Overview of Guidelines for Onboard CO_2 Capture and Storage Systems and Their Latest Revision

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1. INTRODUCTION

Amid growing global awareness of the climate crisis, in 2023, the International Maritime Organization (IMO) adopted a greenhouse gas (GHG) reduction strategy which clearly sets a goal of achieving net-zero GHG emissions from international shipping by around 2050. In response, a wide range of technological developments and policy measures are being pursued, centred on the introduction of carbon-free fuels such as ammonia and hydrogen, as well as carbon-neutral fuels including synthetic fuels (e-fuels) and biofuels. However, it has been pointed out that relying solely on the adoption of these new fuels will make it extremely difficult to achieve net-zero emissions by around 2050 due to time constraints. The International Energy Agency (IEA) has also stated that achieving international climate goals will be virtually impossible without implementing carbon capture, utilization, and storage (CCUS) [1)]. Consequently, there is growing momentum in the maritime sector to reduce CO_2 emissions by implementing onboard CO_2 capture and storage (OCCS) systems, while continuing to use existing fuels with stable supplies, such as heavy fuel oil and LNG.

In 2021, the joint project “CC-OCEAN” conducted by Nippon Kaiji Kyokai (ClassNK), Kawasaki Kisen Kaisha, Ltd., and Mitsubishi Shipbuilding Co., Ltd. (hereinafter, Mitsubishi Shipbuilding) successfully conducted a world-first demonstration of onboard CO_2 capture from exhaust gas at sea using an amine-based chemical absorption process [2)]. This milestone has significantly accelerated interest in deploying onboard carbon capture systems across the shipping industry, leading to the emergence of vessels equipped with various OCCS configurations. Based on Clarksons Research data as of August 2025, Fig. 1 and Fig. 2 show the global number of OCCS-equipped vessels and the trend in retrofit installations, respectively. Although retrofits currently account for the majority of OCCS adoptions, an increasing number of projects now evaluate installation in the newbuilding contract stage, and deployments on newbuilds are expected to increase in the future.

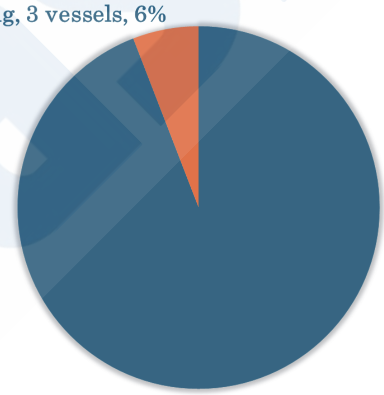

Fig. 1 Global fleet count of OCCS-equipped vessels (Clarksons Research)

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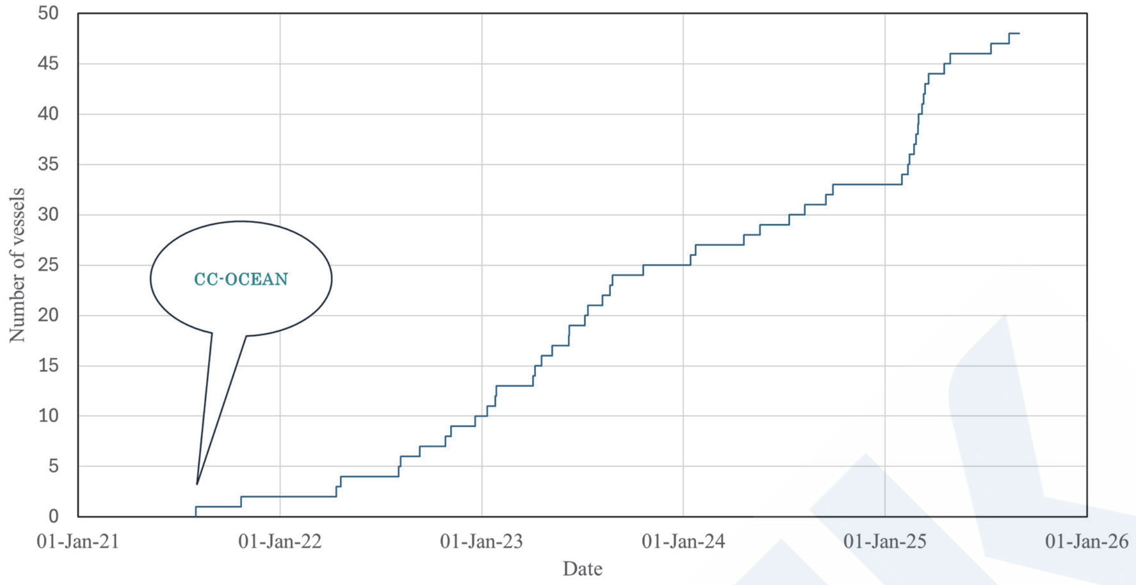


