Ministry of Education and Science of Ukraine
National University "Odesa Maritime Academy"
Educational and Scientific Institute of Engineering
Department of Ship Auxiliary Plants and Refrigeration Equipment

MASTER'S THESIS

on the topic:

ANALYSIS OF THE EFFECT OF OPERATING PARAMETERS ON THE EFFICIENCY OF SHIP'S INERT GAS GENERATION SYSTEMS

Performed by: Cadet Kostiantyn Rudyk

Supervisor: Prof. Olga Khliyeva

Normocontrol ______ Ph.D. Parmenova D.H. ______

The work was heard at the meeting of the Department of Ship Auxiliary Plants and Refrigeration Technology.

Recommended for defense at the EC, Protocol No. __ dated Dec 16 2025.

Head of the Department of SAP&RE,

D.Sc., Professor ______________________ Olga KHLIYEVA

ДОПУЩЕНИЙ ДО ЗАХИСТУ
ЗАВІДУЮЧИЙ КАФЕДРОЮ

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Odesa – 2025

Ministry of Education and Science of Ukraine
National University "Odesa Maritime Academy"
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Department of Ship Auxiliary Plants and Refrigeration Equipment

APPROVED BY
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"10" 09 2025.

ASSIGNMENT
for the completion of the master's thesis

Cadet (student) of ESIE *Kostiantyn Rudyk*

1. Thesis topic: *Analysis of the effect of operating parameters on the efficiency of ship's inert gas generation systems*

Approved by the order of the Rector of NU "OMA" No. 1414 dated 24/11 2025.

2. Object of research: *Ship's inert gas generation systems*

3. Subject of research: *Methods for improving energy efficiency during the operation of shipboard inert gas generation systems*

4. Volume of the explanatory note: *approx. 80 pages of printed text.*

5. Structure of the explanatory note: *Four chapters of the main part: one review, three – calculation and analytical with conclusions and development of recommendations, other elements of the explanatory note - in accordance with the requirements for the master's qualification work.*

6. Content of the main part of the explanatory note (list of issues to be developed): *Description of the prototype vessel and its main engine, basic calculation of the vessel's auxiliary equipment, requirements for shipboard inert gas generators; system configuration and operating principles of two types of shipboard inert gas generators; analysis of the energy performance characteristics of these generators and their environmental performance indicators; assessment of the energy and environmental feasibility of implementing the considered alternative*

7. List of graphic material: *slides designed as a presentation (MS Office Power Point).*

The work must be performed in accordance with the "Methodological Instructions for the Master's Thesis", approved by the Academic Council of ESIE on June 27, 2023, Protocol No. 11.

8. Consultants:

Type of consulting	Consultant (academic title, position, full name)	Signature, date	
		Assignment issued	Assignment received
Reviewing of the English language content	PhD, Tsynova M.V.	23.09.25	15.12.25

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№ з/п	Name of the thesis stage	Supervisor's mark on stage completion (date, signature)
1.	*Problem analysis, review of literary sources*	
2.	*Review and analysis of the system diagram and structure, selection of technical solutions for further analysis*	
3.	*Calculation part*	
4.	*Analysis of obtained results*	
5.	*Energy efficiency*	
6.	*Formatting of the explanatory note, preparation of the work presentation, preparation for the work defense*	
7.		

10. Date of assignment issuance 23/09/25

Deadline for submission of the thesis to the graduating department 15/12/25

Thesis Supervisor ____________ (signature) Prof. Olga Khliyeva (academic title, position, full name)

Thesis Performer ____________ (signature) Kostiantyn Rudyk (full name)

РЕФЕРАТ

Дипломна робота магістра на тему: «Аналіз впливу режимних параметрів на ефективність роботи суднових систем генерації інертних газів»**:** 97 с., 21 рис., 16 табл., 31 джерел, 12 слайдів презентаційного матеріалу.

Актуальність роботи обумовлена зростаючими вимогами міжнародних нормативних документів IMO (SOLAS, FSS Code, ISGOTT, IGC та IBC Codes) щодо вибухопожежної безпеки танкерних суден та необхідністю підвищення енергоефективності допоміжних суднових систем. Виконано аналіз нормативної бази та наукових публікацій щодо застосування систем інертного газу на суднах. Розглянуто конструкцію, принцип дії та експлуатаційні особливості двох систем: генераторів інертного газу на основі продуктів згоряння палива та мембранних азотних установок.

Встановлено, що питома витрата палива генераторів інертного газу на основі згоряння становить 0,07–0,09 кг/Нм^3 при вмісті кисню 2–5 % об. Для мембранних азотних систем питоме електроспоживання складає 0,22–0,28 кВт·год/Нм^3 при чистоті азоту 95–98 % та зростає до 0,35–0,45 кВт·год/Нм^3 при чистоті 99–99,5 %**.** Показано, що підвищення чистоти азоту з 95 % до 99 % призводить до зниження продуктивності мембранних систем на 30–60 % та збільшення навантаження на повітряні компресори.

При вмісті 5 % кисню у інертному газі, мембранна азотна система має переваги як за екологічними, так і за енергетичними показниками порівняно з генератором інертного газу на основі згоряння: питома емісія CO_2 для мембранної системи є меншою приблизно на 30–35 %**,** ніж для combustion-type IGG, а сумарні енерговитрати на генерацію інертного газу є приблизно на 50 % нижчими**,** ніж у генератора на основі згоряння.

СУДНОВА СИСТЕМА ІНЕРТНОГО ГАЗУ, ГЕНЕРАТОР ІНЕРТНОГО ГАЗУ, МЕМБРАННА АЗОТНА УСТАНОВКА, ЕНЕРГОЕФЕКТИВНІСТЬ, ЕЛЕКТРОСПОЖИВАННЯ, ВИБУХОПОЖЕЖНА БЕЗПЕКА, ТАНКЕРНЕ СУДНО.

ABSTRACT

Master's thesis on the topic: "Analysis of the effect of operating parameters on the efficiency of ship's inert gas generation systems": 97 pages, 21 figures, 16 tables, 31 references, 12 presentation slides.

The relevance of the study is determined by the increasing requirements of international IMO regulatory documents (SOLAS, FSS Code, ISGOTT, IGC and IBC Codes) concerning explosion and fire safety of tanker vessels, as well as the need to improve the energy efficiency of auxiliary ship systems. An analysis of the regulatory framework and scientific publications related to the application of inert gas systems on ships has been performed. The design, operating principles, and operational features of two types of systems have been considered: combustion-type inert gas generators and membrane-based nitrogen generation systems.

It has been established that the specific fuel consumption of combustion-type inert gas generators ranges from 0.07 to 0.09 kg/Nm³ at an oxygen content of 2–5% by volume. For membrane nitrogen systems, the specific electrical energy consumption is 0.22–0.28 kWh/Nm³ at a nitrogen purity of 95–98% and increases to 0.35–0.45 kWh/Nm³ at a purity of 99–99.5%. It has been shown that increasing nitrogen purity from 95% to 99% results in a 30–60% reduction in the capacity of membrane systems and a corresponding increase in the load on air compressors.

