Evaluation of Integrating Amine-Based Onboard Carbon Capture and Storage on a Commercial Tanker

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APTAMUS CARBON SOLUTIONS
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1 EXECUTIVE SUMMARY

The objective of this evaluation is to study the feasibility of installing a carbon capture and storage (CCS) system onboard a medium range (MR) tanker.[1] The authors partnered with a maker of shipboard carbon capture systems, Ionada Carbon Solutions LLC, to perform a detailed analysis that applies to nine sisterships in OSG's fleet. Our study determined that while an installation of this emission reduction system is technically feasible on these vessels, there are many challenges which burden its economic feasibility.

Key highlights and lessons learned from the study are as follows:

- Most carbon capture systems commercially available today use amines as the absorption medium. Researchers found that Monoethylene amines (MEA) tend to 'crystalize' in the presence of elevated NOx levels, presenting a significant challenge for ships built before approximately 2015. As a result, these ships must replace the costly amines more frequently.

- Up to 10% of onboard amines can be lost within one hour, potentially resulting in total depletion in just 10 hours—two solutions are proposed for further study to address this critical issue.

- The existing Waste Heat Recovery (WHR) system and Electricity Generating capacity onboard a typical MR Tanker constrain the required amine regeneration energy demand and hinders the business case.

- The ship emits 3,800 kg of CO_2 per hour at sea: implementing CCS increases total emissions by 43%, but captures 1.1 tons per hour from existing emissions, achieving a net reduction of 29%.

- The installation, along with the stored carbon dioxide, will add over 1,000 tons to the weight of the ship, resulting in an equivalent loss of cargo carrying capacity at constant draft.

- The $85 per ton tax credit for carbon dioxide sequestration under 26 U.S. Code § 45Q—a U.S.-flag-specific incentive—illustrates that existing subsidies for carbon capture and storage (CCS) are currently insufficient to fully offset the cost of decarbonizing Jones Act MR tankers.

- Preliminary Hazardous Operations risks assessment suggests that there are no immediate showstoppers with the introduction of an amine-based CCS system on board a chemical tanker.

[1] A Medium Range (MR) tanker is a type of oil or chemical tanker with a carrying capacity of about 25,000 to 54,999 deadweight tons (DWT), commonly used for transporting refined petroleum products. It is the prevalent Jonas Act type of ship delivering energy products in the United States.

2 INTRODUCTION

The 2023 International Maritime Organization (IMO) "Strategy on Reduction of GHG Emissions from Ships" sets ambitious targets for the shipping industry to reduce carbon intensity by 40% by 2030 and reach net-zero emissions by 2050. Achieving these goals requires the adoption of energy-efficient ship designs, alternative fuels, and technologies like on-board CCS. While alternative fuels such as methanol, ammonia, and hydrogen are being developed, the transition to their widespread use will take significant time and investment. And there are other considerations which could lead shipping companies to continue to use fossil fuels when paired with CCS processes. CCS offers a promising short- to medium-term solution, allowing ships to reduce regulated CO_2 emissions during the transition period. CCS technologies based on the use of amines, which are recognized for being well-developed in shore-based applications, are being suggested for use directly on ships. This type of CCS system is the focus of this feasibility study.

The commercial tankers at the focus of this study are the Medium-Range (MR) tankers in OSG's Jones Act fleet. Such tankers are no different than most ships in that they were originally designed for a specific mission and range, with little margin for the addition of systems requiring significant space or energy throughout their service life. Therefore, the integration of CCS systems onboard existing ships is expected to be a challenge due to limited available space and the need for significant additional electrical generating capacity. One promising approach for maritime application of CCS is the use of Hollow Fiber Membrane Contactors (HFMC) technology, which is known for its relatively low energy requirements and compact size. Implementing HFMC technology on an MR tanker could be a feasible approach and is therefore chosen as the basis for this study.

The CCS process is divided into three stages: 1) conditioning the exhaust gas, 2) capturing the CO_2 using amine-based technology, and 3) storing the liquefied CO_2 until it can be offloaded in port. The report highlights several technical challenges, including the need for efficient heat management, space constraints for equipment installation, and uncertainty with CO_2 liquefaction at sea. The potential financial benefits from the 45Q tax credit (see Section 5.1 for a full description of this program) are also discussed, but challenges remain in meeting the annual statutory capture requirement of 12,500 tons of CO_2. Finally, the report emphasizes the need for further engineering studies and regulatory alignments to ensure safe and effective integration of CCS systems into existing commercial ship operations.

This study is based on calculations and design work performed by Ionada Carbon Solutions LLC, a maker and innovator of Hollow Fiber Membrane Contactors (HFMC) technology for shipboard carbon capture.

3 DESIGN AND ENGINEERING

3.1 TARGET SHIP DETAILS

The MR product tankers used in this case study are of the Veteran Class of tankers, built at the Aker Philadelphia Shipyard between 2007 and 2013. These fourteen ships are active in the U.S. Jones Act domestic trade, all of which are still in operation and have many more years of service life left. Moreover, these ships are based on the Hyundai Mipo Dockyard (South Korea) Athenian Class design with more than 150 sister ships of the same design in use throughout the world. This ship has a single HYUNDAI-MAN B&W 6S50MC6 two stroke main engine rated at 8,680kW and three diesel generator auxiliary engines each rated at 800kW. The ship also has an Aalborg AQ7 economizer to harvest thermal energy from the main engine. This ship design is 183 meters long, 32.2 meters wide, with an approximate 46,000-ton deadweight capacity and 330,000-barrel volumetric capacity.

3.2 STUDY APPROACH

To more clearly understand the impact of CCS on ships, three distinct stages in the CCS process are outlined. Each stage is designed to address specific aspects of CCS functionality, as described below and seen on Figure 1.

Stage 1: Conditioning - This initial stage examines the sources of CO_2 on the ship and determines any modifications required to align these emission sources with the capabilities of Hollow Fiber Membrane Contactor (HFMC) carbon capture technology. The goal is to ensure that the exhaust gas is in a suitable condition for the optimum capture process. The primary parameter to be modified at this stage is exhaust gas temperature.

Stage 2: Capture - At this stage, the focus shifts to the actual capture of CO_2 from the emissions that have been conditioned. It involves evaluating the limitations and requirements related to temperature and pressure conditions, considering how these factors affect the capture performance, and examining the capacity of the process to handle the emissions.

Stage 3: Storage - The final stage deals with how the captured CO_2 is stored efficiently on the ship until it can be offloaded. The primary consideration is to provide an adequate amount of onboard storage capacity for captured CO_2 such that the capture process can operate for a reasonable amount of time before it must be shut down because the storage capacity is full. The storage capacity must be adequate for a typical number of sailing days between ports where the stored CO_2 can then be offloaded to a shore side storage facility or, possibly, transferred to a ship acting as a temporary floating storage facility for CO_2, in a bunkering capacity or otherwise.

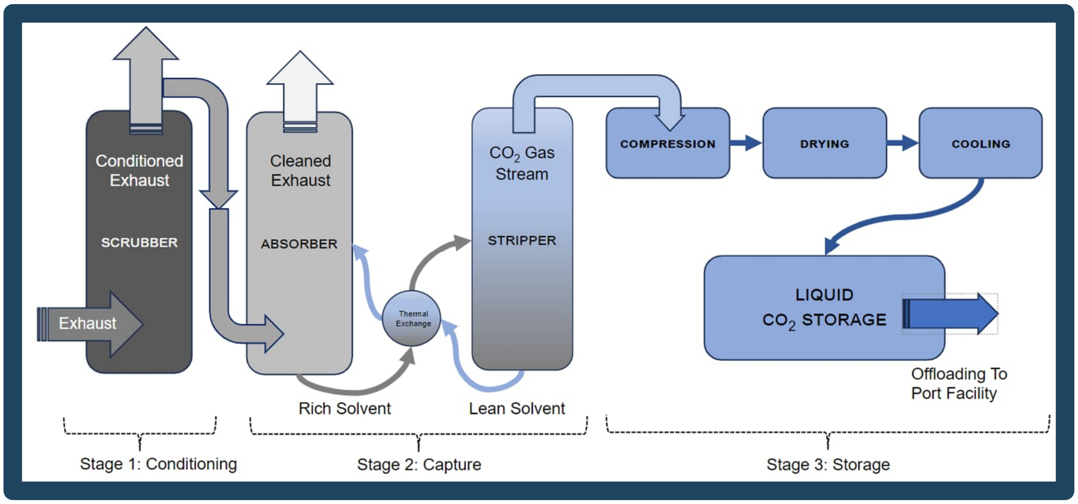

Figure 1. Onboard CCS Process Sketch

The rate of carbon capture in this study is assumed to be 2.3 tons per hour (tph). In a typical at-sea condition the subject vessel emits approximately 90 tons of CO_2 per day, or 3.75 tph. Therefore, a rate of 2.3 tph equates to an approximately 60% capture rate (although some of that capture rate is used to capture the CCS equipment's own CO_2 emissions as discussed below). At this capture rate, and a total of 225 days at sea for a particularly busy vessel, at least 12,500 tons of CO_2 can be captured annually. This is the minimum amount that must be captured at an industrial facility in order to qualify for the federal 45Q cash subsidy, discussed in more detail in Section 5.1. In some sections of this report a capture rate of 1 tph is also summarized for comparative purposes.

3.3 STAGE 1: CONDITIONING

Emissions from Veteran Class ships at sea are primarily produced by the main engine and the auxiliary generators. In a typical at-sea condition, in calm weather and fair winds, the main engine will be running at a 75% load and one of the three diesel generators will be running at 60% load. The exhaust gas from the main engine has a CO_2 concentration of 3.8% and an average temperature of 340°C. Research by Feenstra et al.[2] evaluated the feasibility of adapting land-based amine-based carbon capture systems to a maritime environment. The temperature of the amine required for effective CO_2 absorption typically ranges from around 40 to 120°C in aqueous solutions. The heat of absorption of CO_2 with aqueous solutions of amine (also referred to as the "solvent") has been measured at 40, 80, and 120°C in various studies[3] finding that the absorption capacity increases as the temperature decreases. In other words, the

[2] Maartje Feenstra, Juliana Monteiro, Joan T. van den Akker, Mohammad R.M. Abu-Zahra, Erwin Gilling, Earl Goetheer, Ship-based carbon capture onboard of diesel or LNG-fueled ships, International Journal of Greenhouse Gas Control, Volume 85, 2019, Pages 1-10, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2019.03.008.

[3] Inna Kim, Karl Anders Hoff, Thor Mejdell, Heat of Absorption of CO_2 with Aqueous Solutions of MEA: New Experimental Data, Energy Procedia, Volume 63, 2014, Pages 1446-1455, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2014.11.154.

lower the exhaust gas temperature, the more CO_2 can be removed by the amines from the gas. Not surprisingly, Ionada recommends a temperature of 40°C for their proposed shipboard capture technology.

When considering cost-effective methods for the substantial cooling of exhaust gas, "scrubbers" immediately come to mind. Exhaust gas scrubbers, primarily intended and used to reduce the level of sulfur oxides (SO_x) in ship emissions to meet international regulations when utilizing heavy fuel oil (HFO), have the fortunate secondary effect of substantially reducing exhaust gas temperatures in the process. This is due to the entire exhaust gas stream being placed into direct contact with a large amount of ambient seawater at a typical temperature of less than 30°C. A study presented experimental results confirming that a scrubber effectively reduced the exhaust gas temperature from 650°C to about 50°C[4]. The exhaust temperature of the ship studied in this report is less than 450°C, so the resulting outgoing exhaust gas can be expected to be even cooler than 50°C. The exhaust gas flow rate from the main engine at 75% load (6.5 MW) is expected to be 64,729 kg per hour, therefore a 10MW scrubber capable of handling up to 75,000 kg/hr flow and offered by Value Maritime was chosen.

Using a scrubber to cool the exhaust gas also presents the opportunity to utilize lower-cost Heavy Fuel Oil (HFO) in the main engine rather than higher-cost Low Sulphur Marine Gas Oil (LSMGO) which may positively affect the onboard CCS business case and encourage more widespread adoption. Widespread use of HFO and scrubbers may also result in a net reduction in overall GHG emissions from shipping, due to the higher emissions resulting from the refining of LSMGO.[5] The discontinuation of HFO as bunker fuel for maritime engines was driven by the need to reduce sulfur content in the emissions. However, the exhaust gas conditioning introduces an interesting dynamic. By considering this opportunity while designing the system, ships can maintain the use of HFO while adhering to emission regulations, as the conditioning technology serves an environmental benefit, technical necessity, and financial advantage. This not only ensures compliance with global emission standards but also allows shipping companies to benefit from the cost efficiency of using lower-cost fuel options without compromising on their environmental responsibilities. The cost spread between fuel types has fluctuated over the years. More specifically the prices of these fuels can vary greatly depending on several factors, including market conditions, demand, and changes in regulations. But a conservative average for the cost difference between IFO380 and LSMGO in the U.S. Gulf Coast region is \$350/MT (noting that the standard deviation is \$159/MT)[6].

[4] Abdulwahid, Ahmed, Situ, Rong, Brown, Richard, and Lin, Wenxian, Thermodynamic Analysis of a Diesel Exhaust Wet Scrubber, Proceedings of the 22nd Australasian Fluid Mechanics Conference AFMC2020, 2020, https://doi.org/10.14264/9b3f9c0

[5] https://www.seatrade-maritime.com/europe/new-study-finds-use-heavy-fuel-scrubbers-can-help-reduce-ghg-emissions

[6] Historical pricing between IFO380 and LSMGO from January 2021 to January 2024 at the Port of Houston (source: https://www.oilmonster.com/)

Veteran Class tankers have an economizer in line with the engine exhaust ducting. It is sized for the ship's intended operating profile. However, it is expected that running the main engine on HFO will require the boiler to operate more often because HFO needs to be heated to maintain the desired viscosity. OSG's experience with using HFO in the past is that the existing economizer provides sufficient heat for HFO heating while the ship is underway, and the boiler was only needed when the main engine was not running (i.e. in port and at anchor). More so, the boiler was predominantly used for cargo heating needs. The potential CO_2 impact is examined later in this analysis. The use of the economizer in the Carbon Capture process will also be considered to optimize the thermal energy requirements for amine regeneration needs[7]. This further complicates the analysis when considering space, financial, and operating constraints because available capacity from an economizer in a ship that operates in warm climates may not be able to provide the energy under colder conditions or reduced engine loading. Similarly, the type of cargo and its heating requirements may constrain regeneration heat demand. However, this analysis is based on the existing installation which includes an Aalborg AQ7 economizer. In addition, one must be mindful of not introducing backpressure to the engine exhaust which would affect the engine's efficiency.