Fig. 2　Trend in retrofit installations of onboard CO_2 capture and storage systems (based on Clarksons Research data)

Fig. 3 shows the distribution of OCCS-equipped vessels by vessel type, propulsion system, and deadweight tonnage (DWT). While there are some differences in numbers for different ship types, propulsion systems, and deadweights, OCCS systems have been installed out across a wide range of vessel specifications.

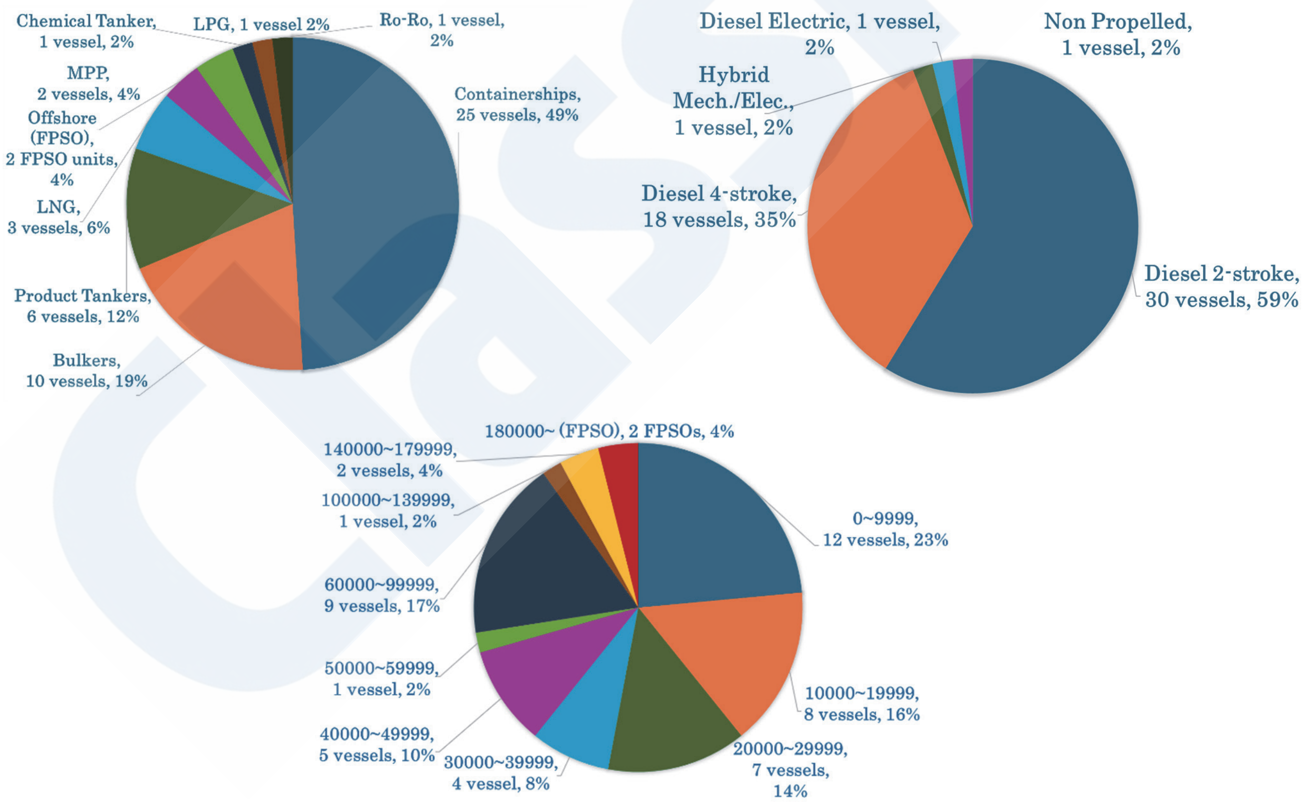


Fig. 3　Composition of OCCS-equipped vessels by type, propulsion configuration, and DWT (Clarksons Research)