At an oxygen content of 5% in the inert gas, membrane nitrogen systems demonstrate advantages in both environmental and energy performance compared to combustion-type inert gas generators: the specific CO_2 emissions of membrane systems are approximately 30–35% lower than those of combustion-type IGGs, while the total energy consumption for inert gas generation is approximately 50% lower than that of combustion-based generators.

SHIPBOARD INERT GAS SYSTEM, INERT GAS GENERATOR, MEMBRANE NITROGEN SYSTEM, ENERGY EFFICIENCY, ELECTRICAL POWER CONSUMPTION, EXPLOSION AND FIRE SAFETY, TANKER VESSEL.

CONTENT

NOMENCLATURE

EEDI – Energy Efficiency Design Index

GHG – Greenhouse gases

IG – Inert Gas

IGS – Inert Gas System

IGG – Inert Gas Generator

FSS Code – Fire Safety Systems Code

IGC Code – International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

IBC Code – International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk

ISGOTT – International Safety Guide for Oil Tankers and Terminals

MSC – Maritime Safety Committee

OCIMF – Oil Companies International Marine Forum

LIN – Liquid Nitrogen

NCAF – Net Cost of Averting a Fatality

CATS – Cost of Averting a Ton of oil Spill

AFEM – Automatic Fuel Efficiency Module

SEC – Specific Energy Consumption

SW – Seawater

DG – Diesel Generator

VFD – Variable Frequency Drive

CAPEX – Capital Expenditures

OPEX – Operational Expenditures

dwt – Deadweight tonnage

MCR – Maximum Continuous Rating

CSO – Continuous Service Output

SFC – Specific Fuel Consumption

Nm^3 – Normal cubic meter

LIN – Liquid Nitrogen

IMO – International Maritime Organization;

MARPOL - International Convention for the Prevention of Pollution from Ships;

MEPC – Marine Environment Protection Committee;

NTP - Normal Temperature and Pressure (T=0 °C=273,15 K, p=1 atm≈)

SOLAS - International Convention for the Safety of Life at Sea;

INTRODUCTION

Ensuring explosion and fire safety during the transportation of petroleum products and chemical cargoes is one of the key challenges of the modern maritime industry. Inert Gas Systems (IGS) play a critical role in preventing the formation of explosive atmospheres in cargo tanks by supplying a gaseous medium with a low oxygen content [1]. On tanker vessels, two fundamentally different types of inert gas generators are most commonly used: flue-gas-type inert gas generators (IGG), which utilize exhaust gases from boilers, and dedicated nitrogen-based IGS, in which nitrogen with a reduced oxygen content is produced by membrane separation units.

The growing requirements of the International Maritime Organization (IMO), in particular the provisions of MARPOL Annex VI, the IGC Code, the IGF Code, and the updated IMO Strategy on the reduction of greenhouse gas emissions [2], encourage shipowners to seek energy-efficient solutions across all auxiliary ship systems. Inert gas systems consume significant amounts of fuel and electrical power, and their performance strongly depends on the supply pressure and temperature, inert gas purity, compressor capacity, membrane separation efficiency, heat exchanger characteristics, and the varying operating modes of the main power plant.

For vessels transporting LNG, LPG, or petroleum products with a low flash point, the stability of IGG operating parameters affects not only voyage safety but also operating costs, equipment wear, and compliance with environmental regulations. In practice, significant variations in IGG efficiency are observed depending on external and internal factors such as seawater temperature, diesel generator load, gas filtration efficiency, changes in membrane permeability, and even the condition of the air pretreatment system upstream of the compressor. Such deviations may lead to excessive fuel consumption, membrane degradation, an increase in oxygen content to hazardous levels, or the occurrence of unstable flow regimes in inert gas pipelines.

Despite the widespread application of IGG systems, the issue of a comprehensive analysis of the influence of operating parameters on their energy efficiency remains insufficiently addressed. For most tanker vessels, integrated models capable of assessing the mutual effects of compressor capacity, cooling temperature, supply pressure, degree of inert gas enrichment, and energy consumption for gas generation are lacking. This significantly limits the possibilities for operating mode optimization, improvement of fuel efficiency, and reduction of the load on the ship's electrical power system.

Therefore, the investigation of relationships between the operating parameters of an IGG system and its overall efficiency is a relevant task of practical importance for tanker fleet operators, shipbuilding companies, and marine engineers. The results of this study can be used to develop recommendations for selecting optimal IGG operating modes, increasing system reliability, and reducing operating costs.

Aim of the Master's Thesis

The aim of this master's thesis is to investigate the performance and energy efficiency of shipboard inert gas generation systems under real operating conditions, based on a comparative assessment of combustion-type inert gas generators and membrane-based nitrogen generation systems, and to justify the technically and economically optimal solution for the selected prototype vessel MV NUNAVIK, taking into account regulatory requirements, energy consumption, enviromental impact, and operational constraints.

Objectives of the Master's Thesis

To achieve the stated aim, the following objectives are formulated:

- To perform calculation-based selection of the main engine-room auxiliary systems for the prototype vessel MV NUNAVIK equipped with the MAN B&W 7S70ME-C main engine, in accordance with classification society requirements.

- To systematise international regulatory requirements (SOLAS, FSS Code, ISGOTT, IGC and IBC Codes) governing the design, capacity, gas quality, safety arrangements and operation of shipboard inert gas systems.

- To analyse the structural design, operating principles and functional features of combustion-type inert gas generators and membrane-based nitrogen inert gas systems.

- To assess the energy characteristics of the compared systems, including specific fuel consumption of combustion IGGs and specific electrical energy consumption of nitrogen membrane systems, under nominal and part-load operating modes.

- To conduct a comparative analysis of combustion-based and nitrogen-based inert gas generation systems in terms of energy efficiency, environmental impact, operational flexibility, maintenance requirements.

- To develop engineering recommendations for the rational selection and optimal operating parameters of inert gas generation systems aimed at reducing energy consumption, improving safety margins and ensuring compliance with modern environmental regulations.

TECHNOLOGICAL CARD OF RESEARCH

1. Research Motivation / Practical Need
Growing international requirements aimed at improving ship safety, reducing greenhouse gas emissions, and increasing energy efficiency of auxiliary

2. Object of Research
Shipboard inert gas generation systems (IGS) installed on tanker vessels.

3. Subject of Research
The influence of operating parameters on the energy efficiency and performance of shipboard inert gas generators, including combustion-type IGGs and membrane-based nitrogen generation systems.

4. Research Hypothesis
Optimization of operating parameters of inert gas generation systems (pressure, temperature, capacity, gas purity, and load conditions) leads to a reduction in energy consumption, improved

5. Main Research Objective
To investigate and evaluate the effect of operating parameters on the efficiency of shipboard inert gas generation systems and to justify rational operating modes for improved energy performance.