3.4 STAGE 2: CAPTURE

At this stage the objective is to remove the carbon dioxide from the pre-conditioned exhaust stream. With the main engine running at 75% load, there is approximately 3,650kg/hr of CO_2 available for removal as per engine's test bed results. Considerations at this stage hinge on the amount of CO_2 that can be "carried" between the absorption and extraction processes as a function of energy. Amine scrubbing stands out as a well-established method for extracting CO_2 from flue gas. This method was chosen for its high maturity, capability to deliver high-purity CO_2 (99.9%), and relatively lower energy demands compared to other technologies like cryogenic separation. And technical developments using Hollow Fiber Membrane Contactors (HFMC) for the interaction between amine and flue gas present efficiency gains for this stage of the process.[8] The use of HFMC has long been used across a variety of industries and modelling the process is understood very well. Detail of the typical HFMC is shown in Figure 2.

HFMCs incorporate an advanced technique that has several characteristics which improve the absorption of carbon dioxide by amines compared to alternative methods. The usual CO_2 capture scenario employs a 20% to 30% by weight AMINE solution[9] and aims to maintain a liquid to gas ratio of 1.5 to 2.5[10]. But the

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[7] Nguyen Van Duc Long, Moonyong Lee, Novel acid gas removal process based on self-heat recuperation technology, International Journal of Greenhouse Gas Control, Volume 64, 2017, Pages 34-42, ISSN 1750-5836,

https://doi.org/10.1016/j.ijggc.2017.07.003.

[8] Bazhenov SD, Bildyukevich AV, Volkov AV. Gas-Liquid Hollow Fiber Membrane Contactors for Different Applications. Fibers. 2018; 6(4):76. https://doi.org/10.3390/fib6040076

[9] Wang N, Wang D, Krook-Riekkola A and Ji X (2023) MEA-based CO_2 capture: a study focuses on MEA concentrations and process parameters. Front. Energy Res. 11 :1230743. doi: 10.3389/fenrg.2023.1230743

[10] https://ccrc.kaust.edu.sa/docs/librariesprovider7/conference-talks/mohammed-al-juaied_compressed.pdf?sfvrsn=220335c1_6

higher contact surface and longer residence time between the exhaust gas and solvent that is inherent with HFMCs allows for the equivalent efficiency in a reduced space.[11] Membrane contactors, when used with CO_2-reactive sorbents like amines, allow for a high surface area for gas-liquid contact, which facilitates efficient mass transfer. This method also avoids problems common in traditional absorbers, such as flooding and foaming, making it an effective solution for enhancing carbon capture processes without the operational challenges of other systems. Improvements to the CO_2 capture and amine regeneration process of this stage come from using HFMC that needs smaller equipment size and has better operating characteristics.

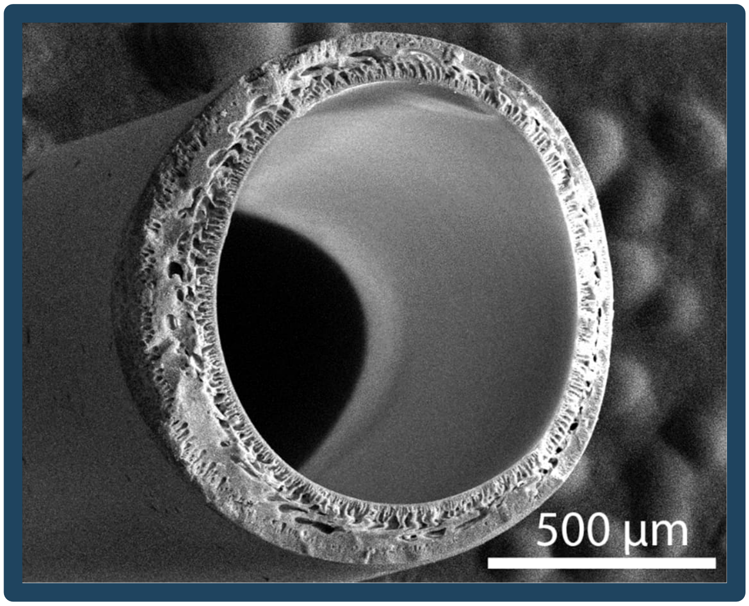

Figure 2. Gas-Liquid Hollow Fiber Membrane Contactors (HFMC) for different applications

Modelling of the CO_2 removal process from the gas stream based on a preferential absorption through HFMC and regeneration of the amine was performed by Ionada using Promax. The model is based on characteristics of CESAR1 type carbon capture media. A representative system schematic from the Promax modelling can be seen in *Figure 3* in Section 3.7, Energy Demand.

Only approximately 60% of the conditioned exhaust gas is directed to the capture stage. The remainder continues up the existing exhaust ducting. Within the capture stage, the amine carbon capture media is circulated with the conditioned exhaust gas. Two phases of the circulating carbon capture media, categorized as rich and lean, respectively, are transferred between absorber and reboiler hardware, as seen in Figure 1. The absorber hardware converts carbon capture media from lean to rich and the reboiler converts it from rich to lean. Carbon dioxide gas boils from the stripper (aka. reboiler) out of the *capture*

[11] Rivero, J.R.; Panagakos, G.; Lieber, A.; Hornbostel, K. Hollow Fiber Membrane Contactors for Post-Combustion Carbon Capture: A Review of Modeling Approaches. MEMBRANES 2020, 10, 382. https://doi.org/10.3390/membranes10120382

stage and enters the *storage* stage of our process where CO_2 is dried, compressed, and ultimately liquefied for storage until it is ready for offloading.

3.5 STAGE 3: STORAGE PREPARATION

The onboard CCS system's storage preparation phase includes compressing, drying, cooling, and liquefying the captured CO_2. The main engine's exhaust gas stream contains water which must be removed. Removing water from carbon dioxide in the process of converting it from a gaseous state to a liquid state through compression and cooling is crucial for several reasons. First, the presence of water in CO_2 can lead to the formation of carbonic acid when CO_2 is compressed and cooled, which can lead to high corrosion rates of the equipment used in the compression and liquefaction systems. This corrosion can reduce the lifespan of the equipment and increase maintenance costs. Second, water can freeze during the cooling process, potentially blocking pipelines and valves, which disrupts the continuous flow of CO_2 and risks damaging the system. Third, in the liquefaction phase, the purity of CO_2 is essential for storage and transportation efficiency; water content can negatively affect the density and volume of the liquid CO_2, complicating these processes. Therefore, drying the CO_2 stream to remove water is a fundamental step to ensure the integrity and efficiency of the system, preventing operational issues and maintaining the quality of the liquefied CO_2.

Converting the captured CO_2 to liquid form is necessary to minimize storage volume onboard. In gas form, 700 tons of CO_2 would occupy 321,000 m^3 of volume, approximately 6½ times the total cargo tank volume in the subject tanker. This is because CO_2 in gas form occupies 513 times more volume than CO_2 in liquid form. Therefore, 700 tons of CO_2 in liquid form will occupy a much more reasonable 615 m^3 of volume. Unfortunately, CO_2 must be stored at relatively low temperatures and relatively high pressure to maintain its liquid form, which adds more technical challenges to onboard storage and handling systems.

While CO_2 liquefaction is a familiar process, finding a reliable marine onboard solution for CO_2 compression and liquefaction has posed significant challenges. Companies like OSG rely on suppliers to deliver suitable products for the maritime sector. Although land-based CO_2 compression and liquefaction technologies are well-established, adapting them for use in maritime environments on constantly moving ships is relatively new. Only recently have efforts been made to implement these technologies on ships, which face unique challenges due to the motion of the ship in a sea state. This motion can cause variability that standard products aren't designed to manage, complicating the achievement of dependable performance at sea. Additionally, issues like contamination from the amine gas stream compositions aggravate the risk of system failures and operational interruptions. Notice for example on Table 1 below, the water content that needs to be removed from the gas stream before liquefaction because water freezes at CO_2 liquefaction temperatures. It is also important to note that Table 1 does not show the presence of amines which need to be maintained as well.

Component Name	Mole Fraction (%)
Water	6.040
Nitrogen	0.008
Oxygen	0.004
Carbon Dioxide	93.947
Carbon Monoxide	0.000
Nitrogen Oxides	0.000
Piperazine	0.000
Adenosine Monophosphate	0.000

Table 1. Expected gas composition from amine regeneration stream.

An additional challenge discovered during this study is the high-power demand of CO_2 compression and liquefaction processes. Ships have limited space and power resources, making it hard to accommodate the energy-intensive needs of these systems which the original electrical system was not designed to support. Furthermore, the marine carbon capture market is quite nascent, with only a few companies beginning to specialize in this area. These companies are currently opting to sell their onboard systems only as complete packages, not as individual components, which limits flexibility in system design.

Given the novelty of the application and relatively small market size, many companies have shown limited interest in developing or supplying CO_2 compression and liquefaction systems specifically for marine use. Most gas liquefaction manufacturers that OSG has contacted during this investigation (e.g. Atlas Copco, Linde, and Sperre) have not actively entered the market. A general sense of size and weight was derived from conversations with a new industry entrant. For a 1 tph liquefaction capacity one can expect a 15m^2 footprint at a weight of 14.3 tons, while for a 2.3 tph capacity one should allocate 24m^2 and at a weight of 20.6 tons. Conversations are still ongoing with industry partners but most of the early conversations suggest that manufacturers of natural gas liquefaction equipment are not yet planning to address the maritime CO_2 liquefaction market.

3.6 INTEGRATION

When the three CCS stages described in the previous sections are integrated into one complete system, they are arranged as shown in Figure 1.

The system consists of blowers, heat exchangers, an absorber where CO_2 is captured by the amine solution, and a stripper where the CO_2 is separated from the amine. The CO_2 is then compressed and stored in liquid form. The system requires heat, which can be sourced from the ship's engines through the economizer. Energy considerations are crucial as higher capture rates significantly increase energy demands, increasing fuel consumption and overall emissions. The integration aims for a capture rate of up to 60% during typical operations, which balances the system's energy requirements against its environmental benefits.

Simultaneously, one must consider that bunkering HFO will demand steam production onboard. The use of HFO in marine engines necessitates the operation of economizers and/or boilers to generate the necessary steam for heating the oil. HFO, due to its high viscosity and heavy composition, must be maintained at elevated temperatures to ensure proper flow and injection into the engine. Heating the bunker fuel lowers viscosity, facilitating efficient combustion and preventing fuel system clogs. Economizers capitalize on waste heat from the exhaust gases to preheat the boiler feed water, enhancing overall energy efficiency. This system is crucial not only for operational efficiency but also for meeting safety and environmental regulations by ensuring complete combustion and minimizing emissions but would divert heating energy away from the CCS system’s amine regeneration needs. Steam consumption calculations by the shipyard indicate that under typical voyage conditions the economizer provides an enthalpy of 2,050kJ/kg.

Modelling the *capture* stage demonstrates that at a rate of 1 ton per hour (tph) the steam requirement exceeds the available capacity of the onboard economizer. Steam requirements for a 1tph amine regeneration cycle requires 1741kg/hr of steam and the economizer is sized for 1000kg/hr. Therefore, an onboard CCS system at 1tph or greater would not harvest sufficient heat from the engine with the existing 1000kg/hr onboard economizer. The onboard CCS system would have to be smaller than rated at 1tph or the economizer would need to be upgraded. Discussions with the economizer supplier revealed a negligible potential for upgrade due to space restrictions. Hence, switching bunker fuel to HFO, as suggested above for economic reasons, will fully utilize the economizer and greater utilization of the boiler will be needed to support the amine regeneration need. The boiler on board the Veteran Class tanker is rated at 18,000kg/hr confirming that a 1tph system, and even a 2.3tph system at 3748kg/hr amine regeneration cycle demand, could be supported while also supporting accommodation heating requirements. Heating from the steam system onboard will be produced with LSMGO which has an average heating value of 42.5MJ/kg.

Further analysis by Ionada revealed that nitrogen oxides (NO_X) content in exhaust gas above a level of 5ppm will accelerate degradation of amines and decrease their absorption efficiency. This should not be a big challenge on newer ships with Tier III engines which are typically fitted with Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) technology to greatly reduce NO_X content per international regulation. SCRs use a catalyst such as urea to convert (NO_X) content from the exhaust gas into nitrogen and water vapor. However, the subject ships in this study are older and outfitted with Tier I or Tier II engines, do not have SCR or EGR, and, as a result, produce a much higher concentration of NO_X in the exhaust. Ionada estimates that in the 2.3 tph case, 0.391 kg of amine would be lost per hour due to a very low NO_X content of 0.5 ppm_v based on a study by TCM in Norway[12]. With an estimated 6,500 m3 of amines aboard circulating through the system, this relatively small rate of degradation could be manageable. But the subject ships have an exhaust NO_X content of approximately 900 ppm. Further study is needed to verify the rate of degradation of the amines due to this much higher concentration of NOx in the exhaust. A quick, initial calculation shows that as much as 10% of the amines onboard could be lost in one hour, or a 100% loss of amines in only 10 hours. Two solutions are proposed for further study to counter this untenable rapid loss of amines:

1. Install a Selective Catalytic Reduction (SCR) unit in the ship's engine room, which may add well over one million dollars to the CCS installation cost, or
2. Find and utilize proprietary solvents which are more resistant to NO_X but at a significantly higher cost.

3.7 ENERGY DEMAND

The capability of capturing carbon dioxide from the main engine exhaust gas comes with energy demand, often referred to as "parasitic load". Harvesting heat from the main engine operations for use in the amine regeneration process provides an opportunity for increased efficiency compared to burning additional fuel in the boiler to create the necessary heat energy. The Veteran Class ships are fitted with an economizer (also described as an exhaust heat recovery system), but its energy contribution on each ship depends on the ship's particular operating profile. Ships operating in warm climates tend to have ample thermal energy available but that is not the case when the ship operates in colder climates.

Ships operating in colder climates harvest thermal heat from the main engine in large part for use in controlling the climate in the accommodation house. Equally important is that the Veteran Class ships are operating with Marine Gas Oil. These ships were designed to harvest thermal heat from the main engine for heavy fuel oil treatment which is not currently in use on the Veteran Class but could be introduced again with the installation of a scrubber in conjunction with an onboard CCS system.