Accordingly, the Society (ClassNK) issued a set of Guidelines in April 2023, specifying the relevant requirements for OCCS systems based on chemical absorption using amine solutions. Since then, the Society has also supported social implementation by providing certification services under the Guidelines. In April 2024, the OCCS system installed on Evergreen's Neopanamax containership (Flag: Panama, RO: ClassNK) successfully captured CO_2 from its exhaust gas emissions and offloaded the captured CO_2 to a shore facility for recycling. ClassNK verified the amount of offloaded CO_2, and deducted the amount from the ship's annual CO_2 emissions in a CII assessment under the direction of the Flag Administration of the Panama Maritime Authority [3]. This series of initiatives is the first case of its type in the world, and anticipates practical operations that may be adopted widely in the future to reduce GHG emissions. Thus, this is a significant step for the maritime industry towards achieving net-zero GHG emissions.

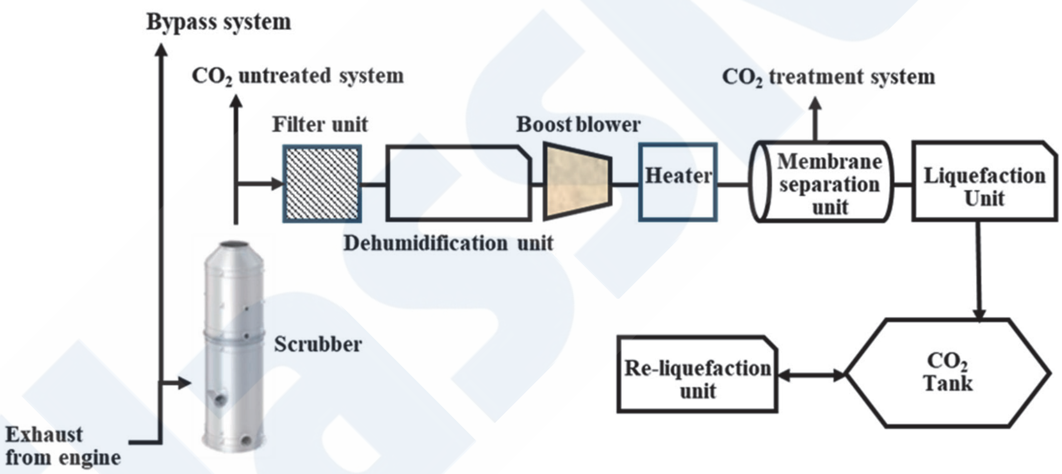
At the IMO, ongoing discussions are underway on appropriate accounting procedures for emissions avoided through capture and storage by vessels equipped with OCCS [4]. At the same time, however, OCCS technologies are expanding beyond chemical absorption methods to various other approaches such as membrane separation, depending on the type of vessel and the capture target, thereby increasing the range of available technical options. To address this technological diversification, the Society issued revised ClassNK Guidelines incorporating requirements for membrane separation methods in October 2025 [5].

This paper explains the basic principles of CO_2 capture and storage by membrane separation, and presents an overview of ClassNK's *Guidelines for Onboard CO_2 Capture and Storage Systems* and the scope of the October 2025 revision.

2. FUNDAMENTAL PRINCIPLES OF CO_2 SEPARATION AND CAPTURE BY MEMBRANE SEPARATION

2.1 Basic Configuration of OCCS Using Membrane Separation

The basic configuration of an OCCS system using membrane separation is shown in Fig. 4. As shown in the figure, the exhaust gas is pretreated in each unit and fed to the separation membranes, where CO_2 is separated, and is then liquefied and stored.