6. Additional Research Tasks
- analysis of international regulatory requirements governing inert gas systems (SOLAS, FSS Code, ISGOTT, IGC and IGF Codes);
- study of design features and operating principles of combustion-type inert gas generators and membrane nitrogen systems;
- assessment of energy consumption characteristics of inert gas systems under various operating conditions;
- evaluation of the influence of external and internal factors on inert gas system performance;
- development of engineering recommendations for optimizing inert gas system operation.

7. Method for Solving the Main Problem
Analytical and calculation-based assessment of inert gas generation systems combined with comparative analysis of different operating modes and system configurations.

8. Scientific Result
Identified relationships between operating parameters of inert gas generation systems and their overall energy efficiency, enabling rational selection of operating modes.

9. Experimental and Source Data
Manufacturer technical documentation, classification society rules, IMO regulatory documents, and published scientific literature on inert gas generation systems and ship energy efficiency.

10. Scientific Value
The obtained results expand the understanding of energy performance characteristics of shipboard inert gas generation systems and provide a basis for further optimization studies.

11. Practical Value
Implementation of the proposed recommendations can reduce fuel and electrical energy consumption, improve system reliability, and ensure compliance with modern safety and environmental requirements on tanker vessels.

12. Scientific Provisions Submitted for Defence
Improvement of the energy efficiency of shipboard inert gas generation systems is achieved through the rational selection of operating parameters and system configuration, taking into account ship type, cargo characteristics, and operational conditions.

1 REGULATORY FRAMEWORK AND LITERATURE REVIEW ON INERT GAS GENERATION SYSTEM

1.1 Regulatory Requirements for Inert Gas Systems on Board Ships (SOLAS, IMO Guidelines, ISGOTT)

This section summarises the mandatory requirements for shipboard inert gas systems derived from the following key regulatory documents:

- *IMO, "Inert Gas Systems", 1990 (IMO-860E)* – a consolidated collection of the Guidelines for Inert Gas Systems together with extracts of relevant SOLAS regulations and IMO Assembly resolutions [3].

- *SOLAS 1974/2000/2014, Chapter II-2 "Construction – Fire protection, fire detection and fire extinction",* in particular Regulations II-2/4.5.5 and II-2/16.3.3, as well as the associated provisions of the FSS Code, Chapter 15 "Inert Gas Systems" [4, 5].

- *ISGOTT, International Safety Guide for Oil Tankers and Terminals,* 5th edition, especially Section 7/10 "Fixed Inert Gas Systems" [6].

These documents form the unified regulatory basis governing the design, installation and operation of inert gas systems (IGS) on oil, product and chemical tankers.

1.1.1. Scope of Application of Inert Gas Systems under SOLAS

Initial SOLAS requirements for crude oil and product tankers. Originally (1980–1981 amendments), SOLAS required inert gas systems to be installed on:

- all tankers of 100,000 dwt and above, later reduced to

- 20,000 dwt and above, carrying crude oil and petroleum products with low flashpoint.

These provisions are reproduced in the IMO publication *Inert Gas Systems (IMO-860E),* including the full text of the relevant SOLAS regulations and Assembly Resolution A.418(XI), which defines the core functions of an inert gas system (inerting, maintaining a non-flammable condition, preventing air ingress).

2016 SOLAS amendments: 8,000 dwt threshold. Following the analysis of incidents on chemical and product carriers, IMO introduced amendments (MSC.365(93), MSC.367(93), MSC.369(93), MEPC.250(66)), effective 1 January 2016, which:

- require all new oil and chemical tankers ≥ 8,000 dwt,
- that carry cargoes with a flashpoint < 60°C,

to be fitted with an inert gas system complying with FSS Code Chapter 15.

These requirements apply to ships constructed on or after 1 January 2016.

Chemical tankers and gas carriers. For chemical tankers, the relevant framework includes:

- Regulation for Inert Gas Systems on Chemical Tankers (IMO Resolution A.567(14)),
- earlier Interim Regulations for Inert Gas Systems on Chemical Tankers Carrying Petroleum Products (A.473(XII)),
- SOLAS Regulation II-2/55.5, covering the carriage of petroleum products on chemical tankers.

These regulations (all reproduced in IMO-860E) allow the use of inert gas systems on chemical tankers while recognising the sensitivity of certain chemical cargoes to CO_2, moisture and contaminants. They also allow equivalent arrangements (e.g., double block-and-bleed instead of a deck water seal), provided an equivalent level of safety is demonstrated.

For gas carriers, specific SOLAS provisions and the IGC/IBC Codes apply, but the core functional requirements for inerting (maintaining O_2 at safe limits and ensuring positive pressure) remain consistent with the IMO Guidelines for Inert Gas Systems.

1.1.2. Functional and Technical Requirements (SOLAS + FSS Code + IMO Guidelines)

Required functions (Revised Regulation 62 / FSS Code Chapter 15). According to the revised SOLAS Regulation 62 (as reproduced in IMO-860E) and FSS Code Chapter

15, an inert gas system must:

- Inert cargo tanks by reducing oxygen concentration to a level at which combustion cannot occur (O_2 typically not exceeding 8% by volume in the tank atmosphere).

- Maintain an inert atmosphere at all times during normal operations, ensuring that oxygen concentration in any part of the tank does not exceed 8% by volume while maintaining positive pressure at sea and in port.

- Prevent the ingress of air into the cargo tanks during all cargo-handling and ballast operations.

FSS Code Chapter 15 specifies these functions in measurable technical terms (minimum capacity, gas quality requirements, system components).

Gas quality requirements. FSS Code Chapter 15 specifies that the inert gas system must:

- supply inert gas with oxygen content not exceeding 5% by volume in the inert gas main at any required throughput;

- maintain $O_2 \leq 8\%$ by volume in the cargo tanks under all normal conditions;

- maintain positive pressure in all tanks except during gas-freeing.

These requirements apply irrespective of the gas source (flue gas, independent IGG, nitrogen generator).

System capacity and arrangement. FSS Code Chapter 15 and the IMO Guidelines require that the inert gas system must:

- be capable of supplying inert gas at a rate not less than 125% of the maximum rated capacity of the cargo pumps;

- for chemical/product tankers, reduced capacity may be accepted if the maximum discharge rate is limited to 80% of the IGS capacity;

- be arranged with reliable blowers/fans, with minimum capacity distribution requirements if two or more units are installed;

- provide full pressure control capability (automatic closure of the regulating valve, opening of the deck vent to atmosphere in case of overpressure).

Acceptable sources of inert gas. According to IMO Guidelines

(MSC/Circ.353/387, included in IMO-860E) and FSS Code, inert gas may be generated from:

- Boiler flue gases (traditional flue-gas IGS).
- Independent inert gas generators (IGG).
- Gas-turbine systems with suitable afterburners, provided they ensure required gas quality.

Each source must include: scrubber, gas cooler, blower(s), deck seal or equivalent arrangement, pressure/vacuum protection devices, oxygen/pressure/temperature monitoring and control.