[12] Campbell, Matthew and Akhter, Sundus and Knarvik, Anette and Muhammad, Zeeshan and Wakaa, Ahmad, CESAR1 Solvent Degradation and Thermal Reclaiming Results from TCM Testing (November 25, 2022). Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: https://ssrn.com/abstract=4286150 or http://dx.doi.org/10.2139/ssrn.4286150

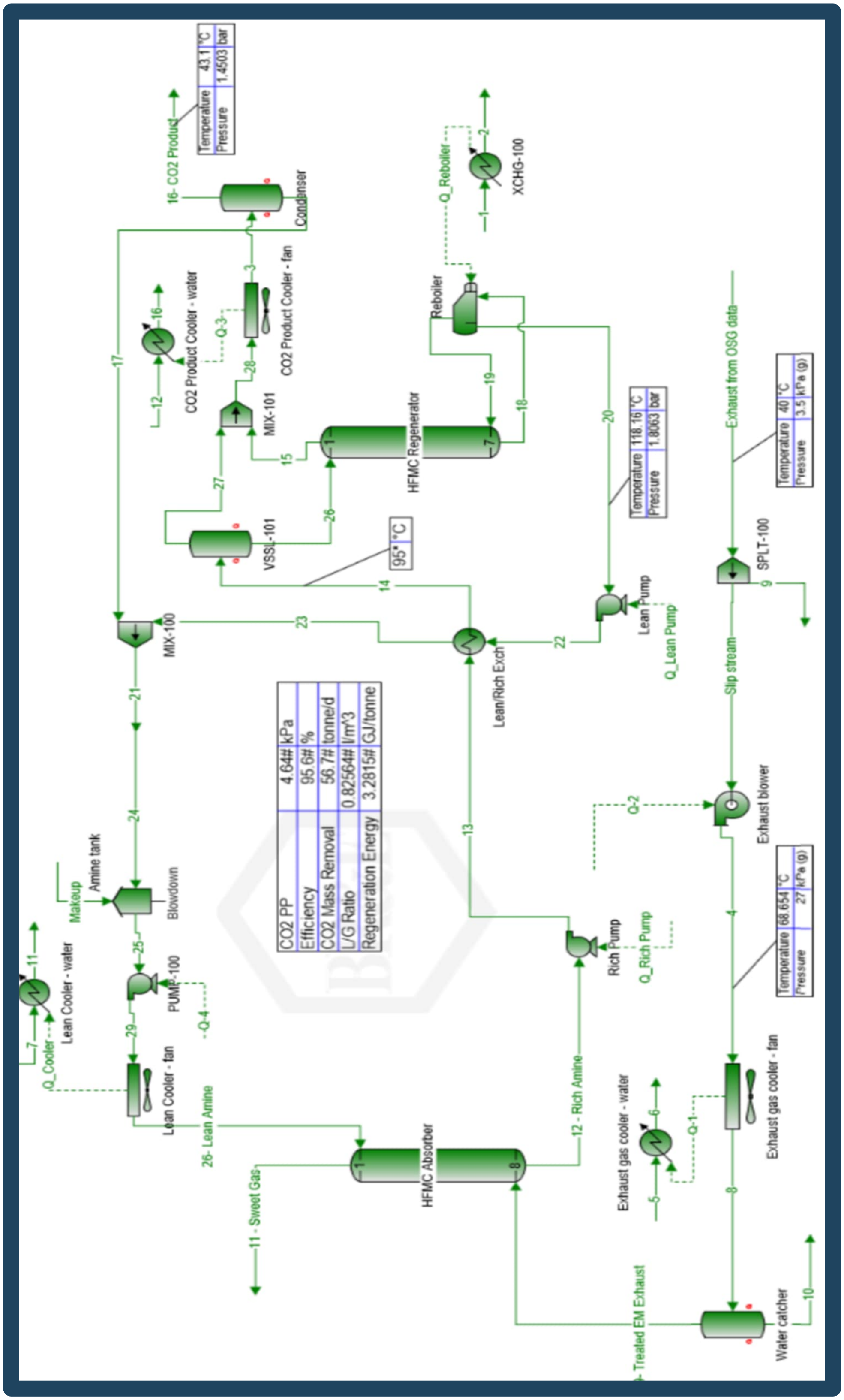

Figure 3. Capture stage steady state electrical load and heat demand values.

This study is focused on operating in the Gulf of Mexico region. Figure 3 above is a representative carbon capture system model used to demonstrate the electrical load and heat demand in this study. Modeling of the system in Promax provided key insights such as the amine regeneration energy demand, which in this study is provided with steam from the boiler. Table 2 below outlines the electrical and heat energy load for a typical ship operating in this region. Generation of heat for the amine regeneration is produced by the boiler using LSMGO bunker fuel. Alternatively, an electric heater could be considered[13] but availability of an existing boiler and energy conversion principles dictate that using existing steam capacity will be the most effective means to produce heat for the amine regeneration needs.

[13] https://www.alfalaval.us/products/heat-transfer/tubular-heat-exchangers/shell-and-tube-heat-exchangers/aalborg-eh/

CO_2 Capture Rate / Energy Demand	2.3 tph	1 tph
Available Power (at 80% load)	1280kW (two generators)	1280kW (two generators)
Electrical Demand		
Base Load (without CCS)	547kW	547kW
Conditioning Stage	120.1kW (131.1kW on startup)	120.1kW (131.1kW on startup)
Capture Stage (water cooled)	363kW	163kW
Liquefaction Stage	520kW[14]	225kW[15]
Total CCS Power needs	1,003.1kW (best case)	508.1kW
Remaining Power	- 270.1kW (deficit)	224.9kW
Steam Demand		
Capture Stage (regeneration)[16]	3748 kg/hr (steam)	1741 kg/hr (steam)
Energy demands listed above, converted into Joules		
Total Electrical Demand	3.61 GJ/hr	1.83 GJ/hr
Total Heat Demand	7.75 GJ/hr	3.60 GJ/hr
Total CCS system demand	11.36 GJ/hr	5.43 GJ/hr

Table 2. Energy and Services Load Analysis (@ 75% Main Engine Load)

Operating the main engine at 50% load will generate an estimated 3.2% CO_2 concentration (as opposed to 3.8% at 75% load) suggesting that the onboard CCS will be subject to less concentration in the exhaust gas stream, therefore negatively affecting efficiency. However, the ship's original electric load analysis in the "At Sea" condition showed increases in electrical load from additional operations such as "Tank Cleaning" while at sea. Such a condition will elevate the electrical base load to 862kW from the minimum 547kW as indicated on Table 2 above. Additional concurrent operation under consideration is "Tank Heating" with a base load of 725kW. It is important to note as well that the electrical demand of a 2.3tph system would require the use of all three available generators. In practical terms it is highly unlikely to continuously run all three generators on board due to maintenance cycles and equipment availability. The costs summarized later in this study do not include the cost of additional electrical generating

[14] Liquefaction electrical energy demand provided by Carbotreat.

[15] Liquefaction electrical energy demand provided by Carbotreat.

[16] Enthalpy from Boiler Steam at 7kg/cm2, saturated at 2769kJ/kg

capacity, but that must be considered in the next phase of analysis. The installation of a shaft generator to provide additional electrical supply at sea is currently anticipated to be the most cost-effective solution.

The increase in the ship's fuel consumption due to the parasitic electrical loads and steam production is converted to the equivalent increase in the ship's overall CO_2 emissions using a conversion factor of 3.206 kg/kg. Using a basis of 0.21 kg/kW of fuel consumption by the generators, they can be expected to consume 210.6 kg of fuel to produce the 1003.1 kW required by the 2.3tph rate CCS. Multiplying the generators consumed fuel by 3.206 yields 675 kg of additional CO_2 emitted per hour. In addition, the boiler demands (assuming no losses) 23.53kg of fuel to produce 1 GJ. At 0.0426 GJ/kg the steam generation represents 584 kg of CO_2 per hour to generate the necessary heat for amine regeneration. That sums to 1,260 kg of increased CO_2 emissions just to run the onboard CCS. Compared to the ship's existing emissions of 3,800 kg of CO_2 per hour (while at sea), the CCS results in a 43% increase in the ship's CO_2 emissions. A net of 1.1 tph is captured from the ship's existing emissions, a net reduction of 29%.

The CO_2 generated from parasitic loads is attributed 32% and 34% to electricity demand, while heating need demands 68% and 66%, for the 2.3 tph and 1 tph systems, respectively. The larger on-board CCS system does not reflect efficiencies from using bigger electrical equipment and suggests that the amine regeneration heat demand is linear with the amount of carbon captured. Note that the operation of the 2.3tph on-board CCS will require more than two generators to be online or installation of a Shaft Generator. Generating electricity with a Shaft Generator from a Main Engine would improve the CO_2 penalties because power from the two-stroke diesel engine comes at a rate of 170g/kW-hr, rather than 210g/kW-hr with the auxiliary generator engines. We also conclude that heat demand for amine regeneration is critical parameter. Advancements in amine technology can also significantly alter these results. For example, using N-methyl-diethanolamine (MDEA)/PZ, as opposed to CESAR1 can increase efficiency.[17] To further reduce the penalties, in this case from boiler use for amine regeneration, it is observed that on-board CCS be constrained to harvesting the available exhaust heat from engines and other machinery. Consideration for use of a shaft generator and optimizing available heat from machinery are recommendations for further exploration outside the scope of this study which aims to meet the 12,500-ton CO_2 capture threshold of Sec. 45Q cash subsidy incentive legislation.

Another significant challenge is to find or create physical space on the ship's existing main switchboard and feeder panels to power all these additional electrical loads associated with the onboard CCS. As a rule of thumb, ships are typically delivered from the new construction shipyard with 15-20% spare capacity in the electrical distribution system. However, spare capacity on the Veteran Class ships that are the subject of this study has been taken up for new equipment systems since they were delivered 13 to 17 years ago. The primary culprits are ballast water treatment systems which in most cases are capable of consuming relatively large amounts of power, up to 200 kW. Some ships of this class were converted

[17] Nguyen Van Duc Long, Dong Young Lee, Choongyong Kwag, Young Mok Lee, Sung Won Lee, Volker Hessel, Moonyong Lee, Improvement of marine carbon capture onboard diesel fueled ships, Chemical Engineering and Processing - Process Intensification, Volume 168, 2021.

to shuttle tankers with the addition of controllable pitch propeller systems and bow loading systems, using up even more of the vessels' spare electrical capacity. Therefore, it is expected that most, if not all, ships of the class will require significant expansion of their electrical generating and distribution capacity to support the installation of onboard CCS. Such work is not within the scope of this study but should be a primary focus in the next phase of CCS review.

3.8 SPACE AND GENERAL ARRANGEMENT

It is always a challenge to find space aboard a ship for new equipment that the ship was not originally designed for. Normally, ships are designed to be just large enough to accommodate the desired cargo capacity, machinery, and accommodations needed to safely operate the ship in its intended trade. When the subject ships were designed approximately twenty years ago, it was not conceivable that one day the owner would seek to fit them with carbon capture equipment. Another common, recent example is the international regulation to retrofit ballast water treatment equipment on all ships worldwide. In our company's experience, there was not enough room to reasonably place such equipment underdeck or in the existing machinery space where it would be protected from the elements. As is typical for ships of this size range, OSG created new deckhouses above deck to house the ballast water treatment equipment. The same is true for retrofitting carbon capture equipment onboard. As described above, the *conditioning* stage of the intended carbon capture installation primarily comprises the exhaust gas scrubber designed by Value Maritime. An important design feature of Value Maritime's system is a prefabricated enclosure to house the scrubber chamber and most associated equipment for installation on the ship. This makes it easier for the shipowner to have the scrubber installed at a shipyard since it arrives with the necessary enclosure which can be immediately placed onboard the ship without having to wait for the shipyard to build a custom enclosure for the system.

OSG studied various alternatives for placing this scrubber enclosure onboard and determined that the starboard side of the existing exhaust stack would be the best location for it. First, this area of the ship is relatively clear of potential obstacles and obstructions and, second, the main engine's exhaust pipe runs up the starboard side of the existing stack, minimizing the length of new piping needed to connect the existing main engine exhaust pipe to the scrubber. See Figure 10 in Appendix E for a drawing of such a scrubber installation. The scrubber enclosure is also shown as a dark blue vertical box in the 3D renderings of the complete carbon capture system as shown in the next section.

This installation description is not intended to minimize the size of the equipment or its impact on the ship's arrangement and existing systems. Even without the follow-on installation of the carbon capture equipment, installing only the exhaust gas scrubber is a major effort. The scrubber with enclosure measures 3.5 meters x 3.0 meters (11.5 ft x 10 ft) and is 10.3 meters (34 ft) tall and weighs 24 tons (53,000 lbs.).

The *capture* stage is a major part of the overall installation and is the primary focus of this study. The capture equipment maker, Ionada, developed the suggested arrangement of their equipment at two capture levels. At the 1 ton/hour CO_2 capture level, Ionada suggests arranging their equipment in three shipping container-sized enclosures. Like the exhaust gas scrubber described above, Ionada would prefabricate the enclosures at their shop and install all associated equipment within them. This will ease installation at the shipyard, minimizing the time out of service required to commission the system. See Figure 4 for the preliminary 1 ton/hour arrangement. The three enclosures have been placed on the aft side of the exhaust stack, under the lifeboat davit and access walkways and over the mooring winches on the main deck below. This area was wasted space on the ship so this arrangement should have a minimal impact on the day-to-day operations of the ship.

According to Ionada, increasing the capacity of the system to 2.3 tons per hour makes the prefabricated, containerized enclosures impractical and makes custom deckhouses the more practical, though challenging, solution. Figure 5 represents Ionada's recommended layout of deckhouses with their equipment inside. So as not to disturb the current lifeboat arrangement, new deckhouses are constructed to either side of the lifeboat with a central portion of the enclosure under the lifeboat connecting the two sides. A space of one meter is left between the deckhouses and each side of the lifeboat davit to allow unimpeded access for maintenance of the davit.

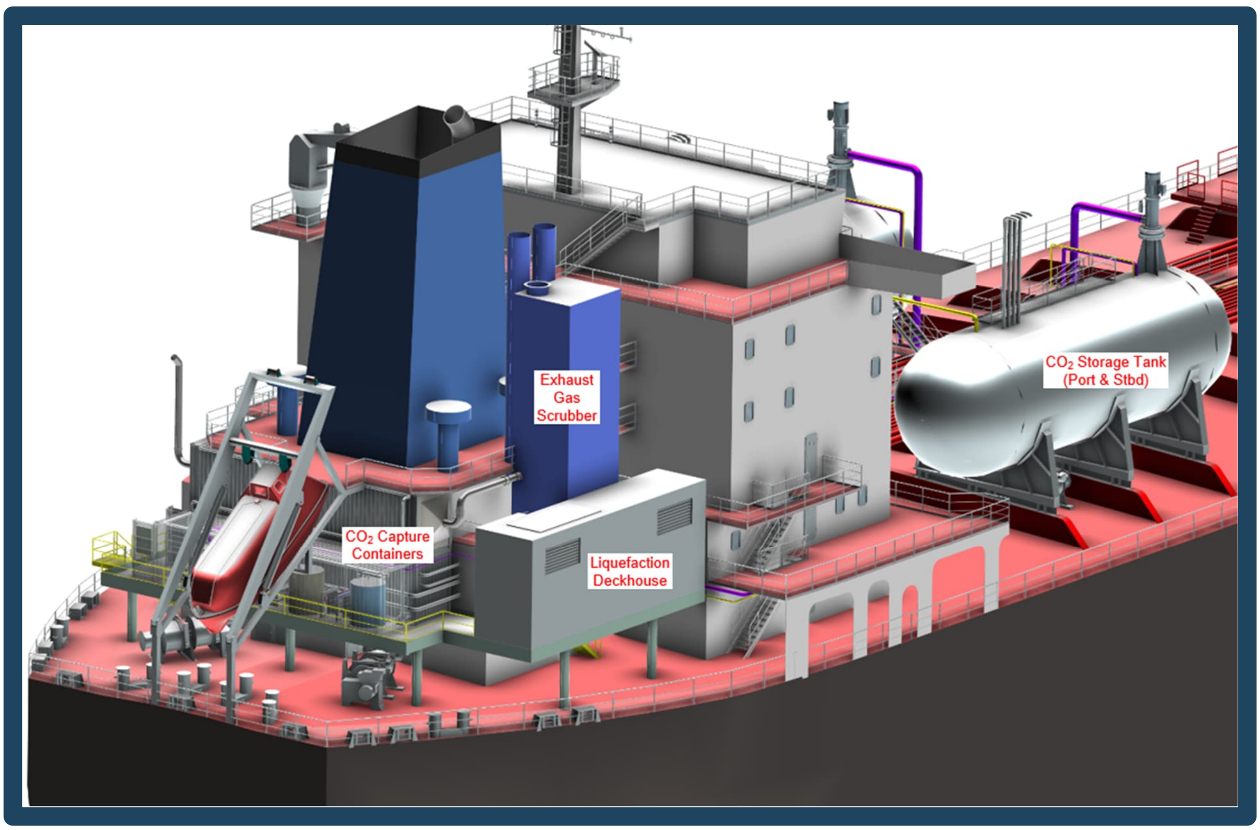

Figure 4. Conditioning and Capture equipment locations for 1 ton per hour capacity.