Desulfurization Heat removal Dust removal	Dust removal Desalination	Dehumidification	Boosting	Anti-condensation	Capture	Liquefaction	Storage	Re-liquefaction
Scrubber	Filter unit	Dehumidification unit	Boost blower	Heater	Membrane separation unit	Liquefaction unit	CO_2 tank	Re-liquefaction Unit

Fig. 4 Overall schematic of OCCS system based on membrane separation

2.2 Membrane Performance

The performance of a separation membrane is characterized by CO_2 permeance and CO_2 selectivity. Although permeance reflects interrelated mass-transfer phenomena such as dissolution and diffusion, it can be broadly understood in terms of molecular sieving governed by kinetic diameter, as illustrated schematically in Fig. 5. Kinetic diameter is a convenient representative dimension that indicates how readily a molecular species can pass through membrane pores. Table 1 shows the gas species relevant to engine exhaust and their kinetic diameters. Because H_2O has a smaller kinetic diameter than CO_2, dehumidification (drying) is required before membrane separation.

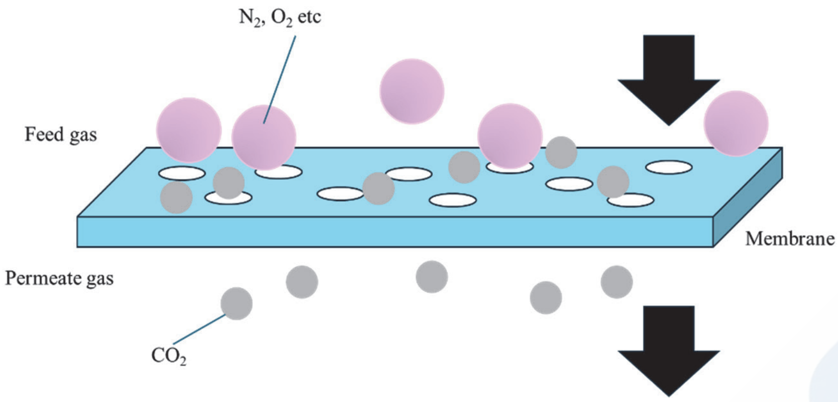


Fig. 5　Conceptual illustration of molecular sieving

Table 1　Representative kinetic diameters of selected gases

Molecule name	Molucular weight	Kinetic diameter (pm)
CO_2	44	330
O_2	32	346
N_2	28	364
H_2O	18	265
CH_4	16	380
NH_3	17	260
N_2O	44	330

Table 2 shows the permeance and selectivity of CO_2, O_2, and N_2 at various temperatures. As the temperature increases, the permeance of CO_2, O_2, and N_2 also increases because, as suggested by Fig. 5, membrane pores are not ideal straight cylinders but rather tortuous, maze-like pathways. In other words, gas molecules must have sufficient kinetic energy to pass through the membrane. For this reason, permeance is a key parameter when considering how to maximize CO_2 recovery through a membrane.

Selectivity is defined as the ratio of the permeances of two gases. For example, CO_2/N_2 in Table 2 is the permeance of CO_2 divided by permeance of N_2 ($CO_2/N_2 = P_{CO2}/P_{N2}$). Although the permeance of CO_2 increases with temperature, the permeance of N_2 also increases, causing selectivity to decrease as temperature rises. Thus, selectivity and permeance have a trade-off relationship with respect to temperature. It may also be noted that selectivity is the critical parameter when targeting high purity of the recovered CO_2.

Table 2　Examples of permeance and selectivity

Temperature (°C)	Permeance (GPU)※			Selectivity	
	CO_2	O_2	N_2	CO_2/N_2	CO_2/O_2
21	530	28	12	44	19
35	908	50	22	41	18
50	1,160	93	43	27	12

※GPU (Gas Permeation Unit): Indicator of permeance.

$$X = 10^{-6} \times V / (A \times T \times \Delta P) \qquad (1GPU = 10^{-6} \frac{cm^3(STP)}{cm^2 \cdot s \cdot cmHg})$$

V: Gas volume converted to standard conditions, (cm^3 (STP))

A: Membrane area (cm^2)

T: Time required for permeation, (s)

ΔP: Pressure difference across the membrane (as head of mercury, cmHg)

Maintaining the CO_2 capture performance of membrane separation devices depends critically on the pressure (partial pressure of CO_2) difference before and after the membrane. This pressure difference can be created by two methods, as shown in Fig. 4. One involves increasing the gas pressure upstream of the membrane by using a boost blower, and the other uses a vacuum pump downstream of the membrane to reduce the pressure.