Non-return and safety devices (deck seal, non-return valve, block-and-bleed). The "Regulation for Inert Gas Systems on Chemical Tankers" (A.567(14)) requires that:

- at least two independent non-return arrangements be fitted;
- one of these must be a deck water seal, unless an approved double block-and-bleed arrangement is used;
- a mechanical non-return valve must be located between the deck seal (or block-and-bleed) and the first branch to any tank;
- a deck vent valve must be installed to relieve excess pressure between the regulating valve and deck isolating valve.

These devices must prevent backflow of hydrocarbon vapours toward machinery spaces.

1.1.3. Operational and Procedural Requirements (SOLAS + ISGOTT)

Maintaining tanks in an inerted condition. ISGOTT (Section 7/10) states that all ships fitted with inert gas systems should:

- maintain the system in full working order,
- operate it in accordance with ISGOTT procedures,
- keep cargo tanks in an inert condition whenever practicable, except during required gas-freeing.

ISGOTT also describes the recommended procedures for inerting, purging, gas-freeing and tank atmosphere control during all cargo operations.

Procedures in case of inert gas system failure. ISGOTT and SOLAS require that each vessel have an Inert Gas System Operating Manual containing detailed failure procedures. In the event that the system cannot:

- supply gas of the required quality ($O_2 \leq 5\%$),
- or maintain positive pressure,

then:

- all cargo/ballast operations that may cause air ingress must stop immediately,
- the deck isolating valve must be closed,
- the deck vent valve opens to relieve pressure,
- operations may resume only after the system is restored or the tanks are placed in a safe gas-free condition.

Documentation, training, and survey requirements. SOLAS and FSS Code require that ships fitted with IGS carry:

- a comprehensive operating and maintenance manual,
- a failure procedure,
- detailed instructions for safety and emergency actions.

During statutory surveys (HSSC), inert gas systems are subject to:

- testing of alarms (high/low pressure, O_2 content),
- verification of the accuracy of oxygen analysers,
- inspection of non-return arrangements,
- testing of valves and pipeline tightness.

ISGOTT and associated tanker safety guides require pre-operation checks confirming that the system is supplying inert gas with $O_2 \leq 5\%$, all valves are correctly set, and all alarms and interlocks are functional.

1.1.4. Application to Product and Chemical Tankers (ISGOTT + SOLAS)

When product/chemical tankers must be fitted with IGS. ISGOTT sections “Product Carriers Required to be Fitted with an Inert Gas System” and “Combination Carriers” state that:

- the principles of inerting for product carriers follow the same principles as for crude oil tankers;

- the requirement for IGS is tied to the carriage of cargoes with flashpoint < 60°C;
- such cargoes must remain in an inert condition throughout the voyage.

These recommendations are consistent with SOLAS II-2/4.5.5 and II-2/16.3.3, which mandate IGS on new oil and chemical tankers ≥ 8,000 dwt carrying low-flashpoint cargoes.

Chemical tankers and the carriage of petroleum products. OCIMF guidance clarifies that for chemical tankers carrying petroleum products, the relevant requirements come from:

- SOLAS II-2/55.5,
- Resolution A.567(14) for inert gas systems on chemical tankers.

For most modern chemical tankers these requirements are met using nitrogen inerting systems, but regardless of the source (flue gas, IGG, nitrogen generator), the functional SOLAS/FSS requirements remain identical:

- O_2 in the inert gas main ≤ 5%,
- O_2 in tanks ≤ 8%,
- positive pressure maintained,
- compliant non-return arrangements,
- adequate capacity and alarm systems.

1.1.5. Overal conclusions

Based on the analysis of SOLAS (II-2/4.5.5, II-2/16.3.3), IMO "Inert Gas Systems" (1990, IMO-860E) and ISGOTT (5th edition), the following key points can be formulated:

1. The installation of inert gas systems is a mandatory SOLAS requirement, depending on ship type, cargo flashpoint, deadweight and date of construction. Since 2016, nearly all new oil and chemical tankers of ≥ 8,000 dwt carrying cargoes with flashpoint < 60°C must be equipped with an IGS.

2. Functional requirements (inerting, maintaining oxygen ≤ 8% with positive pressure, preventing ingress of air) are defined in the revised SOLAS Regulation 62 and detailed in FSS Code Chapter 15, incorporated into IMO-860E.

3. Technical parameters — gas source, minimum capacity (≥125% of cargo pump capacity), maximum O_2 content (≤5% in the inert gas main), construction, non-return devices, pressure control, alarms — are prescribed through SOLAS, the FSS Code and the IMO Guidelines for Inert Gas Systems.

1.2 Review of the Published Literature on the Performance of Marine Inert Gas Generation Systems

In their multi-criteria analysis [7], the authors evaluate five inert gas generation options for ensuring the safe maritime transportation of Direct Reduced Iron. Considering installation cost, safety level, operating and maintenance costs, and time losses, the authors conclude that the most suitable option is inert gas or nitrogen supplied from external (port) facilities.

The rationale is the following [7]:

External nitrogen/inert gas supply (port facility system) ranks first overall because it avoids onboard installation, reduces maintenance efforts, and minimizes delays during cargo operations.

Although fixed nitrogen tube systems and onboard nitrogen generators show good safety performance, they are less favorable economically when the ship does not routinely carry dangerous cargo requiring inerting.

Independent IGG units and boiler uptake gas systems receive the lowest ranking due to high installation and operating costs, limited practicality on dry bulk ships, and insufficient economic justification for vessels that carry Direct Reduced Iron only occasionally.

Study [8] shows that different inert gas concepts are optimal for different ship types and operating conditions. Based on a technical and economic comparison of flue-gas inert gas systems, independent inert gas generators and membrane nitrogen generators, the authors conclude that a nitrogen generator has lower installation and maintenance costs than an inert gas generator, does not require additional fuel (only electrical power for compression), and provides higher-quality, cleaner inert gas, which is particularly important for chemical tankers and “sensitive” cargoes. At the same time, a flue-gas inert gas system remains the most efficient in terms of fuel, space and electrical consumption and is considered justified on large oil tankers that already have powerful steam boilers in operation (e.g. for steam cargo pumps) and do not require high-purity gas. In such cases, retrofitting an additional generator is not economically attractive. Conversely, on ships without a large steam boiler plant, or on chemical tankers, the practical choice lies between an inert gas generator and a nitrogen generator, and the authors emphasise that nitrogen systems are often preferable due to better gas quality, easier automation and favourable life-cycle costs despite their lower capacity.

In their comparative study Adrián and González [9] conclude that, for the type of product/asphalt tanker they analyse, an on-board nitrogen generation plant based on non-cryogenic membranes is clearly more advantageous than a conventional flue-gas inert gas plant. The N_2 system provides faster inerting (the conventional IGS would need about 88 % more time for the same vessel), lower annual fuel consumption and markedly lower emissions, while also avoiding typical drawbacks of boiler-flue systems such as tank corrosion, higher complexity and maintenance effort. Overall, they judge that membrane-type N_2 plants offer higher efficiency, simpler installation and operation, and better safety/environmental performance, so they are the preferred option for modern tankers carrying refined products—although the final choice of inert gas system should still consider cargo type, ship size and power-plant configuration.