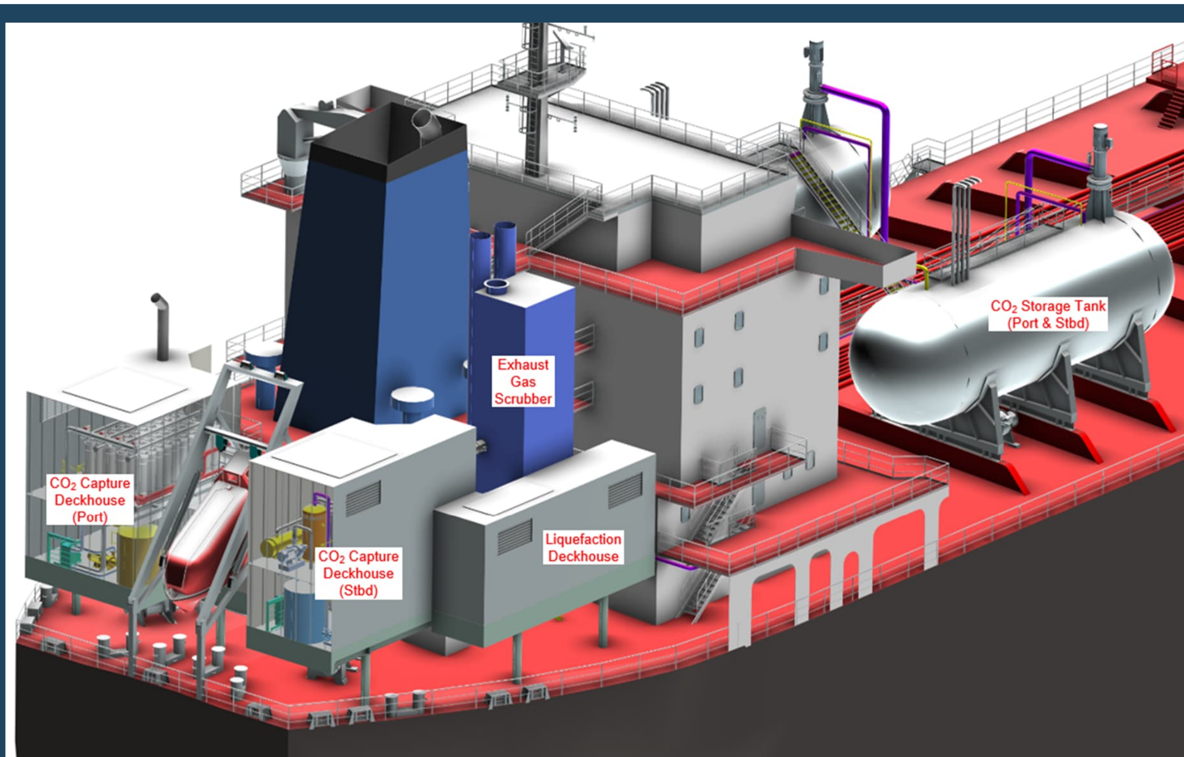

Figure 5. Conditioning and Capture equipment locations for 2.3 ton per hour capacity.

Liquefaction equipment is anticipated to fit in a separate deckhouse on the starboard side of the funnel, under the exhaust gas scrubber, as also depicted in Figure 5, above.

3.9 STORAGE TANKS

Because captured CO_2 must be stored in a cryogenic state at high pressure to maintain it in a liquid phase, a standard shipboard tank designed to hold liquids at atmospheric temperature and pressure will not be suitable. Instead, a Type C independent tank is necessary. Such a tank is cylindrical in shape and is best placed above the deck of the vessel so as not to require substantial modifications to the vessel's existing internal hull structures and arrangements.

A CO_2 storage capacity sized for 12 days of captured CO_2 is assumed for this study to be appropriate for the average MR tanker in U.S. Jones Act service. This should provide sufficient storage capacity for the round-trip travel time of a tanker carrying refined products from the Gulf Coast to the upper East Coast, or two round trips between ports in Texas and Florida. At a capture rate of 55 tons per day, that results in a storage tank capacity of approximately 660 tons of CO_2. Setting a maximum LCO_2 level in the storage tank of 95%, the gross tank capacity required is approximately 700 tons.

The optimum number and placement of storage tanks must be determined. A single storage tank of 700 tons capacity is likely to be less expensive overall than two storage tanks of 350 tons capacity each. A single storage tank would need to be placed on the centerline of the vessel so that the vessel's transverse heel angle does not change as the level of liquid CO_2 in the tank changes over time. However, a typical tanker has a raised "pipe rack" and elevated personnel walkway on centerline which would require the tank to be placed vertically higher above the deck than if the tank were placed to either side of this raised centerline pipe rack and walkway. A preliminary stability analysis has shown that placing that much additional weight that high on the vessel will result in insufficient stability.

Utilizing two storage tanks of 350 tons each enables the tanks to be placed lower on the vessel, significantly reducing the tanks' vertical center of gravity and resulting in marginally acceptable stability. The filling of the tanks with captured CO_2 will need to be managed carefully by the crew so as not to adversely affect the transverse heel angle, either by filling both tanks simultaneously, or filling one for a while, then the other, and so on.

Placing two smaller tanks to either side of centerline will also be more advantageous in terms of supporting the weight of the tank and its contents with the ship's existing deck structure. The combined weight of one tank and a full load of LCO_2 is expected to be approximately 425 tons. That is a substantial amount of additional weight to be supported by the hull structure. Extensive reinforcements will be required to the deck structure to properly support this weight. Figures 6 and 7 depict a potential location for these two tanks where the tank weight is evenly distributed across three above deck web frames, and the tanks are elevated above existing equipment on deck like mooring winches.

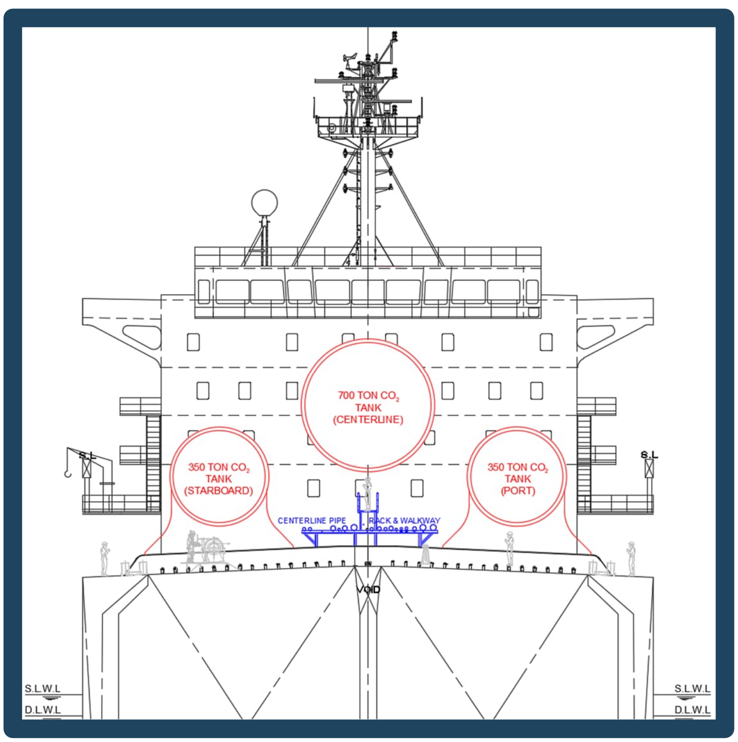

Figure 6. Section View Showing Potential CO_2 Storage Tank Locations

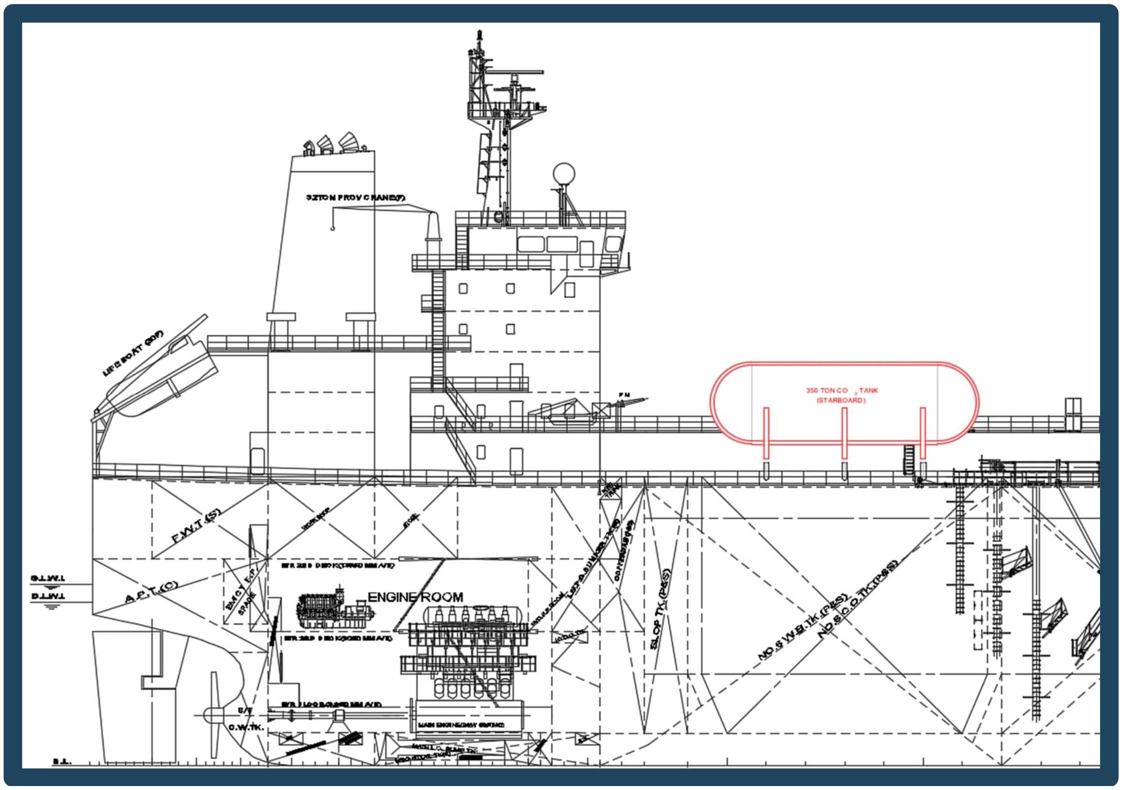

Figure 7. Elevation View Showing CO_2 Storage Tank Location

3.10 VESSEL STABILITY

Any time a substantial amount of weight is added to a vessel, preserving safe and adequate stability is a primary concern. Tankers like the subject vessels usually have a much more comfortable margin for stability than other vessel types like containerships and car carriers due to tankers' fuller hull form and lower cargo centers of gravity within the hull. However, the carbon capture system installation envisioned herein adds a substantial amount of weight to the vessel that must be analyzed for its impact on stability.

Table 3 summarizes the weight of equipment and structure expected to be added to the vessel. Given the vessel's current lightship weight of 9,961 metric tons, the envisioned installation adds 3.9% to it. Most of that added weight is high above the main deck which will negatively impact the ship's transverse stability.

Item	tonnes	LCG	VCG
Value Maritime Scrubber	24.0	74.5	30.9
Scrubber Seawater Piping	1.0	75.6	15.3
Scrubber Pump	0.2	75.8	4.0
Carbon Capture Equipment	77.1	83.6	25.1
Carbon Capture Deckhouse	60.0	83.6	25.9
Liquefaction Equipment	20.6	75.6	24.2
Liquefaction Deckhouse	25.0	75.6	24.4
CO_2 Storage Tanks	150.0	40.3	24.1
Misc Pipe & Electrical	10.0	69.5	22.5
Weight Margin (5%)	18.4	69.5	22.5
Lightship Weight Addition	386.3	64.2	24.9
CO_2 Tank Contents	700.0	40.3	24.1
Total Weight Addition	1,086.3	48.8	24.4

Table 3: Carbon Capture Installation Weight Estimate

The following table summarizes the vessel's drafts and stability with and without the CCS installation.

	Without CCS	With CCS
Mean Draft (meters)	11.86	12.05
Displacement (metric tons)	54,305	55,391
GMt Margin (meters)	0.37	0.01

Table 4: Carbon Capture and Storage (CCS) stability impact

The mean draft is the average of the bow and stern drafts of the vessel. With an installed carbon capture and storage system and a full load of captured CO_2 in its storage tanks, the vessel sits 0.19 meters deeper in the water (7½ inches). While that may not seem like much for such a large ship, ships are often loaded down to a maximum draft stipulated by a certain navigational channel or berth. In some cases the ship may need to load approximately one thousand tons less cargo in order to meet the same stipulated maximum draft with CCS installed. That short-loading of cargo could have serious long term commercial implications.

The value "GMt margin" given in the bottom row of the table represents the amount of available transverse metacentric height in excess of the minimum metacentric height required by regulation, which ensures adequate stability of the vessel in a seaway. Transverse metacentric height is an indication of the ability of a ship to right itself if it is heeled over due to waves or wind. In general, the higher the weight is placed on a ship, the lower the GMt will be and the more in danger of capsizing the ship will be. As summarized in the table, with CCS and full storage tanks the vessel's stability margin will be reduced to practically zero. As a result, the vessel's maximum allowable draft (and corresponding cargo carrying capacity) is reduced, and the vessel meets only the bare minimum of stability requirements.

3.11 OFFLOADING ARRANGEMENT

Lessons learned from existing CO_2 transportation tankers demonstrate that the piping and offloading manifold arrangement for onboard carbon capture systems is technically mature for effective handling and transfer of captured CO_2 from ships to offloading facilities. Four CO_2 tanker ships currently in operation (Embla, Froya, Gerda, and Helle, all with capacities <5,000 MT of CO_2) and their ports-of-call provide references for the offloading of liquid carbon dioxide. Froya routinely calls into Equinor's rig at Herøya Industrial Park in Norway.[18] The multiphase CO_2 testing facility provides insight to the challenges and opportunities managing CO_2 in gaseous and liquid form. In addition, two CO_2 tankers (7,500MT CO_2) for delivery this year to the Northern Lights project also located in the North Sea, the conversion of the MV Coral Methane (from LNG carrier repurposed for transporting liquified CO_2), and a few >20,000MT ships under construction in foreign yards suggest the oncoming of a rapidly developing of CO_2 transportation sector in the maritime industry.

