoxide (CO) and methane (CH_4).

When LCO_2 contains a trace amount of these non-condensable components, its vapour pressure tends to be higher than that of pure LCO_2, and the pressure may exceed the design pressure of the tank. Therefore, individual study of the allowable pressures of these non-condensable components is necessary to ensure that, at minimum, the vapour pressure does not exceed the range of the working pressure (0.58MPaG to 0.76MPaG) of the ship's cargo tanks. In addition, these non-condensable components are an obstacle when reliquefying BOG, and reliquefaction may become impossible.

(2) Formation of Corrosive Substances

Water (H_2O) reacts with CO_2 to form carbonic acid, which causes corrosion of carbon steel.

Similarly, water (H_2O) also reacts with oxygen (O_2), sulfur oxides (SOx), nitrogen oxides (NOx), hydrogen sulfide (H_2S) and carbon monoxide (CO), forming corrosive compounds. Mercury (Hg) reacts with aluminum, forming amalgam. From a different viewpoint, there is a possibility that corrosion-related problems can be significantly reduced by reducing the moisture content as far as possible.

Although it has also been reported that moisture (H_2O) does not exist in liquid form in liquid LNG at cryogenic temperatures, and corrosion does not occur because acids are not formed. Additional research and verification of whether similar behavior also occurs in LCO_2 at –50°C or not will be necessary in the future.

(3) Components with Adverse Effects on Human Health and the Environment

As emission standards for exhaust gas containing CO_2 that has been discharged into the atmosphere, until now, emissions were controlled based on Japan's Air Pollution Control Act. The laws and regulations regulating impurities contained in CO_2 are as follows.

- Air Pollution Control Act
- Japanese Industrial Standard JIS K 1106, Liquid carbon dioxide
- Food Sanitation Act, Standards for Food Additives

It may be necessary to note the allowable concentrations so as not to exceed the regulatory values under these standards when a leak occurs.

5.3 Issues for Future Research

Although the First Edition of "Guidelines for Setting Common Specifications in the LCO_2 Ship Transportation Value Chain" was issued recently, there are two subjects that still have not been adequately confirmed, as follows. These will be issues for future research by the Common Guidelines Council.

(1) Determination of types of impurities to be limited and maximum allowable concentrations

Processes that remove impurities from LCO_2 impact the CAPEX of separation/recovery facilities, but it is difficult to judge the required level of cleanliness of LCO_2, which is primarily a waste to be sequestered underground, and not a product. As mentioned previously, the only published table of the types of impurity contained in LCO_2 transported by ship and their allowable concentrations is the list published by Northern Lights (medium temperature/medium pressure), and in many other projects, there is a tendency to study this issue based on that document. Moreover, the corrosion tests were performed by a certain European research group, and were experiments under a gas environment, and not in liquid LCO_2. Based on the reaction equation, it is thought that the corrosion tests of the steel materials were carried after corrosive substances were first formed by reactions involving water (H_2O) in impurity gases, making it difficult to refer directly to those results.

Therefore, in order to determine the type of impurities and allowable concentrations that should be listed, assuming the low temperature/low pressure conditions of the Japanese standard, it is necessary to prepare phase diagrams for CO_2 containing impurities based on convincing scientific grounds and computer simulations, carry out experiments actually using LCO_2 at –50°C, and provide evidence supporting economic rationality.

Even assuming the type of impurities and maximum allowable concentrations are determined and a list is prepared, in the first place, it will be necessary to investigate whether methods for continuous measurement of individual substances with precision at the ppm order are actually available, and whether it is necessary to measure and verify all of those substances, and at what points in the value chain and with what frequency, and also to determine the range of responsibility and implementation procedure. Here, it may be noted that in the Northern Lights project, the three types of impurities (O_2, H_2O and H_2S) were measured in-line, immediately before the LCO_2 was transferred into the receiving-side storage tanks.

(2) Determination of the safe maximum flow velocity in cargo-handling

Increasing the LCO_2 flow velocity has the advantages of increasing cargo-handling efficiency and making it possible to reduce the number of piping, but is also considered to increase the risk of abnormal vibration and dry-icing. There are already several examples of CFD (Computational Fluid Dynamics) simulations of the behavior in piping during ship cargo-handling, premised on pure LCO_2, and no technically significant problems have been reported. In the NEDO demonstration project described previously, construction of a high-flow velocity liquid transfer technology verification facility of liquefied CO_2 began at the Tomakomai terminal in July 2025, and high-flow velocity tests are also planned. However, since the behavior of LCO_2 (changes in pressure, etc.) containing impurities studied in (1) above still has not been adequately clarified, further research is needed, particularly to determine what kind of behavior occurs at higher flow velocities when non-condensable impurities exist in the LCO_2.

6. CONCLUSION

This paper has presented an overview and explanation of low temperature/low pressure ship transportation of LCO_2 based on "Guidelines for Setting Common Specifications in the LCO_2 Ship Transportation Value Chain," which was issued by JOGMEC in conjunction with its Advanced CCS Project. Long-distance, large-volume transportation by ships is an essential technology for social implementation of CCS businesses in Japan, and research on this technology is progressing steadily. Navigation and cargo-handling demonstrations tests of the low temperature/low pressure method are being carried out on a continuing basis, actually using pure LCO_2 at –50°C and a demonstration test ship for low temperature/low pressure transportation. As a result, considerable knowledge has been obtained, and the technical advantages of the low temperature/low pressure method have been verified. However, since it can be inferred that overseas competitors are rapidly catching up, it is considered that further research (particularly on the two issues discussed in Chapter 5.3 above) should also be promoted in the future, and a low temperature/low pressure transportation for LCO_2 should be established in Japan at the earliest possible timing.

REFERENCES

1) JOGMEC: "Guidelines for Setting Common Specifications in the LCO_2 Ship Transportation Value Chain"
2) ClassNK: Rules for the Survey and Construction of Steel Ships
3) ABS: CO_2 Impurities and LCO_2 Carrier Design: Practical Considerations
4) ZEP: Guidance for CO_2 transport by ship 2022
5) ZEP: Achieving a European market for CO_2 transport by ship
6) SINTEF: "At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 Barg Shipping," 2021
7) CCUS Projects Network: Briefing on carbon dioxide specifications for transport, 2019
8) SIGTTO: Carbon Dioxide Cargo on Gas Carriers - First Edition, 2024
9) The High Pressure Gas Safety Institute of Japan (KHK): Materials of the High Pressure Gas LNG Association, "Effect of Impurities in Natural Gas on Equipment"
10) Equinor: Northern Lights Project Concept report – RE-PM673-00001