The first method requires a relatively large amount of energy, since a large volume of gas must be compressed simultaneously. In the second method, the vacuum pump mainly reduces the pressure of the CO_2 that permeates through the membrane, so the energy requirement is comparatively low. However, the vacuum pump may not generate a sufficient pressure difference, and in this case, it may be necessary to increase the membrane surface area in order to recover a larger amount of CO_2.

2.3 Structure of Separation Membranes

There are two main forms of CO_2 separation membranes, flat-sheet membranes and hollow fibers. These two types are described below.

2.3.1 Structure of Flat-Sheet Membranes and Modules

A flat-sheet membrane is a thin, planar separation film. Exhaust gas at a higher pressure is passed along one side of the membrane, and the CO_2 in the gas permeates through the membrane and is collected on the opposite, lower-pressure side. Because the selective layer itself is extremely thin, a three-layer construction is typically used to ensure mechanical strength, as shown in Fig. 6. The bottom support layer has a porous structure that combines high strength with high gas permeability and ensures the mechanical integrity of the membrane package. An intermediate “gutter layer” is usually provided between the selective layer and the support to prevent the selective film from being pushed into the pores of the support under the applied pressure differential.

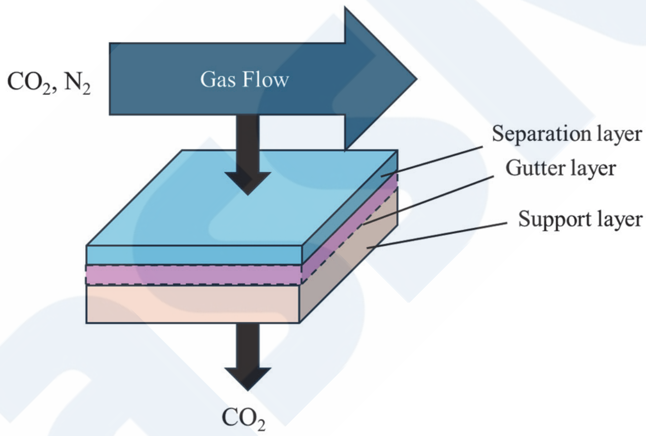


Fig. 6 Structure of flat-sheet membrane

As shown in Fig. 7, the membrane area density of flat-sheet modules is typically increased by stacking a feed (upstream) spacer, selective membrane, and permeate (downstream) spacer, in that order. The higher-pressure exhaust stream flows across the membrane on the feed side, and CO_2 permeates to the lower-pressure side, where it is separated and collected.