The design of these carbon capture systems must ensure the safe, efficient flow of liquefied CO_2 (LCO_2) under controlled conditions to prevent any operational failures or safety hazards. One recommended arrangement involves the use of dual manifold systems, which allow for simultaneous connections to multiple receiving facilities, thereby minimizing downtime and increasing operational flexibility. This setup typically includes dedicated pumps and valves that maintain the CO_2 at optimal pressure and temperature throughout the transfer process.

For onboard carbon capture systems, offloading the stored CO_2 to a barge or shore facility requires careful consideration to ensure the CO_2 can be transferred with minimal additional risk compared to the current vessel operations. Tankers are designed to transfer dangerous liquids onto and off ships safely as a routine matter. On a tanker, all liquid transfer points are arranged at the "manifold", a series of piping connections at the mid-length point of the ship. This is where the crew connect hoses from shore or barges alongside the ship's piping systems to transfer dangerous liquid cargoes, fuel, lube oil, and even fresh water. It makes sense to place the CO_2 transfer connections at this midpoint manifold as well to minimize changes to the crew's routine which should in turn minimize risk, where major changes to the crew's routine onboard can be expected to introduce unnecessary risk. An additional benefit is that at this amidships manifold location, the side of the hull is flat so that a CO_2 transfer barge can moor securely alongside the vessel during transfer operations. If the CO_2 transfer point were placed further aft on the ship, the curvature of the hull inward for proper water flow into the propeller would make it difficult to securely moor a CO_2 barge alongside. Another benefit is that if the ship is transferring its CO_2 ashore at

[18] https://www.heroya-industripark.no/en/news/co2-transport-results-from-equinors-test-team-at-heroeya-bode-well-for-norways-biggest-climate-initiative

an oil terminal, the terminals transfer hoses and piping are all arranged to line up with the ship's midpoint manifold, making it more straightforward to add CO_2 transfer arrangements in the same general location.

Two sets of CO_2 piping would be installed onboard, one to transport LCO_2 from the onboard tanks to shore or barge, and another to transport CO_2 in gas form back into the tank from shore to fill the volume vacated by the liquid and maintain pressure inside the tank while discharging the liquid (called "vapor balancing"). This "vapor" line can also be used to purge the storage tanks of ambient, humid air for first use at commissioning or after lengthy empty periods for inspection and maintenance. The air inside the tank must be purged with an appropriate dry and purified gas to remove moisture and lower the dew point so that when LCO_2 is introduced at cryogenic temperatures the moisture in the tank does not turn to water ice. For the purposes of this study, it is assumed that the LCO_2 receiving facility or barge has the appropriate equipment to provide this purging gas to the ship via the vapor line at the required flow rate.

All piping and valves will be AISI 316L stainless steel which provides good corrosion resistance and toughness at cryogenic temperatures. They will also be fitted with external insulation, like the storage tank itself, to minimize temperature rise of LCO_2 flowing through the piping as well as to prevent injury to crew should they accidentally touch the piping or valve bodies. The use of high-grade stainless-steel piping is advised especially when it is captured in impure forms which can increase corrosion rates.[19] These materials help to reduce maintenance needs and extend the lifespan of the system, although they do increase initial capital costs.

See Figure 8 for a basic LCO_2 transfer system onboard.

[19] Selection of materials for high pressure CO2 transport - TWI (twi-global.com)

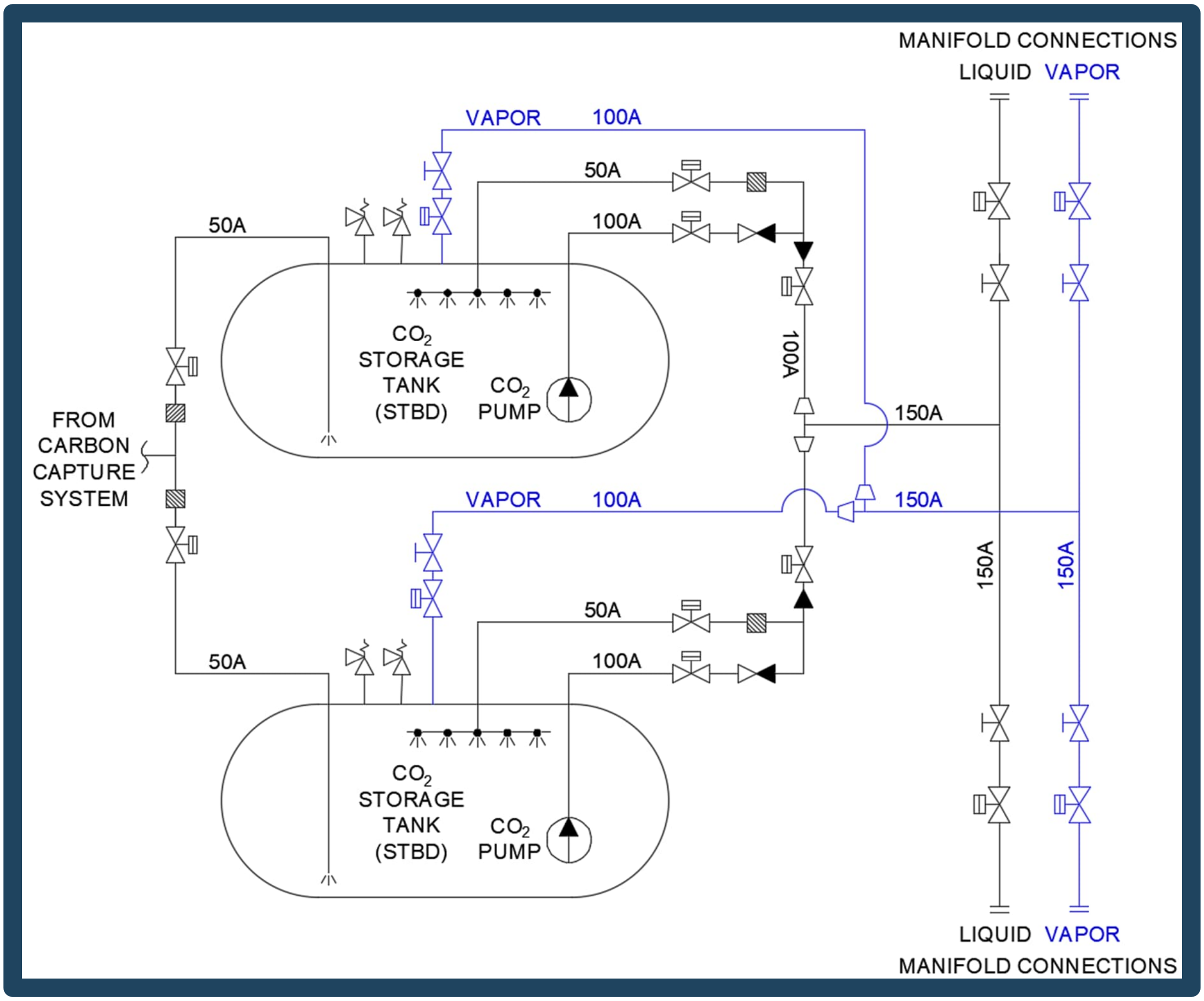

Figure 8: CO_2 Tank and Offloading Schematic

One of the few CO_2 tanker ships currently in operation includes an inspection window to be able to visually inspect the liquid CO_2 (see Figure 9). A similar presentation flange can be provided on this ship to help ensure that the LCO_2 is not solidifying into dry ice.

From a technical standpoint, the manifold and piping system faces challenges, particularly related to the thermodynamic properties of CO_2. CO_2 must be maintained above its triple point to ensure it remains in a liquid state during transfer; otherwise, it can solidify or vaporize, causing blockages or pressure surges.[20] The design must also account for the expansion and contraction of pipes due to temperature fluctuations, which can lead to mechanical stresses and potential failures. To manage these issues, expansion joints and proper insulation are critical components of the system. Moreover, safety measures such as pressure

[20] Bostock, T., Scurlock, R.G. (2019). The Handling and Transfer of Cryogenic Liquids. In: Low-Loss Storage and Handling of Cryogenic Liquids. International Cryogenics Monograph Series. Springer, Cham. https://doi.org/10.1007/978-3-030-10641-6_6

relief valves and leak detection sensors are essential to quickly address any irregularities that could lead to safety risks or environmental contamination.

Cost premiums for these specialized LCO_2 piping systems are significant compared to the other service piping systems onboard a commercial tanker such as those for fuel, lubricating oil, and ballast water. AISI 316L stainless steel pipe is on the order of four times the cost of carbon steel pipe between diameters of 25mm and 200mm. That is in addition to the cost of applying thermal insulation on all LCO_2 piping and maintaining it over the life of the vessel. The use of specialized materials and safety equipment, coupled with the need for specialized engineering and regular maintenance, leads to higher CAPEX and OPEX compared to the more conventional fluid transfer piping systems onboard the typical petroleum tanker.

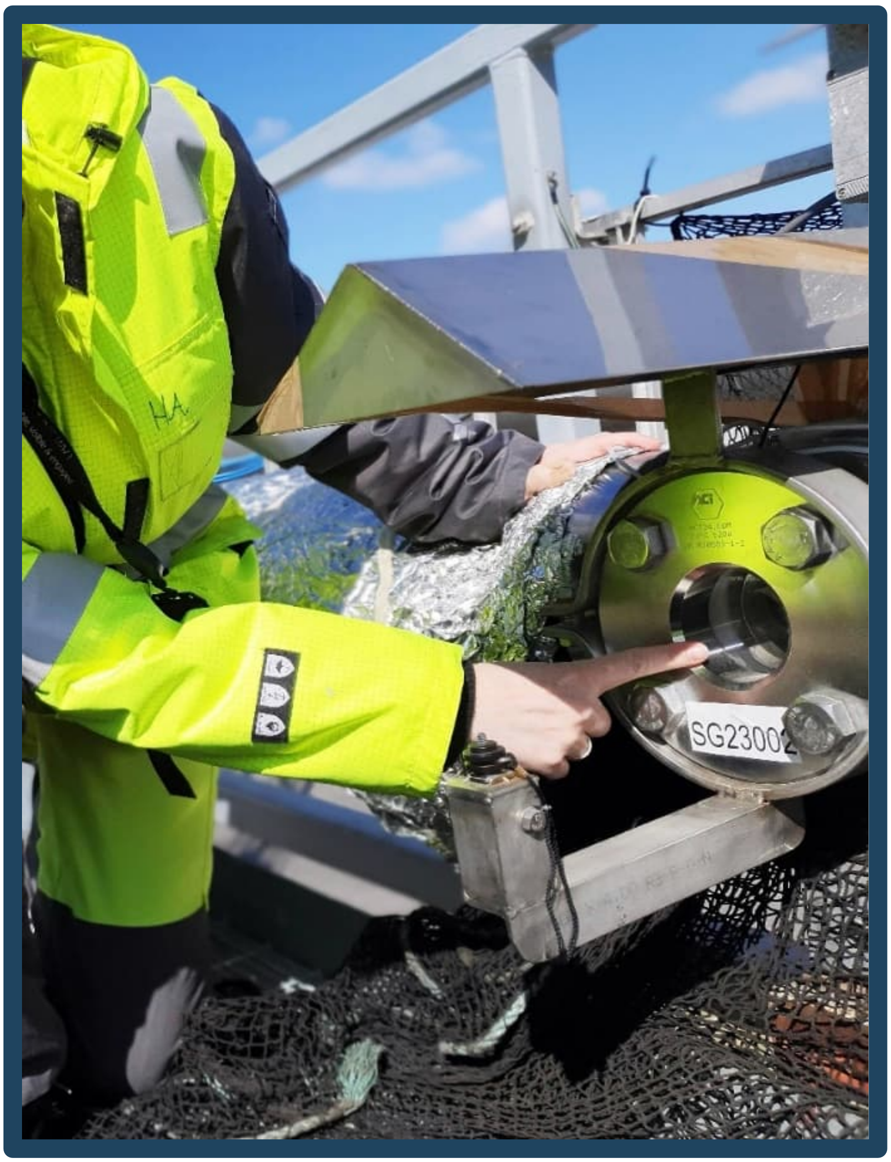

Figure 9. Inspection Window in LCO_2 pipeline (credit: Siri Krohn-Fagervoll)

4 RISK ASSESSMENT:

4.1 CURRENT RISK MANAGEMENT FRAMEWORK: SUMMARY

While the marine industry is familiar with the handling, storage, and transportation of cryogenic chemicals, the introduction of onboard carbon capture and storage systems has introduced unique hazards associated with carbon capture machinery and the aggregation of large volumes of carbon dioxide (CO_2). These new risks, primarily driven by the introduction of carbon capture media and liquefied CO_2, necessitate an expansion of the current risk management framework used in vessel operations. This expanded framework should include potential safety and operational risks inherent in operating a CCS and managing CO_2 storage after capture, which can be addressed through a Hazard Identification (HAZID) and subsequent Hazard and Operability Study (HAZOP) exercise.

The research also pointed out the challenges of managing impurities in LCO_2 after capture, emphasizing the risks and operational issues they pose. These include corrosion, safety hazards from pressure build-up, potential blockages in pipelines, material degradation, and health risks from toxic substances. Even small amounts of impurities, like water or non-condensable gases, can lead to serious issues such as corrosion, hydrate formation, increased energy needs for compression, and safety risks in CO_2 storage and transport. The process of ensuring captured CO_2 meets quality standards for safe storage and transport is critical, with specifications varying depending on the final use of the CO_2 as illustrated by the Northern Lights project in Norway.

OSG assessed the safety and operating risks of the shipboard CCS using the “What-If Analysis” methodology typically used in the chemicals industry. The CCS system conceptualized for the Veteran Class ship, in conjunction with cryogenic liquid bulk cargo handling, was examined with a brainstorming approach where an experienced maritime industry engineer asks a question, considers the probabilities, and each undesirable scenario becomes the basis for analysis. This effort focused on discovering how the current risk management framework used in a vessel’s operations could be expanded to include potential safety and operational risks inherent in operating the CCS system and managing the CO_2 storage and handling.

Based on the scope of the shipboard CCS, the following circumstances were considered.

1. MR Product Tanker at sea capturing CO_2 at 2.3 tons per hour.
2. Replenishing the amine carbon capture media.
3. Offloading LCO_2 stored at 7 bar / -49 °C.

Identification of potential hazards associated with a carbon capture system has multiple dimensions as follows:

1. People: Identifying potential risks associated with the handling and use of chemicals like amines, which can be hazardous to health if not managed properly. This includes risks from exposure to toxic fumes, leaks, or spills.