In the paper [10], Aftaniuk et al. conclude that for modern chemical tankers only nitrogen-based inert gas systems are practically suitable, in line with SOLAS requirements, whereas conventional oil-fired flue-gas IGS are generally inappropriate for chemical cargoes because of CO_2, moisture and other impurities that can damage or contaminate the product. They compare high-pressure nitrogen cylinders, liquid-nitrogen (LIN) storage and on-board nitrogen generators, noting that LIN tanks supply very clean, dry nitrogen but suffer from significant boil-off losses during long sea passages, which forces operators to vent excess high-quality nitrogen to the atmosphere. Therefore, the authors consider nitrogen systems (LIN tanks and generators) to be the expedient solution for chemical tankers, while stressing that optimizing the design and thermal insulation of LIN tanks is essential to reduce operational nitrogen losses.

In [11] Thomas and Skjong show, within a Formal Safety Assessment framework, that installing inert gas systems on small tankers clearly pays off in risk reduction versus cost. For 8,000–20,000 dwt chemical tankers they conclude that nitrogen inert gas systems (N_2 IGS) are cost-effective: both the Net Cost of Averting a Fatality (NCAF) and the Cost of Averting a Ton of oil Spill (CATS) fall within acceptable ranges, so fitting N_2 IGS on newbuilds in this size range is recommended. For 8,000–20,000 dwt oil/product tankers they find that conventional oil-fired IGS is likewise cost-effective (favourable GCAF, NCAF and CATS), and therefore also recommend making IGS mandatory for newbuilds in this segment, as it can reduce cargo-tank fire/explosion risk by about 90+% compared with similar ships without IGS.

In [12] Matieiko analyses three nitrogen-based inerting schemes for LNG/gas carriers – cascade, parallel and semi-cascade – using two key criteria: nitrogen consumption and duration of the inerting process for ships with cargo capacities from about 38,600 to 62,000 m^3. The main conclusions are:

Cascade inerting is the most economical in terms of nitrogen consumption: it is taken as the reference (relative consumption = 1.0).

Parallel and semi-cascade schemes require substantially more nitrogen – by about 1.74–2.42 times and 1.28–1.83 times, respectively, depending on ship cargo capacity.

However, the cascade scheme is the slowest: its relative duration is taken as 1.0, whereas the semi-cascade scheme shortens inerting time to about 0.43–0.64, and the parallel scheme to about 0.58–0.75 of the cascade duration.

Thus, the author concludes that there is no single universally “best” inerting scheme: the cascade scheme is optimal when minimizing nitrogen consumption (and therefore operating costs) is the priority and a longer inerting time is acceptable; the semi-cascade and parallel schemes are preferable when the main requirement is to reduce the time spent on inerting and port stay, at the expense of higher nitrogen usage.

The final choice of an inerting scheme should therefore be based on voyage assignment, port environmental and safety requirements, characteristics of the ship's nitrogen generation system, and the possibility of using shore-supplied inert gas.

General Conclusion Based on the Literature Review

The analysed body of research clearly demonstrates that the optimal choice of an inert gas system for a given vessel is not universal but depends on a combination of technical, operational, economic, and regulatory factors. For dry bulk carriers that transport dangerous cargoes such as Direct Reduced Iron only occasionally, the most rational solution is to use inert gas or nitrogen supplied directly from shore-based facilities. This option minimizes capital expenditure, eliminates the need to install and maintain specialised onboard equipment, and reduces additional operational risks associated with systems unfamiliar to bulk carrier crews.

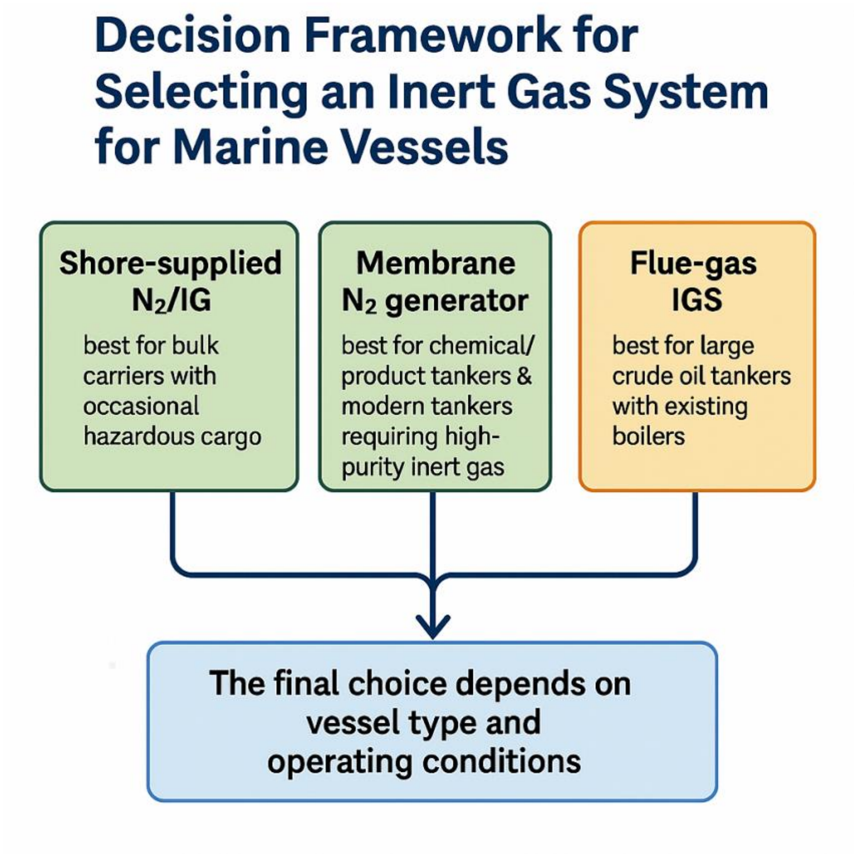

Fig. 1.1 The final choice of Inert Gas System depends on vessel type and operating conditions

For tanker fleets the picture is more complex. Comparative studies show that membrane-type nitrogen generators provide significantly higher inert gas purity, better controllability, and lower lifecycle operating costs—features that are particularly important for chemical tankers and vessels carrying sensitive or high-value products. Conversely, for large crude or product tankers already equipped with powerful steam boilers, conventional flue-gas inert gas systems remain economically justified due to their low specific fuel consumption and minimal additional investment requirements. In such cases, installing a nitrogen generator offers limited benefits relative to its cost.

For LNG and LPG carriers, the choice of nitrogen inerting scheme (cascade, parallel, or semi-cascade) depends on whether the priority is to minimise nitrogen consumption or to reduce total inerting time and port stay. No single approach is universally best: the cascade scheme is most economical in nitrogen usage, whereas the semi-cascade and parallel schemes significantly shorten inerting duration at the cost of higher consumption.