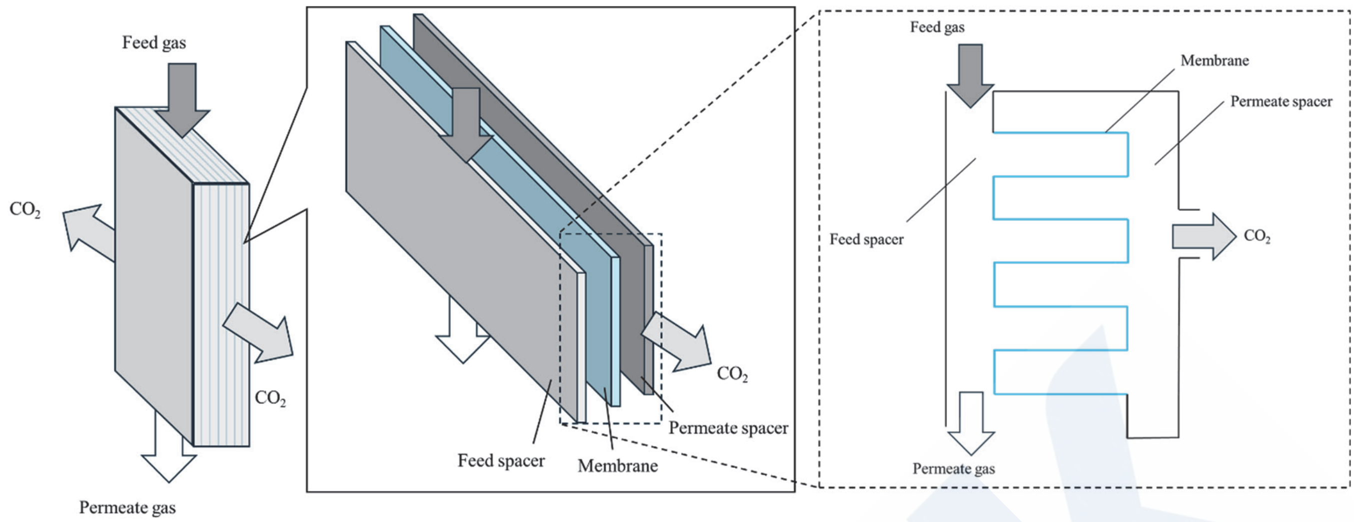
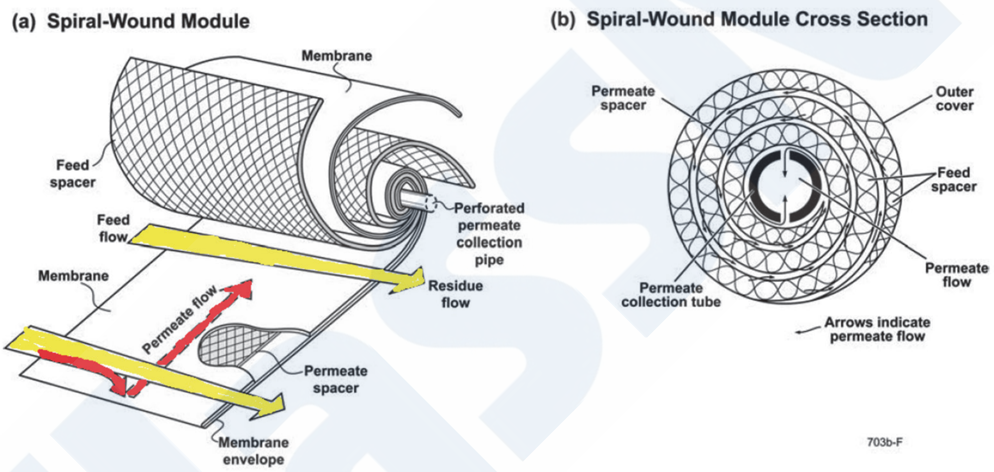
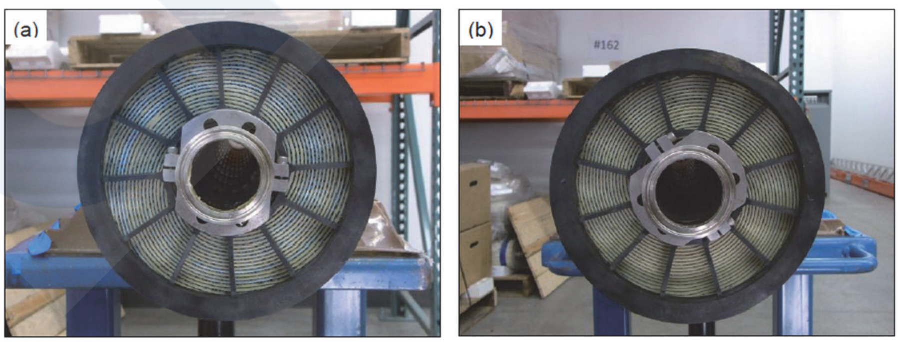


Fig. 7　Module architecture of flat-sheet membrane

A design in which the membrane area density is improved by forming a flat-sheet into a spiral-wound element is also used. For reference, Fig. 8 shows a module devised by Membrane Technology and Research, Inc. (MTR) [6, 7)*1]. In this design, the gas flows through the spiral channel, and the separated CO_2 is collected at the central core.