2. Assets: Ensuring that the equipment used for the capture, regeneration, compression, and liquefaction of CO_2 operates within safe parameters to prevent mechanical failures that could lead to accidents with damage to equipment or environmental harm.

3. Environmental Protection: Assessing risks related to accidental releases of CO_2 or amine into the marine environment, which could have adverse effects on marine life and ecosystems.

4. Reputation: Ensuring all operations comply with international maritime laws and regulations, including those related to environmental protection, safety standards, labor agreements, and company standards of conduct.

5. Emergency Response Preparedness: Developing effective response strategies for potential emergencies involving carbon capture systems, including containment and mitigation of chemical spills, dispersion of CO_2 in the air both underway at sea and in a port facility.

Each of these objectives aims to minimize the risks associated with the technology, ensuring safety for the crew, the ship, and the environment.

4.2 METHODOLOGY

Our methodology fundamentally uses brainstorming based on years of maritime industry experience handling hazardous cargos and asking multiple “what-if” questions to uncover undesirable scenarios. We begin with collection of data in preparation to understand the changes and new elements introduced to operations. Data includes detailed information about the carbon capture system, including design specifications, operational data, chemical properties of the amine, and system layout. The information was discussed with Health, Safety, Quality, Environment (HSQE) team members and reviewed by the Director of Technical Services.

The hazard identification process is iterative in nature. A list of hazards is made available to the team, reviewed in discussion sessions, and maintained to discover potential failure modes of the carbon capture process. This includes all stages from amine absorption of CO_2 to the regeneration of amine, and the compression and liquefaction of CO_2. The list of hazards, which is derived from the "what-if" scenario, describes potential causes, the likelihood of occurrence, possible consequences, and existing controls. An “adapted” fuzzy risk matrix tool is used to rank the scenarios based on their potential impact, likelihood, and situational knowledge.[21] The novelty of fitting a CCS system on an ocean-going ship dictates that the likelihood of occurrence cannot be based on actual count of events but rather measures around similar shipboard equipment. Therefore, the likelihoods were ranked as “similar occurrence” frequencies using our situational knowledge.

[21] Adam S. Markowski, M. Sam Mannan, Fuzzy risk matrix, Journal of Hazardous Materials, Volume 159, Issue 1, 2008, Pages 152-157, ISSN 0304-3894, https://doi.org/10.1016/j.jhazmat.2008.03.055.

This helps prioritize the hazards for further analysis. Based on the risk assessment, the hazards are ranked to identify which scenarios should be removed, reduced in likelihood, require operation management controls or mitigation strategies. Our list of identified hazards is then used to document all identified hazards, analysis findings, and recommended control measures. The hazards identification (HAZID) is used to identify the risks and develop the operational controls needed to manage operations of the shipboard carbon capture and storage. Management of the shipboard CCS system is expected to include training programs for the crew on handling potential hazards and emergency response procedures. More so, drills based on the scenarios to ensure the crew is prepared for actual events is part of the expectation.

4.3 HAZARD IDENTIFICATION:

Appendix C includes the “What-If” questions associated with each scenario described above.

The “What-If” questions consider events related to equipment failure, process deviations, human error, environmental factors, and other unexpected circumstances that can occur regardless of likelihood. Analysis based on likelihood, consequences, and severity, using the risk assessment matrix (Appendix A), of each event identified provides the prioritize and associated management recommendations.

The “What-If Analysis” considers also measures to mitigate or eliminate the identified hazards. These measures can include engineering controls, administrative controls, and procedural safeguards. In addition, evaluation of every scenario considers also potential needs for redundancy, safety interlocks, alarms, training, and emergency response plans.

4.4 IMPURITIES

The research discovered the importance of managing impurities in the post-*capture* stage, from the amine regeneration stream to the CO_2 liquefaction and storage. Impurities in liquid carbon dioxide (LCO_2) present a variety of threats. Corrosion of storage and transfer equipment can occur due to sulfur compounds and water. Safety hazards may arise from pressure build-up in storage tanks caused by non-condensable gases like nitrogen or oxygen. Water impurities can freeze, blocking pipelines and potentially damaging infrastructure. Material degradation can occur when certain impurities react with the materials used in system construction. Some impurities could have a negative environmental impact if released, which contradicts the purpose of carbon capture and storage. Health risks to personnel involved in handling and transportation can be posed by toxic gases or volatile organic compounds (VOCs).

Furthermore, the impacts of impurities on operations were confirmed when exploring LCO_2 offloading quality specifications. Minor impurity concentrations, such as more than 30 ppm of water content or more than 0.3% by volume of non-condensable gases like hydrogen or nitrogen, can cause corrosion, form hydrates, increase compression power requirements, and jeopardize the safety of CO_2 storage and transport pipelines. The system design must account for the influence of impurities, such as more than 0.3% by volume of nitrogen, on the triple point.

The processing of captured CO_2 to meet quality standards depends on ensuring safe storage, offloading, and transportation through allowable impurity concentrations. The captured CO_2 must meet product specifications, which are dictated by the end use of the offloaded CO_2, whether for utilization or geological sequestration. Case in point is the LCO_2 quality specifications published for the Northern Lights site in Norway.[22]

4.5 RECOMMENDATIONS

The list of resulting recommendations from the "what-If" analysis is summarized below. Where overlapping recommendations addressed more than one scenario, it is noted on the far most left column. The list is grouped by risk level from greatest to least, red to light blue, respectively.

	Medium Risk (Dark Blue)	Scenario #
1	Focus on maintenance of process control automation	1.01, 1.02, 1.03, 1.04, 1.05, 1.06, 1.07, 1.09
2	"Confined space entry" process in Operational Procedures	1.05, 1.06
3	Mark entry points to space with warning signs of potential risk	1.05, 1.06
4	Regularly verify tightness of flanges and pipe fittings	1.06
5	Consider Amine Leak Detection	1.08
6	Add carbon capture media to the handling of hazardous chemicals list	1.08, 2.01, 2.02,
7	Training and certification process for handling chemicals	1.08, 2.01, 2.02,
8	Situation awareness training	1.09
9	Boom around ship while carbon capture media operations	2.01
10	Focus on maintenance of Emergency Shut-Off	2.03, 2.06
11	Operational Procedures needed for handling of amine transfer	2.03, 2.04
12	Regular testing Emergency Shut-Off	2.04
13	Fail Safe Design (energized to transfer LCO_2)	2.04
14	Consider not storing amine onboard	2.07
15	Add amine to the handling of hazardous chemicals in Operating Procedures	2.07
16	Training and certification process	2.07
17	Certified qualifications for marine personnel	3.01, 3.02

[22] https://norlights.com/wp-content/uploads/2021/12/Quality-specification-for-liquified-c02.pdf

18	Consider Re-Certification and Testing regime of cryogenic equipment	3.01, 3.02
19	Safety barricade cryogenic transfer equipment when in use	3.01, 3.02
20	Consider awareness training for marine personnel	3.01, 3.02
21	Certified qualification for marine personnel	3.03, 3.04
22	Consider Re-Certification and Testing regime of cryogenic equipment	3.03, 3.04
23	Consider awareness training for marine personnel	3.03, 3.04
24	Certified qualification for marine personnel.	3.05
25	Consider Re-Certification and Testing regime of cryogenic equipment	3.05
26	Consider awareness training for marine personnel	3.05
27	Low Risk (Light Blue)	
28	Focus on maintenance of process control automation	1.01, 1.02, 1.03, 1.04, 1.07
29	Focus on maintenance of Emergency Shut-Off	2.06
30	Operational Procedures needed for handling of amine transfer	2.06

Table 5. Risk Management Recommendations

4.6 RISK ASSESSMENT CONCLUSION

While the marine industry is familiar with the handling, storage, and transportation of cryogenic chemicals, the introduction of onboard carbon capture and storage systems has introduced unique hazards associated with carbon capture machinery and the aggregation of large volumes of CO_2. These new risks, primarily driven by the introduction of carbon capture media and liquefied CO_2, necessitate an expansion of the current risk management framework used in vessel operations. This expanded framework can include potential safety and operational risks inherent in operating the Carbon Capture and Storage (CCS) system and managing CO_2 storage and handling after capture, which can be addressed through a Hazard Identification (HAZID) and subsequent Hazard and Operability Study (HAZOP) exercise.

5 INVESTMENT DECISION

5.1 45Q TAX INCENTIVES PROGRAM

The 45Q financial incentive program, formally outlined in 26 U.S. Code § 45Q, is a federal incentive program in the United States designed to promote the capture and storage of carbon dioxide emissions, encouraging the reduction of greenhouse gas emissions. This program provides a performance-based direct cash subsidy for carbon management projects which capture carbon oxides from eligible industry and power facilities, as well as directly from the atmosphere. The captured CO_2 can be securely stored in appropriate geologic formations, including saline or other geologic formations or oil and gas fields. Alternatively, the captured CO_2 or its precursor carbon monoxide (CO) can be reused as a feedstock to produce low embodied carbon products such as fuels, chemicals, and building materials.

The party eligible to claim the subsidy is the owner of the capture equipment. But the subsidy is intended to be shared among all the participants in the supply chain used by that emitter and would include the transport firm and sequestration site operator. The emitter must physically or contractually ensure the storage or reuse of the carbon oxide and may elect to transfer the credit to another taxpaying entity. Eligible projects that begin construction before January 1, 2033, can claim credit for up to 12 years after being placed in service.

The 45Q subsidy provides a foundational policy for incentivizing carbon capture deployment in multiple industries, in the same way that federal tax credits have incentivized wind and solar development. It is a significant step towards reducing industrial carbon dioxide emissions to meet the national 2050 net zero carbon emission goal. Since the amount of the subsidy was increased in 2022, it has accelerated substantial private sector investment and activity in carbon capture. The captured CO_2 can then be permanently sequestered in deep underground saline formation pore spaces or through mineralization, or utilize it for industrial purposes including for enhanced oil recovery (EOR).

The 45Q incentive program is primarily designed to incentivize the capture and storage of carbon dioxide emissions from large industrial sources and power plants.[23] The program does not explicitly mention its applicability to ships. However, if a ship has the necessary carbon capture equipment and meets the other requirements of the program (such as ensuring the capture and disposal, injection, or utilization of the carbon oxide), it could potentially be eligible[24].

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[23] IRS Releases Section 45Q Carbon Capture Tax Credit Guidance Regarding .... https://www.bakerbotts.com/thought-leadership/publications/2021/july/irs-releases-section-45q-carbon-capture-tax-credit-guidance-regarding-qualifying-equipment-ownership.

[24] The Section 45Q Tax Credit for Carbon Sequestration. https://crsreports.congress.gov/product/pdf/IF/IF11455.

It is important to call out requirements for non-generation facilities under the 45Q tax incentives program which are those that do not generate power (such as a ship). These facilities, despite not being power plants, can still be significant sources of carbon emissions. For these facilities to be eligible for the 45Q tax credit, they must meet certain requirements. Specifically, there is no percent-capture threshold for these facilities, meaning they do not need to capture a certain percentage of their total emissions. However, they must capture at least 12,500 metric tons of CO_2 each year to remain eligible. For carbon capture equipment placed in service after 2022, where prevailing wage and apprenticeship requirements are met, the Section 45Q credit is currently $85 per metric ton if permanently sequestered in approved underground Class VI wells and $60 per metric ton if utilized commercially (such as in Enhanced Oil Recovery operations). This requirement ensures that the program is effectively targeting and incentivizing significant carbon capture efforts across a range of industries.

5.2 CAPEX ESTIMATE

The capital expenditures (CAPEX) necessary to purchase the various components of the complete CCS system, and to install them at a shipyard, must be determined as it will be a significant factor in the overall cost per ton of CO_2 captured. The first step in confirming the findings in this feasibility study and proceeding towards installation is to conduct a Front-End Engineering and Design (FEED) study. The FEED study is the critical first step in a large-scale project such as this, aimed at confirming the overall system capability, the integration of components into existing ship's systems, the equipment arrangement, and overall incorporation into the ship. During this phase, detailed engineering work is performed to produce accurate cost estimates that guide budgeting and financial planning. A significant aspect of a FEED study is cost and schedule risk assessment, where potential challenges are identified and mitigation strategies are devised to ensure smooth project progression. Ultimately, a FEED acts as a comprehensive blueprint, minimizing uncertainties and setting a clear path forward for project execution. The CCS system maker has estimated $350,000 to conduct their portion of the FEED study. Additional FEED-level engineering is necessary for items not covered by the CCS equipment maker. Those additional engineering costs are estimated to be $200,000, for $550,000 total in FEED costs.

The next step towards installation is to purchase the long lead time equipment, including the CCS system itself but also all the ancillary equipment necessary to support the CCS that is not provided by the CCS maker. Primary examples of such ancillary equipment, all of which are discussed earlier in this report, include the scrubber for exhaust gas conditioning, the post-capture purification and liquefaction plant, and the Type C storage tanks. It is important to note that most of this equipment will have long lead times, meaning a lengthy period from ordering the equipment to when it will be ready for delivery to the shipyard performing the system installation. Some critical pieces of equipment may have a lead time of longer than one year.

Pricing is readily available for exhaust gas scrubbers since they are proven technology and have been used onboard vessels for many years. In Table 6 below a price estimate for a scrubber sized for an MR tanker is listed based on recent discussions with a scrubber maker.

Cost estimates for the Carbon Capture Equipment and Liquefaction & Purification equipment are included in Table 6. But it is important to note that these are rough-order-of-magnitude (ROM) estimates until the FEED study is completed. The ROM cost given for the Liquefaction and Purification equipment is at the top end of the range of between $450,000 and $800,000, given verbally by more than one potential future supplier of shipboard equipment. It is possible that at the end of the FEED study, a maker will have further matured shipboard liquefaction technology and the price will be proven to be at the lower end of that range.

The estimated cost of two Type C CO_2 storage tanks is taken from multiple quotations for Type C tanks OSG has received over the past year. Of course, prices will vary significantly depending on where the tanks are constructed and the market price for raw steel at the time of order. The least expensive tanks can be expected to be built in China, but transportation costs to the Gulf or East Coast of the United States where the tanks will be installed will be highest. Such tanks are also built in Eastern Europe and Spain, which would result in significantly lower transportation costs. During a FEED study, the tank would be preliminarily designed and firm quotes for construction and transportation would be solicited from multiple companies throughout the world to determine the most cost-effective construction location. Depending on the results of that effort, the tank price estimate shown in Table 6 below could increase significantly, or potentially even decrease somewhat. As of January 2025, steel prices are approximately half what they were just approximately two years ago, which will also drive the tank price down. Although steel prices could swing back up again by the time a contract to build the tanks is signed.

The cost of shipyard labor and routine materials to install the CCS system aboard the ship will be a significant component of the total CAPEX, but it is impossible to obtain accurate shipyard pricing for installing such a complex system before completing the FEED study. A shipyard needs detailed drawings of each component of the installation to estimate the labor hours and materials to construct all of the steel deckhouses, run large and small diameter piping in the Engine Room and across the deck, and lay potentially miles of electrical power and signal cable through the aft third of the ship. For the purposes of this pre-FEED study, OSG draws on its experience installing ballast water treatment systems on every ship in its fleet from 2019 through 2022. Based on shipyard costs actually incurred to install those systems, which are considerably less complex than the CCS system contemplated by this study, the shipyard installation cost for CCS is estimated to be $1.5 million.