Overall, the literature shows a clear modern trend: nitrogen-based systems—especially membrane generators—are increasingly becoming the preferred solution for chemical tankers, product tankers, and gas carriers, owing to their high gas purity, operational flexibility, and favourable long-term economics. Traditional flue-gas systems remain appropriate mainly for large crude carriers whose existing machinery makes their operation cost-effective. Thus, the choice of an inert gas system must be based on the vessel's type, cargo characteristics, onboard energy systems, cargo quality requirements, and operational priorities such as safety, speed of inerting, and cost minimisation.

1.3 Energy Characteristics and Advantages and Disadvantages of Comparative Inert Gas Generation Systems

1.3.1 Combustion-type IGG

A comprehensive search confirms that no full "specific fuel consumption vs. inert gas flow" curve for Alfa Laval Smit Combustion inert gas generators (IGGs) exists in open access; manufacturers do not publish detailed SFC–flow characteristics publicly [13–15].

In [13] for a Smit Gas Systems inert gas generator provides the following nominal operating point: capacity 2000 m^3/h at 0.15 bar and fuel consumption of approximately 162 kg/h [13]. The corresponding specific fuel consumption is:

SFC = 162 / 2000 = 0.081 $kg/Nm^3 \approx 81$ kg / 1000 Nm^3.

Open technical sheets for other combustion-type IGGs support a similar SFC range. For example, a Wärtsilä Moss inert gas generator has a nominal specific fuel consumption of approximately 0.075 kg/Nm^3 [14], while Maritime Protection IGGs typically fall in the range 0.07–0.09 kg/Nm^3 [15]. The value of 0.081 kg/Nm^3 therefore lies well within the common range of 0.07–0.09 kg/Nm^3 for modern combustion-type IGGs.

Due to the absence of detailed SFC–flow curves for Smit Combustion IGGs, engineering models usually adopt a simplified representation based on nominal values and qualitative trends [13–15]. A typical approach assumes:

1) nominal SFC at design flow of 0.075–0.080 kg/Nm^3;

2) increased SFC at low flows due to manual control inefficiencies, fixed firing rates and excess inert gas venting;

3) an AFEM-corrected SFC curve obtained by multiplying the manual-mode fuel consumption by a factor of 0.60–0.70 to represent the documented 30–40 % reduction in fuel use when the Automatic Fuel Efficiency Module is installed.

1.3.2 Membrane Nitrogen System

For marine membrane-type inert gas systems (nitrogen generators), manufacturers likewise do not publish complete “specific energy consumption vs. nitrogen flow” curves [16–20]. Detailed performance maps are typically restricted to vessel-specific technical documentation. Most publicly available data describe only nominal nitrogen purity, generator capacity range, compressor power demand and specific energy consumption (SEC) at one or several operating points [16–19].

Open datasheets for marine membrane nitrogen generators provide relatively consistent nominal SEC values. For small and medium-capacity systems at 95–98 % nitrogen purity, typical SEC values lie in the range 0.22–0.28 kWh/Nm³ [16–19]. For high-purity nitrogen in the range 99–99.5 %, SEC usually increases to approximately 0.35–0.45 kWh/Nm³ [16–19]. These values are representative of systems offered by Parker Hannifin, Wilhelmsen Maritime Services and N2 Generators AS.

Membrane separation performance depends strongly on feed-air conditions and required nitrogen purity [16–20]. The key parameters are feed-air temperature, feed-air pressure (typically 7–13 bar), feed-air dew point and target purity level. Increasing N_2 purity from 95 % to 99 % at constant compressor power can reduce the nitrogen flow output by 30–60 %, which effectively increases SEC. Likewise, membrane permeability decreases at lower temperatures, while a moderate increase of feed-air temperature by 10–15 °C may raise nitrogen output by roughly 5–12 % [16–19].

When modelling nitrogen membrane IG systems for marine applications, the following assumptions are commonly adopted based on open-source information [16–20]:

1) nominal SEC of 0.22–0.28 kWh/Nm³ for 95–98 % N_2 purity and 0.35–0.45 kWh/Nm³ for 99–99.5 % N_2 purity;

2) compressor efficiency dominates total energy use, with up to 80–90 % of power consumed by the feed-air compressor;

3) SEC grows at partial load because reduced feed-air flow lowers membrane recovery efficiency;

4) temperature control is important, since membrane permeability decreases at low temperatures;

5) there is an optimal feed-pressure window (typically 11–12 bar(g)), as nitrogen yield increases with pressure, while compressor power rises more steeply with speed.

Table 1.1 Comparative of Combustion IGG vs Membrane Nitrogen Systems

Aspect	Combustion-type IGG	Membrane Nitrogen System
Produced gas / suitability	**Advantages (Pros):** - Adequate IG quality (O_2 2–5%) for oil/product tankers. **Disadvantages (Cons):** Contains CO_2, SOx, NOx, moisture; not suitable for sensitive cargoes.	**Advantages (Pros):** - High-purity, dry N_2 (95–99.5%). **Disadvantages (Cons):** Reduced flow at high purity; ultra-high purity may require additional steps.
Energy source	**Pros:** Uses liquid fuel; independent from electrical load. **Cons:** Requires continuous fuel burning + power for pumps/fans.	**Pros:** No flame or fuel; electrically driven only. **Cons:** High compressor power demand; may overload generator capacity.
Part-load behavior	**Pros:** AFEM reduces fuel waste by 30–40% at partial loads. **Cons:** Without AFEM: severe overproduction at low cargo rates.	**Pros:** Good turndown with VFD compressors and modular membranes. **Cons:** SEC increases at low loads and at high purity requirements.
Startup & response	**Pros:** Standardized and well-understood procedures. **Cons:** Requires ignition, flame stabilization, warm-up.	**Pros:** Fast cold start via compressor. **Cons:** High start currents; compressor wear from frequent cycling.
Safety	**Pros:** Mature SOLAS-based safety framework; long operational history. **Cons:** Open flame and fuel systems increase fire/explosion risk.	**Pros:** No combustion; lower fire and explosion risk. **Cons:** High-pressure air hazards; membrane failure if air quality is poor.
Cooling water	**Pros:** Utilizes existing seawater networks. **Cons:** High SW demand; scrubber scaling and corrosion.	**Pros:** Minimal seawater use. - Compressor cooling (air/water) required, especially in warm climates.

Table 1.1 (continued)

Maintenance	**Pros:** Global service experience; robust design. **Cons:** Burner/scrubber/seal require heavy maintenance; corrosion risk.	**Pros:** No burner or scrubber; simpler maintenance regime. - Membranes sensitive to oil/particles; periodic replacement required.
Environmental impact	**Pros:** Predictable emission profile; well-integrated operational rules. **Cons:** Additional CO_2, NOx, SOx from fuel combustion.	**Pros:** No direct combustion emissions; only electrical load. **Cons:** Indirect CO_2 footprint depends on DG efficiency; SEC rises at high purity.
Space & weight	**Pros:** Integrated into boiler systems on newbuilds. **Cons:** Large/heavy scrubber, deck seal and pumps.	**Pros:** Compact membrane racks; good for retrofits. **Cons:** Compressors and air-treatment skids may require significant space.
Capital Expenditures / Operational Expenditures (CAPEX / OPEX)	**Pros:** Lower CAPEX for large tankers with boilers. **Cons:** High fuel OPEX; manual mode inefficient.	**Pros:** Lower OPEX where electricity is inexpensive; no fuel cost. **Cons:** Higher CAPEX for high N_2 flows; membrane replacement cost.