(a) Exploded view of a conventional spiral-wound gas separation module and (b) a cross-section of this module.



Pictures of feed gas inlet (a) and residue gas outlet (b) of module 6419. The module was tested on the 1 TPD system at NCCC from April to August of 2012.

Fig. 8　Spiral-wound flat-sheet membrane module

[*1] The colored portions in Fig. 8 were added by the authors.

2.3.2 Structure of Hollow-Fiber Membranes and Modules

In a hollow-fiber membrane, the exhaust gas flows through the lumen (bore) of each fiber. As the gas travels along the fiber, CO_2 permeates through the fiber wall and is collected on the shell side (Fig. 9). In practice, multiple fibers are bundled and arranged in parallel flow lines to form a module that enables effective CO_2 recovery.

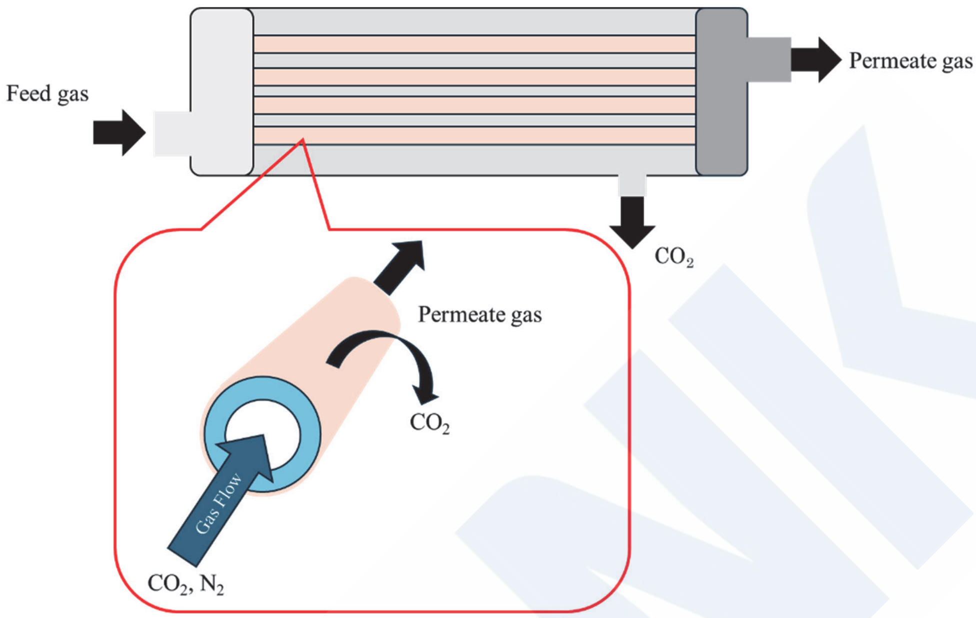


Fig. 9 Structure of hollow-fiber membrane and its module

3. OVERVIEW OF CLASSNK GUIDELINES FOR ONBOARD CO_2 CAPTURE AND STORAGE SYSTEMS (EDITION 2.0)

3.1 Background of Development and Revision

The first edition of the Guidelines was prepared based on chemical absorption. This technology has an extensive land-based track record and a high level of maturity, and even today, systems based on chemical absorption remain the mainstream.

At the same time, recent years have seen a growing number of trials of alternative capture methods tailored to specific application needs, considering the vessel type and size, fuel choice, and trading area. In particular, membrane separation has attracted increasing attention. Large-scale land-based trials of this technology are underway, and commercialization efforts are accelerating [8]. Because multiple companies are already studying OCCS using membranes and wider deployment is also foreseen, ClassNK issued a revised edition of the Guidelines. Fig. 10 shows the cover of the revised Guidelines.