Category	Cost
Front-End Engineering & Design (FEED)	$550,000
Exhaust Gas Scrubber	$1,250,000
Carbon Capture Equipment	$2,500,000
Liquefaction & Purification	$800,000
Type C Storage Tanks	$2,000,000
Deckhouses	$750,000
Shipyard Installation Cost	$1,500,000
Grand Total	$9,350,000

Table 6: Shipboard CCS CAPEX Estimate

This CAPEX estimate does not consider potential lost revenue due to the ship's time out of service required to install such a complex system. It is envisioned that the installation would take place during a normally scheduled shipyard period so that lost revenue would not need to be accounted for in the CCS installation budget. However, it is highly likely that the CCS installation would take longer than the normal shipyard period of approximately twenty-one days, depending on the capabilities and resources of the particular shipyard. Therefore, it must be considered that, at a current Jones Act MR tanker market rate of approximately $90,000 per day, an additional two weeks out of service to complete the CCS installation could add over one million dollars to the shipowner's true cost. For international flag tankers with significantly lower charter rates, there may be greater ability to financially absorb such out of service time.

5.3 OPEX ESTIMATE

The expected operating expenses (OPEX) associated with operating the CCS system daily must also be estimated and factored into the overall cost per ton of CO_2 captured. The aggregated energy demand and associated operating expenses due to running a CCS system onboard is summarized in Table 7.

System Capacity	2.3 tph	1 tph
Electrical Demand (kW)	1003.1kW	508.1kW
Heating Load (Steam)	3748 kg/hr	1741 kg/hr
Cost of Electricity (kW) *LSMGO: $700/Ton	$150.46	$76.22
Cost of Regeneration (Steam) *LSMGO: $700/Ton	$127.48	$62.23
Offloading Cost	$34.50	$15.00
Carbon Capture Media refresh	$10.00	$5.00
Maintenance Cost – Hardware	$27.20	$13.60
Maintenance Cost – Personnel	$1.00	$1.00
Total Operating Cost	$350.64	$173.05
Cost per CO_2 Ton	$152.45	$173.05

Table 7. Operating Cost Summary

Operating data for two scenarios were examined: 1 ton of CO_2 captured per hour to simplify the math and 2.3 tons of CO_2 per hour which is the rate at which the ship would need to capture CO_2 to meet the 45Q tax incentives thresholds. To qualify as an *industrial facility,* the ship will need to be in operation 70% of the year to capture the 12,500-ton threshold per year which translates to a rate of 2.3 tons per hour. Power is the energy required to run the carbon capture system as summarized in Table 2. Cost of electricity as discussed in Section 2.8 and comes out to be $0.15 per kW for the energy demands of the carbon capture system. The system harvests heat from the engine using an exhaust gas boiler (EGB) rated at 1000kg/hr (saturated steam) which supports also the heat needed for heavy fuel oil viscosity requirements and consequently demanding additional fuel cost by using the shipboard boiler for amine regeneration heat demand. The steam on board is saturated at 7kg/cm^2 and it has an enthalpy of 2760kJ/kg while HFO fuel is expected to have an energy density of 42.5 MJ/kg. Cost calculations are all based off $700/ton (LSMGO) for the fuel. Carbon Capture Media refers to the amine solution required to capture CO_2. This study was based on using the most generic amine (CESAR1) which is an MEA type which has a cost of $1000 to $1500 per ton. Ionada suggests that 6.5 m^3 of CESAR1 be used to operate the carbon capture system with a quarterly refresh to maintain quality. Other Amine solutions have been explored and performance improvements could be achieved using MEA-PZ but the price jumps to $5,000 per ton.

Using the operating demands discussed above, we can predict the cost of running an Onboard CCS plant at a rate of 1 TPH to be as follows. For all the electrical demand from the conditioning, capture medium circulation, and gas liquefaction stages the total is calculated to be at 683.1kW. As for the heat demand for amine regeneration, the saturated steam on board has a pressure of 7 kg/cm^2 and an enthalpy of 2760 kJ/kg. So, to go from water (enthalpy = 697) to steam we need 2065 kJ/kg of energy. To produce 1741 kg/hr of steam at 2065kJ/kg, we will need 3,599,765 kJ/hr which rounds up to roughly 3,600 MJ/hr. The energy inside a kilogram of LSMGO fuel is on average 42.5 MJ/kg. So, we can expect to need an additional 3600 / 42.5 = 88.9 kg/hr of bunker fuel which is currently quoted at about $700/Ton and translates to $62.23 to regenerate amine at a 1 TPH rate and 7,740 MJ/hr or $127.48 to regenerate amine at 2.3 THP.

The *maintenance hours cost* for the CCS system is based on early discussions with the manufacturer and operating experience that break down as follows: Capture module equipment: 5 hours/week; amine regeneration machinery: 5 hours/week; gas liquefaction compressors and liquefaction: 2 hours/week; and piping/storage/controls auxiliaries: 10 hours/year; which projects a small fractional maintenance cost per hour for either 1 or 2.3 TPH systems. Nonetheless, at a cost of $50/hour labor, for an annual demand of 634 hours, we reserve $1 of maintenance hours cost at either capture rate. Membrane replacements and consumables is estimated at a cost of $170,000 per year for the 2.3 TPH system by the supplier. Generalizing the hardware maintenance cost for either scenario results in $13.60 per ton of CO_2. The carbon capture medium (amine) tank has a capacity of 6.5 m^3 and MEA type of amine (e.g. CESAR1) has been quoted between $1,000 to $1,500 per ton. Estimates provided by the supplier predict an annual cost of $62,000 per year for the 2.3 TPH system, which suggests a cost of $5/$CO_2$ ton. Separately, early conversations with potential CO_2 offtake venues placed the cost per ton between $15 and $25.

5.4 BUSINESS CASE

Aggregating all the costs associated with the on-board CCS system projects a cost of at least $153 dollars per ton of CO_2 removed from shipboard emissions with an additional monthly cost of $73,939 to finance the ship's conversion (see Table 8). Dividing the monthly financing cost per the expected amount of CO_2 captured on a yearly basis adds at least $70 per ton. In other words, the all-in cost of capturing CO_2 on board a Veteran Class tanker is approximately $223 per ton of CO_2 at the minimum annual quantity necessary to meet the 45Q tax incentive threshold for industrial facilities. Opportunities to reduce the operating expenses exist in customizing the system to fit within the constraints of the existing exhaust gas boiler and possibly using alternative carbon capture media. Furthermore, a drop in energy cost, such as $300/ton for LSMGO would result in a cost of capture of $83/Ton CO_2 (not including the financing burden). The current 45Q cash subsidy covers capture, transport and sequestration costs. Although 45Q does not appear to fully cover the costs of an amine-based CCS system onboard an MR tanker, more work is needed to bring yearly capture rate thresholds and incentives in line with feasible opportunities. More so, some businesses may see beyond the 45Q cash subsidy and find additional carbon reduction incentives that complete a compelling argument.

Description	Cost
Capital Expenditure (2.3 tph system)	$9,350,000
Cost of Capital	5%
Loan Term	15 years
Monthly Financing Cost	$73,939

Table 8. Project Financing Highlights[25]

It is important to consider that many variables will affect the business case for onboard CCS. One primary example is the size of the storage tanks selected. There is a practical limit to the size of the storage tanks due to size, weight, and capital cost. The storage tank volume assumed in this study is based on a voyage length of 12 days. So a vessel itinerary that sees it visiting a port with CO_2 offloading capability every 12 days will result in optimum utilization of the storage tanks. However, for a vessel with longer voyages as shown in Columns B and C of Table 9 below, the CCS will have to be shut down before the end of the voyage resulting in a reduction in carbon captured over the year and a net increase in cost per ton of CO_2 captured. This is due to the CAPEX, which doesn't change with voyage length, being spread over fewer tons captured. A reduction of 20% of CO_2 captured can result in an extra cost of $20 per ton of CO_2 captured (from approximately $223 per ton to $243 per ton).

Having CO_2 offloading capabilities at the Panama Canal would be necessary to offload the captured CO_2 and meet the 45Q threshold requirements on the Houston to Los Angeles voyage, but the 45Q cash subsidy requires sequestration in the geographical USA to qualify for the subsidy. Therefore, any offloading and sequestration in Panama/Latin America would not qualify for the cash subsidy. In the case of transatlantic voyages, the storage capacity will be filled in less than 13 days at sea. The challenge of surpassing the storage capacity means that we risk not being able to meet the 45Q cash subsidy thresholds. For example, if the ship operates 65% of the time at sea, capturing over 13,000 tons of CO_2 at 2.3tph, but can only offload 50% of its operating emissions because the storage capacity has been filled, it would eliminate 100% of the financial incentives. This demonstrates the importance of having a CO_2 offloading facility at all U.S. ports.

[25] Monthly cost calculated using loan amortization formula M=P×[(r(1+r)^n)/(1+r)^n-1)], where *P* is the size of the loan, *r* is the monthly interest rate, and *n* is the number of payments.

Route	a) Houston to Port of Tampa Bay	b) Houston to Port of Los Angeles	c) Houston to Algeciras, Spain
Distance (nm)	796	5574	4475
Time at Sea (days)[26]	2.4	16.6	13.5
CO_2 captured (2.3tph)	132.5	700*	700*
CCS running cost[27]	$19,342	$102,200	$102,200
CO_2 storage filled	19%	100%	100%

*Limited by storage tank capacity.

Table 9: Onboard CCS operating costs

Cost of energy and cost of capital are significant business case drivers identified in this study. Understanding the sensitivity of these costs on the feasibility of meeting the 45Q tax incentives is further demonstrated by Table 10. Although novel technological developments may enhance amine-based CCS efficiencies, the energy burden of amine regeneration and CO_2 liquefaction processes suggest that to align with the 45Q tax incentives bunker costs must be limited to a $325 price per ton. For example, bunker cost at $500/ton results in a cost of $271/hour plant operation or $118 per ton CO_2 captured, liquified, and offloaded[28]. We also recognize that the capital-intensive cost of retrofitting the ship with onboard CCS functionality will not be supported by the current financial incentives at typical costs of capital. We find that acquisition and installation of the equipment would overshadow the current tax incentives provided by the Inflation Reduction Act.

[26] Operating speed 14 knots

[27] Cost of On-Board CCS operation $153/Ton CO_2

[28] OpEx / 2.3tph column values include the costs from Table 7 normalized per ton of CO_2 captured, liquified, and offloaded.

	Operating Expenses			Capital Investment Costs		
Bunker Cost LSMGO Price/Ton	210grs/kW 909kW kW Cost	42.5MJ/kg 7740MJ/hr MJ Cost	OpEx 2.3tph offloaded Cost/CO_2Ton	CO_2Ton/Year 12,500 Cost/CO_2Ton	interest rate %	Monthly Financing Cost $6,350,000
275	$52	$50	$76	$42	0.25%	-$43,852
300	$57	$55	$80	$51	0.50%	-$53,585
325	$62	$59	$84	$62	0.75%	-$64,406
350	$67	$64	$88	$73	1.00%	-$76,211
375	$72	$68	$92	$85	1.25%	-$88,874
400	$76	$73	$96	$98	1.50%	-$102,262
425	$81	$77	$100	$112	1.75%	-$116,244
450	$86	$82	$105	$125	2.00%	-$130,700
475	$91	$87	$109	$140	2.25%	-$145,527
500	$95	$91	$113	$154	2.50%	-$160,636
525	$100	$96	$117	$169	2.75%	-$175,958
550	$105	$100	$121	$184	3.00%	-$191,436
575	$110	$105	$125	$199	3.25%	-$207,029
600	$115	$109	$129	$214	3.50%	-$222,705
625	$119	$114	$133	$229	3.75%	-$238,441
650	$124	$118	$137	$244	4.00%	-$254,218
675	$129	$123	$141	$259	4.25%	-$270,026
700	$134	$127	$145	$274	4.50%	-$285,854
725	$138	$132	$149	$290	4.75%	-$301,696
750	$143	$137	$153	$305	5.00%	-$317,549
775	$148	$141	$157	$320	5.25%	-$333,408
800	$153	$146	$161	$335	5.50%	-$349,273
825	$157	$150	$165	$350	5.75%	-$365,141
850	$162	$155	$169	$366	6.00%	-$381,011
875	$167	$159	$173	$381	6.25%	-$396,882
900	$172	$164	$177	$396	6.50%	-$412,755
925	$177	$168	$182	$411	6.75%	-$428,628
950	$181	$173	$186	$427	7.00%	-$444,502
975	$186	$178	$190	$442	7.25%	-$460,377
1000	$191	$182	$194	$457	7.50%	-$476,251

Table 10. Bunker and Financing Costs

6 CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the feasibility of retrofitting a Jones Act MR chemical tanker with Hollow Fiber Membrane Contactor (HFMC) technology for carbon capture, focusing on cost-effective integration across conditioning, capture, and storage stages.

The exhaust gas scrubber for conditioning emissions plays a pivotal role by lowering temperatures and enabling the use of heavy fuel oil (HFO), which offers financial benefits despite its higher operational complexity. HFMC technology is highlighted for its compact size and energy efficiency. CO_2 capture involves amine-based technology, which is mature, but requires sufficient heat and space, as well as careful management of impurities like nitrogen oxides to maintain efficiency.

Storing CO_2 in liquid form aboard the vessel is critical to minimizing volume, but the process of compressing and liquefying CO_2 demands significant power and specialized equipment, which poses a logistical challenge in a marine environment. The study notes the limited availability of marine-specific CO_2 liquefaction systems, with few suppliers willing to enter this niche market.

The design of the CCS system is influenced by space limitations, with the capture and liquefaction systems housed in prefabricated deckhouses. The placement of these structures is key to maintaining ship stability, which is further addressed by using two smaller storage tanks instead of one large tank to improve weight distribution and stability.

Energy demand for the CCS system is substantial, and the parasitic load on the ship's auxiliary power systems requires careful consideration, particularly when operating in colder climates or at lower engine loads. The risk of insufficient steam from the economizer also necessitates reliance on the ship's boiler, adding to fuel costs. The integration of CCS must also consider the broader risk management framework, especially in managing the storage and transfer of large volumes of CO_2 at cryogenic temperatures.

In terms of financial considerations, the study explores the applicability of the 45Q tax incentives program, which offers potential cost savings through cash subsidies for captured CO_2. However, achieving the required capture rate to qualify for these credits may not be fully feasible for ships operating under current technological and operational constraints.

The overall conclusion of the study is that while technically feasible, the integration of CCS onboard an MR tanker faces significant engineering, operational, and financial hurdles. The recommendation is for further research into optimizing the energy demand of the system, exploring alternative capture technologies, and engaging industry in developing marine-specific CO_2 compression and storage solutions. Although financial incentives like the 45Q support decarbonization efforts, introducing industry-specific maritime incentives and grants will help accelerate solutions to the technological and financial challenges required for the maritime industry to adopt onboard carbon capture systems as an effective emissions reduction measure. Continued collaboration between government agencies and shipowners will be key to driving these advancements.