2. CALCULATION AND SELECTION OF ENGINE-ROOM AUXILIARY SYSTEMS FOR MV NUNAVIK

All calculations presented in this section were performed in accordance with the Rules for the Classification and Construction of Seagoing Ships of the Ukrainian Register of Shipping [21].

The input data for the calculations are adopted based on the information for the prototype vessel NUNAVIK and the main engine MAN B&W 7S70ME-C, as presented in Sections 2.1 and 2.2.

2.1 Description of the Prototype MV NUNAVIK

Table 2.1 Ship NUNAVIK Particulars

SHIP NAME:	**NUNAVIK**
OWNERS:	FEDERAL HUDSON LTD. Suite 3500, 1000 De La Gauchetiere West, Montreal, Quebec, Canada, H3B 4W5
COMMERCIAL OPERATORS:	FEDNAV INTERNATIONAL LTD. Suite 3500, 1000 De La Gauchetiere West, Montreal, Quebec, Canada, H3B 4W5
MANAGEMENT CO.:	ANGLO EASTERN SHIP MANAGEMENT LTD. 1868 Des Sources Boulevard, Suite 504, Pointe-Claire, Quebec, H9R 5R2, Canada
NATIONALITY:	Marshall Islands
PORT OF REGISTRY:	MAJURO
CALL SIGN;	V7CK9
OFFICIAL NO.:	5278
IMO / MMSI / SAT C NO.:	9673850 / 538005278 / 453838818
INMARSAT “F” TEL: Speech/Voice FAX:	FBB500 TEL: (870) 773701500 FAX: 870783823108
VSAT / MOBILE	+1 (613) 7015038, Cell: +358 466844485 (in ports only)

Continuation of Table 2.1

EMAIL:	master.nunavik@aesmvsl.com
SAT-C EMAIL:	453838818@c12.stratosmobile.net
BUILT:	(2014) Japan Marine United Corporation, Tsu, Japan
CLASS:	DNV IA1 ICE-15 PC4 BULK CARRIER ESP BC-A ECO DAT(-30C) DK(+) HA(+) IB-3 Holds (2,4 or 3) may be empty inert TMON Nauticus (Newbuilding) COAT-PSPC(B)
TYPE OF SHIP:	Double Hull Construction I.B. Bulk Carrier
ICE STRENGTHENING:	DNV ICE CLASS (IA1-15) PC4
LBP:	178.000 m / 583.990 ft
LOA:	188.800 m / 619.423 ft
BREADTH (MOULDED):	26.600 m / 87.270 ft
DEPTH (MOULDED):	15.700 m / 51.509 ft
LIGHTSHIP DISPLACEMENT:	13,058.0 MT / 12,848.1 LT
FREEBOARD CONSTANT:	15.754 m / 51.686 ft
SUMMER FREEBOARD:	4.003 m / 13.133 ft
SUMMER LOAD DRAFT (Extreme):	11.751 m / 38.553 ft
DISPLACEMENT @ SUMMER LOAD DRAFT (SW):	44,812.0 MT / 44,091.8 LT
DWT (SUMMER):	31,754.0 MT / 31,243.7 LT
TPC:	44.850 MT / 44.129 LT
FWA:	250.0 mm / 9.843 in
WINTER LOAD DRAFT (SW)	11.507 m / 37.753 ft
DISPLACEMENT @ WINTER LOAD DRAFT (SW)	43,722.0 MT / 43,019.3 LT
DWT (WINTER)	30,664.0 MT / 30,171.2 LT

Continuation of Table 2.1

TPC (WINTER)	44.510 MT / 43.795 LT
GRT / NRT	22,622.0 / 8,841.0
MAIN ENGINE: TYPE	Hitachi Zosen – MAN B&W 7S70ME-C
OUTPUT:	29,540 BHP (21,770 kW) @ 91 RPM
M.E. CONSUMPTION @ CSO (11.50m Draft with 15% Set Margin):	34.9 MT/day (IFO)
PROPELLER TYPE / SIZE:	Controllable pitch, 4 blades, left hand screw Fixed nozzle (Type NSMB37) /Diameter: 6.5 m (21.33 ft)
RUDDER:	Balanced, streamlined double plate type
SPD (MCO @ 11.5m draft with 15% Sea Margine):	18.10 kts
SPD (CSO @ 11.5m draft with 15% Sea Margine):	13.50 kts
BUNKER CAPACITY: IFO/DO:	2015.5 cu.m @96% / 80.9 cu.m @96%
BALLAST CAPACITY:	25915.4 cu.m @100% 26563.3 MT (SW)
DOMESTIC FW CAPACITY / PRODUCTION:	152.7 MT / 20 MT/day @ peak
HEIGHT OF KEEL TO MAST HEAD:	45.260 m / 148.491 ft
DISTANCE BRIDGE FRONT TO BOW:	149.550 m / 490.650 ft
DISTANCE BRIDGE FRONT TO STERN:	39.250 m / 128.773 ft
DISTANCE BCM:	97.500 m / 319.882 ft
DISTANCE DCM:	2.000 m / 6.562 ft

2.2 General technical data for MAN B&W 7S70ME-C low-speed marine diesel engine

The MAN B&W 7S70ME-C is a low-speed, two-stroke, crosshead marine diesel engine manufactured by Hitachi Zosen Corporation (Japan) under MAN B&W licence. It is used as the main propulsion engine for large merchant vessels such as oil tankers, bulk carriers, and LNG carriers.

Table 2.2 Main Characteristics, Geometric Parameters, Power Rating and Operating Conditions of MAN B&W 7S70ME-C

Parameter	Value
Full engine designation	HITACHI ZOSEN – MAN B&W 7S70ME-C
Manufacturer	Hitachi Zosen Corporation (Japan), MAN B&W licensee
Application	Main propulsion engine for large commercial vessels
Engine type	Two-stroke, low-speed, crosshead, electronically controlled (ME-C)
Scavenging system	Uniflow scavenging with exhaust valve; turbocharging at constant pressure
Number of cylinders	7 (in-line)
Stroke class	Super Long-Stroke “S”
Parameter	Value
Cylinder bore	700 mm
Piston stroke	2800 mm
Stroke–bore ratio	≈ 4.0
Swept volume per cylinder	≈ 1.08 m^3
Total swept volume	≈ 7.54 m^3
Parameter	Value

Continuation of Table 2.2

Nominal speed (MCR)	≈ 91 rpm (operational range ~77–91 rpm)
Nominal power (MCR)	≈ 21.7 MW (≈ 21,770 kW)
Specific fuel oil consumption	≈ 160–170 g/kWh at MCR
Fuel type	HFO in compliance with MARPOL Annex VI; LSFO when required

2.3 Hourly Fuel Consumption of the Main Engine MAN B&W 7S70ME-C

$Q_e = g_e \cdot \Sigma N_e$

$Q_e = 0.165 \cdot 21700 = 3580$ kg/h

where g_e – specific effective fuel consumption, kg/(kW·h);

ΣN_e – total effective power of the main engines, kW.