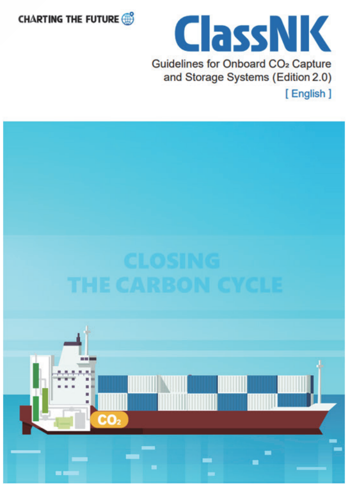


Fig. 10 Cover of revised ClassNK Guidelines

3.2 Structure of ClassNK Guidelines for Onboard CO_2 Capture and Storage Systems (Edition 2.0)

The Guidelines consist of six chapters and an appendix. Table 3 shows the titles and a brief summary of each chapter.

Table 3 Titles of the Guidelines and their summaries

Chapter	Title	Summary
Chapter 1	General	Describes scope of application, terminology, an overview of basic post-combustion CO_2 separation and capture technologies, and properties of CO_2.
Chapter 2	Functional Requirements	Specifies requirements to ensure the safety, maintainability, and reliability of OCCS (CO_2 capture and storage) equipment.
Chapter 3	CO_2 Capture Systems and Associated Equipment	Sets requirements for CO_2 capture systems using chemical absorption and membrane separation, including functions, materials, risk assessment, construction and arrangement, controls and alarms, stability, electrical installations, and safety/protective equipment.
Chapter 4	CO_2 Storage Systems and Associated Equipment	Specifies requirements for CO_2 storage systems: functions, materials, risk assessment, storage tanks, pumps, compressors, heat exchangers, stability, construction and arrangement, ventilation, controls, safety and alarm systems, gas detection/monitoring, and protective equipment.
Chapter 5	Class Notation	Defines the handling of class notation assignments for ships that comply with part or all of the Guidelines (including OCCS Ready and ships with installed OCCS).
Chapter 6	Surveys	Specifies inspection requirements during and after manufacture for the capture and storage equipment defined in Chapters 3 and 4 (Initial, Periodical, and Occasional surveys).
—	Appendix	Provides approximate calculations of additional energy for OCCS with amine solution and principal dimensions of related equipment (capture unit and liquefied CO_2 storage tank).

3.3 Update Details of the Revised Guideline

The requirements for membrane-based systems added in this revision appear in Section 1.4 ("CO_2 Capture and Storage Systems Using Membrane Separation") and Section 3.3 of the Guidelines. Section 1.4 outlines the basic system configuration of a membrane-based OCCS system, the functions of each unit, and the fundamental membrane performance parameters. Section 3.3 primarily specifies the risk mitigation requirements for membrane-based CO_2 capture systems.

3.3.1 Newly-Added Functional Requirements

To ensure that the design, construction, and operation of equipment related to OCCS systems give due consideration to safety, the following four functional requirements have been newly added:

1. Filter unit: Shall provide dust removal and de-salting functions necessary to protect downstream equipment.
2. Dehumidification unit: Shall ensure the humidity required by the separation membranes.
3. Boost blower: Shall be capable of supplying the pressure and flow rate required by the separation membranes.
4. Heater: Shall ensure the temperature required by the separation membranes.

3.3.2 Newly-Added Risk Mitigation Requirements

The revised Guidelines stipulate that risks to personnel, the environment, and the structural strength or integrity of the ship arising from the installation and use of OCCS are to be assessed using an approved risk analysis methodology. Requirements for membrane separation have been added, stipulating consideration of the following risks 1 to 3.

1. Gas leakage
2. Failures of membrane-based capture equipment downstream of the scrubber
3. Membrane integrity

It is also desirable to conduct appropriate design- and operation-related risk assessments suited to the specifications of the equipment.

4. CONCLUSION

ClassNK published *Guidelines for Onboard CO_2 Capture and Storage Systems, Edition 2.0* in October 2025, which includes new provisions for membrane separation. In the future, when capture and storage systems employing new technologies not yet covered by the Guidelines reach the stage of practical use, they can be reviewed as appropriate based on the fundamental principles of the Guidelines. Successive updates of the Guidelines are also expected, accompanying the accumulation of new knowledge and operational experience with OCCS systems.

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