Appendix A: Risk Assessment Matrix[29]

	Consequence				Likelyhood				
Severity	People	Assets	Environment	Reputation	A Never happened in Industry	B Similar situation has happened in industry	C Similar occurrence at Company or happens more than once a year in industry	D Similar occurrence at Company more than once a year	E Similar occurrence at Company more than once a year on any Ship
0	No injury nor health effect	No damage	No effect	No impact					
1	Slight injury or health effect	Slight damage	Slight effect	Slight impact					
2	Minor injury or health effect	Minor damage	Minor effect	Minor impact					
3	Major injury or health effect	Moderate damage	Moderate effect	Moderate impact					
4	Permanent injury or fatality	Major damage	Major effect	Major impact					
5	Three or more fatalities	Massive damage	Massive effect	Massive impact					

29 https://entirelysafe.com/ram-risk-assessment-matrix/

Appendix B: MSDS - Monoethanolamine (MEA)[30]

(example for illustration)

parchem
fine & specialty chemicals

Safety Data Sheet
(Monoethanolamine)
DATE PREPARED: 7/24/2015

Section 1. Product and Company Identification

Product Name Monoethanolamine
CAS Number 141-43-5

Parchem - fine & specialty chemicals
415 Huguenot Street
New Rochelle, NY 10801
(914) 654-6800 **(914) 654-6899**
parchem.com **info@parchem.com**

EMERGENCY RESPONSE NUMBER
CHEMTEL
Toll Free US & Canada: 1 (800) 255-3924
All other Origins: 1 (813) 248-0585
Collect Calls Accepted

Section 2. Hazards Identification

Classification of the substance or mixture
GHS Classification in accordance with 29 CFR 1910 (OSHA HCS)
Flammable liquids (Category 4), H227
Acute toxicity, Oral (Category 4), H302
Acute toxicity, Inhalation (Category 4), H332
Acute toxicity, Dermal (Category 4), H312
Skin corrosion (Category 1B), H314
Serious eye damage (Category 1), H318
Specific target organ toxicity - single exposure (Category 3), Respiratory system, H335
Acute aquatic toxicity (Category 2), H401
Chronic aquatic toxicity (Category 3), H412

GHS Label Elements
Pictograms:

Signal word: DANGER

Hazard and precautionary statements
Hazard Statements
H227 Combustible liquid.

[30] https://www.parchem.com/siteimages/attachment/ghs%20monoethanolamine%20msds.pdf

Appendix C: Onboard HAZID List

Appendix C

Onboard HAZID list

Onboard CCS										
Mode 1	MR Product Tanker at sea capturing CO2 at 2.3 tons per hour.									
Scenario #	What if ... ?	Consequences	Safeguards	People	Assets	Environment	Reputation	Likelihood	Risk	Recommendations (Emergency Response Preparedness)
1.01	Gas Conditioning (scrubber) fails	Carbon Capture and Storage system stops operating	System automation. Routine testing of automation and mechanical safeguards. Qualifications and crew training.	0	0	0	1	B		1. Focus on maintenance of process control automation
1.02	Exhaust fan fails (no conditioned gas directed to capture stage)	Carbon Capture and Storage system stops operating	System automation. Routine testing of automation and mechanical safeguards. Qualifications and crew training.	0	0	0	1	B		1. Focus on maintenance of process control automation
1.03	Carbon capture media recirculation pump fails (rich side)	Carbon Capture and Storage system stops operating	System automation. Routine testing of automation and mechanical safeguards. Qualifications and crew training.	0	0	0	1	B		1. Focus on maintenance of process control automation
1.04	Carbon capture media recirculation pump fails (lean side)	Carbon Capture and Storage system stops operating	System automation. Routine testing of automation and mechanical safeguards. Qualifications and crew training.	0	0	0	1	B		1. Focus on maintenance of process control automation
1.05	Reboiler condenser leaks (CO2 gas extraction from amine)	CO2 escapes into environment	Continuously CO2 monitor in space. Routine testing of air sensing safeguards. Qualifications and crew training.	2	0	0	1	B		1. Focus on maintenance of process control automation "confined space entry" process in Operational Procedures. 3. Mark entry points to space with warning signs of potential risk
1.06	Liquified CO2 leakage	CO2 escapes into environment. Cryogenic media on surfaces	Continuously CO2 monitor in space. Routine testing of air sensing safeguards. Shield around joints and connection points. Qualifications and crew training.	3	3	2	1	B		1. Regurlarly verify tightness of flanges and and pipe fttings. 2. Focus on maintenance of process control automation 3. "confined space entry" process in Operational Procedures. 4. Mark entry points to space with warning signs of potential risk
1.07	Loss of power	CCS fans and pumps stop. CO2 compression suddenly stops	Non-Return Valves Emergency ShutDown process	0	0	0	1	B		1. Focus on maintenance of process control automation
1.08	Carbon capture media leaks, Monoethanolamine (MEA)	Monoethanolamine (MEA) leak. MEA is a corrosive. Causes severe skin burns, eye damage upon contact, and vapors can cause respiratory irritation	Amine piping pressure	3	1	1	1	B		1. Consider Amine Leak Detection 2. Add carbon capture media to the handling of hazardous chemicals in Operating Procedures 3. Training and certification process.
1.09	Someone touches the MEA regeneration hardware	Thermal burns from heated equipment	Warning Signage Isolated machinery space	2	0	0	0	B		1. Focus on maintenance 2. Situation awarness training

Appendix C

Onboard HAZID list

Onboard CCS										
Mode 2	Replenishing monoethanolamine (MEA) carbon capture media.									
Scenario #	What If ... ?	Consequences	Safeguards	People	Assets	Environment	Reputation	Likelihood	Risk	Recommendations (Emergency Response Preparedness)
2.01	Monoethanolamine (MEA) carbon capture media hose rupture (High Velocity)	Monoethanolamine (MEA) leak at high velocity. MEA is a corrosive. Causes severe skin burns, eye damage upon contact, and vapors can cause respiratory irritation. Risk of going overboard.	Personal Protection Equipment (PPE) Protective shields	3	0	2	2	B		1. Add carbon capture media to the handling of hazardous chemicals in Operating Procedures 2. Training and certification process for handling chemicals 3. Boom around ship while carbon capture media operations.
2.02	Monoethanolamine (MEA) carbon capture media leaks (Low Velocity)	Monoethanolamine (MEA) leak. MEA is a corrosive. Causes severe skin burns, eye damage upon contact, and vapors can cause respiratory irritation	Personal Protection Equipment (PPE) Protective shields	2	0	2	2	B		1. Add carbon capture media to the handling of hazardous chemicals in Operating Procedures 2. Training and certification process for handling chemicals
2.03	Loss of verbal communication	Carbon Capture Media can overfill or uncontrollably spill. Immediate safety risks from chemical exposure and environmental contamination	Personal Protection Equipment (PPE) Emergency Shut-Off System	2	0	2	2	B		1. Focus on maintenance of Emergency Shut-Off 2. Operational Procedures needed for handling of MEA transfer.
2.04	Loss of power onboard	Level sensing lost in carbon capture media tank, potential to overflow when loading (if unloading it stops flowing)	Personal Protection Equipment (PPE) Emergency Shut-Off System	2	0	2	2	C		1. Regular testing Emergency Shut-Off 2. Fail Safe Design (energized to transfer LCO2) 3. Operational Procedures needed for handling of MEA transfer.
2.05	Sudden change in the weather	scenario 2.01 (ship pulled away from dock)								
2.06	Fire at the terminal / barge	Monoethanolamine (MEA) transfer needs to Shut-Off urgently	Emergency Shut-Off System	1	1	1	1	B		1. Focus on maintenance of Emergency Shut-Off 2. Operational Procedures needed for handling of MEA transfer.
2.07	Monoethanolamine (MEA) comes in contact with another chemical	MEA can react with other chemicals, potentially leading to hazardous conditions including the release of toxic gases or fires.	Store MEA away from incompatible substances as per chemical compatibility guidelines.	3	2	1	2	B		1. Consider not storing MEA onboard 2. Add MEA to the handling of hazardous chemicals in Operating Procedures 3. Training and certification process.

Appendix C

Onboard HAZID list

Onboard CCS										
Mode 3	Offloading Liquid CO_2 stored at 7 bar / -49 °C.									
Scenario #	**What If … ?**	**Consequences**	**Safeguards**	**People**	**Assets**	**Environment**	**Reputation**	**Likelihood**	**Risk**	**Recommendations (Emergency Response Preparedness)**
3.01	Cryogenic leak (sudden)	Sudden release of high-pressure, supercooled CO_2. Cold burns or frostbite to personnel. Rapid expansion of CO_2 creates flying debris or hose whipping.	Certified fit for purpose equipment. Emergency Shutdown Procedure. Pressure-Relief Devices (prevent overpressure) Competent and trained personnel.	3	1	1	1	B		1. Certified qualification for marine personnel. 2. Consider Re-Certification and Testing regime of cryogenic equipment 3. Safety barricade cryogenic transfer equipment when in use. 4. Consider awarness training for marine personnel.
3.02	Cryogenic leak (gradual)	Gradual loss of supercooled CO_2. Cold burns or frostbite to personnel. Unexpected CO_2 accumulation.	Certified fit for purpose equipment. Emergency Shutdown Procedure. Pressure-Relief Devices (prevent overpressure) Competent and trained personnel.	2	1	0	1	B		1. Certified qualification for marine personnel. 2. Consider Re-Certification and Testing regime of cryogenic equipment 3. Safety barricade cryogenic transfer equipment when in use. 4. Consider awarness training for marine personnel.
3.03	Loss of Power on board / Loss of Control Over Transfer Equipment	Uncontrolled flow or stoppage, potential overpressure, or vacuum conditions resulting in hoses or equipment to fail, risking spills or rapid gas expansion	Certified fit for purpose equipment. Emergency Shutdown Procedure. Pressure-Relief Devices (prevent overpressure) Competent and trained personnel.	1	1	1	1	A		1. Certified qualification for marine personnel. 2. Consider Re-Certification and Testing regime of cryogenic equipment 3. Consider awarness training for marine personnel.
3.04	Loss of Power at Terminal	Uncontrolled flow or stoppage, potential overpressure resulting in hoses or equipment to fail, risking spills or rapid gas expansion	Certified fit for purpose equipment. Emergency Shutdown Procedure. Pressure-Relief Devices (prevent overpressure) Competent and trained personnel.	1	1	1	1	A		1. Certified qualification for marine personnel. 2. Consider Re-Certification and Testing regime of cryogenic equipment 3. Consider awarness training for marine personnel.
3.05	Loss of verbal communication	Potential Uncontrolled flow or stoppage	Emergency Shutdown Procedure. Pressure-Relief Devices (prevent overpressure) Competent and trained personnel.	1	1	1	1	B		1. Certified qualification for marine personnel. 2. Consider Re-Certification and Testing regime of cryogenic equipment 3. Consider awarness training for marine personnel.
3.06	Sudden change in the weather	scenario 3.01 (ship pulled away from dock)								

Appendix D: Reference Materials

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Appendix E: Exhaust Gas Scrubber Installation

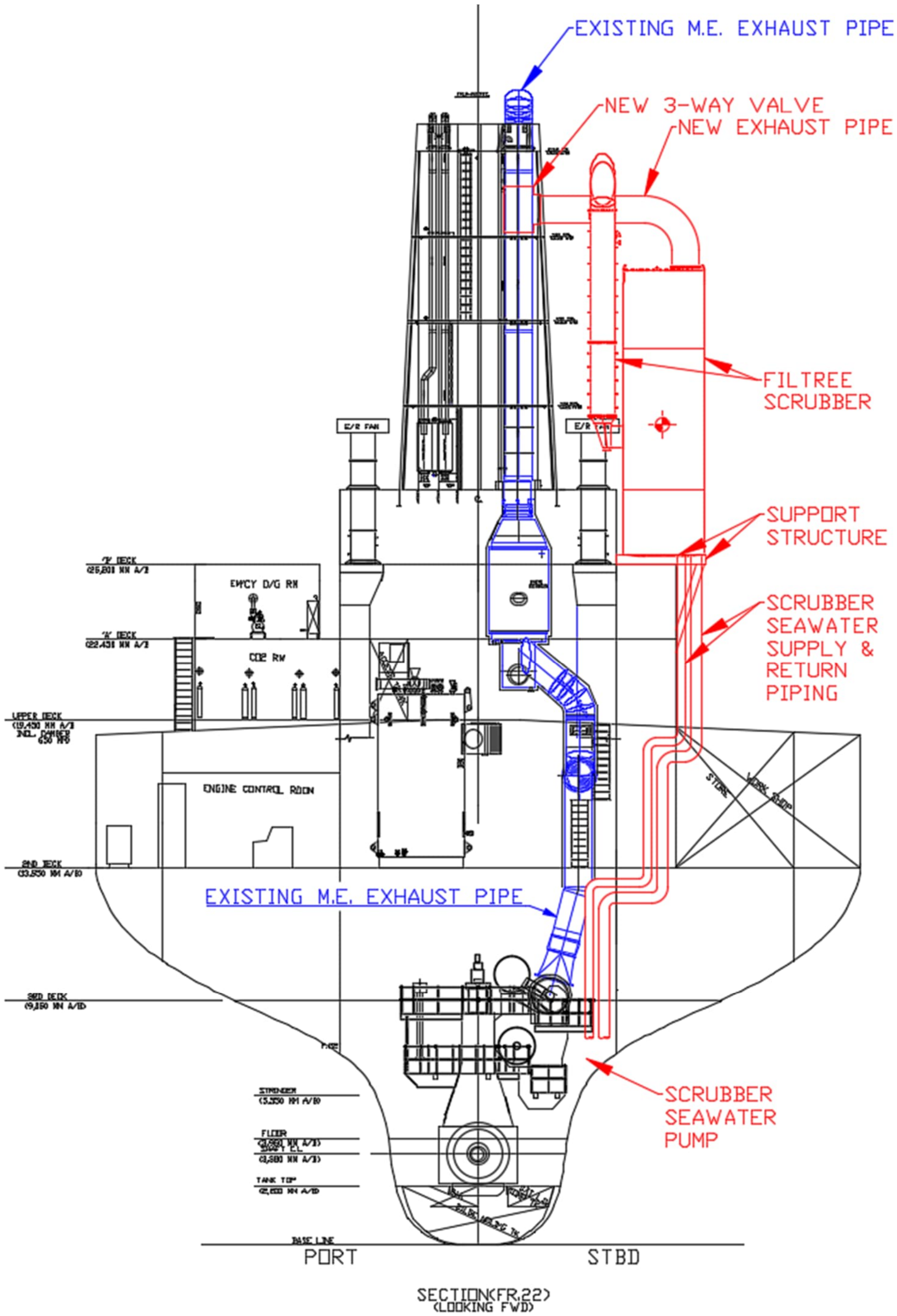

Figure 10: Section View at Scrubber Installation