The amount of heat released during fuel combustion:

$q = Q_e \cdot Q_н$

$q = 3580 \cdot 41000 = 146780000$ kJ/kg,

where $Q_н$ is lower heating value of the fuel, kJ/kg.

For the fuel used by the MAN B&W 7S70ME-C engine, the lower heating value is taken as $Q_н = 41000$ *kJ/kg*.

2.4 Machinery and Equipment Serving the Main Engine MAN B&W 7S70ME-C

Flow velocities of working fluids in the ship systems of MV NUNAVIK required for pipeline diameter calculations:

– fuel in the transfer system – 1.6 m/s,

– fuel in the supply (booster) system – 1.3 m/s,

– lubricating oil in the circulation system – 2.6 m/s,

– cooling water in the cooling systems – 2.7 m/s,

– water in the sanitary systems – 3.2 m/s.

2.4.1 Fuel system

Designed for receiving, storing, pumping, cleaning, heating, and supplying fuel to main and auxiliary engines and boilers, as well as for pumping it ashore or to another vessel.

The MAN B&W 7S70ME-C diesel engine is designed to operate on heavy fuel grades, for which the ship's power plants are equipped with a special fuel preparation system. The system includes heavy fuel and diesel fuel separators, steam heaters equipped with thermostats, heavy fuel and diesel fuel storage and consumption tanks, and coarse and fine filters. Each separator has two paired fuel pumps (for injection and pumping). The tanks of the prototype vessel MV NUNAVIK are equipped with a steam heating system. The fuel is pumped to the settling tank, where, after settling for 20 to 24 hours, it is pumped to the heater, then to the separators, and then to the consumption tank. From the consumption tank, the fuel is fed by fuel transfer pumps through the heater to the main engine MAN B&W 7S70ME-C. The fuel system also includes pumps for transferring fuel from one tank to another.

Fuel tanks. The capacity of each of the two settling tanks and two heavy fuel service tanks $V_{вт}$ is selected based on the calculation of ensuring the operation of the main engine MAN B&W 7S70ME-C over time $\tau_1 = 24$ hours.

$$V_{вт} = (Q_e \cdot \tau_1)/\rho_m$$

$$V_{вт} = (3580 \cdot 24)/\,960 = 89{,}5\ м^3,$$

where ρ_m is fuel density, kg/ m^3.

For heavy fuel assumed ρ_m = 960 kg/ m^3.

The volume of each of the two diesel fuel storage tanks is assumed to be equal to 80% of the volume of the two heavy fuel tanks, i.e., 71,6м^3.

The supply of simultaneously operating fuel separators is calculated based on the condition of separating the daily fuel consumption for $\tau_{с.п.}$ from 8 to 12 hours.

$$Q_c = V_{вт}/\tau_{с.п.}$$

$$Q_c = 89{,}5/12 = 7{,}46\ м^3/год$$

where $\tau_{с.п.}$ assumed as 12 hours.

Purifiers. We install two heavy fuel purifiers and one diesel fuel purifier. The diesel fuel purifier is accepted as the same for standardization. We select separators based on supply [22].

The fuel transfer pump must ensure that fuel is pumped out of the larger main storage tank $V_з$ for the time $\tau_{відк}$ = 4 hours. At the same time, it must ensure the transfer of at least the daily fuel consumption by the main engines for the time τ_2 = 6 hours.

For the selected prototype vessel, the storage tank has a volume of $V_з = 500$ m^3.

$Q_{нп} \geq V_з / \tau_{відк}$

$Q_{нп} \geq 500/4 = 125{,}0$ m^3/hour,

$Q_{нп} \geq V_{вт} / \tau_2$.

$Q_{нп} \geq 89{,}5/6 \geq 14.9$ m^3/hour,

where $Q_{нп}$ is fuel transfer pump supply, m^3/hour.

Pressure delivered by the pump $H_{пн}$ equals 0.4 MPa.

The power consumption of the fuel transfer pump drive motor is determined by the formula:

$$P = \frac{Q \cdot p}{3{,}6 \cdot \eta}, \text{ kW}$$

where Q is pump supply, m^3/hour;

p is pump delivery pressure, MPa;

η is pump efficiency.

For screw pump η from 0.75 to 0.85. We assume $\eta = 0{,}8$.

$P=(125{,}0 \cdot 0{,}4)/(3{,}6 \cdot 0{,}8)=17{,}4$ kW.

There should be two fuel transfer pumps with independent drives, one of which is a backup.

The diesel fuel transfer pump is the same as the heavy fuel pump.

The fuel transfer pump flow rate is calculated using the following formula:

$Q_{пн} = (K_{пн} \cdot Q_e)/\rho_m$

$Q_{пн} = (3 \cdot 3580)/960 = 11{,}2$ m^3/hour

where $K_{пн}$ can be taken in the range from 2 to 5. We adopt $K_{пн}$ = 3.

$p_{пн}$ is the pressure developed by the pump for the MAN B&W 7S70ME-C engines is taken in the range from 0.25 to 0.50 MPa. we adopt p_{pn} = 0.30 MPa.

The power consumption of the drive motor of the fuel booster pump is determined by the formul:

$$P= (11,2 \cdot 0,30)/(3,6 \cdot 0,8)= 1,165\ kW .$$

for the drive motor of the fuel booster pump, we assume $\eta = 0,8$.

Heavy fuel heaters provide heating to the required viscosity. Steam shell-and-tube heaters are used.

Heat amount q_m, which is supplied to the fuel to reach the temperature at which the fuel will have the required viscosity:

$$q_m= Q_{пн} \cdot \rho_m \cdot c_n \cdot (T_2 - T_1)$$

$q_m =11,2 \cdot 960 \cdot 1,8 \cdot (353 -310) = 832205$ kJ/hour,

where c_n is specific heat capacity of fuel, from 1.68 to 2.1 kJ/(kg·K);

T_1 is initial fuel temperature (approximately 310 K);

T_2 is final fuel temperature, corresponding to the viscosity of the fuel used, required for this engine (approximately from 2 to 2.5 ° E), according to the rules of the Registry.

$T_2 \le T_{cn}$ – 10 °C. Flash point T_{cn} for viscous fuels is in the range from 60 to 110 °C.

Heat exchange surface area of the fuel heater:

$$A_m = q_m/(k_m\ \Delta T_m),$$

$$A_m = 832205/(1000 \cdot 68,5) = 12,15\ м^2,$$

where k_m heat transfer coefficient, can be accepted 1000 kJ/(m^2·hour·K).

ΔT_m – thermal head in the heat exchanger.

$$\Delta T_m = T_s – (T_1 + T_2)/2.$$

$$\Delta T_m= 400 – (310+353)/2 = 68,5\ K$$

where T_s is steam temperature at operating pressure, T_s approximately from 390 to 400 K. We assumed $T_s = 400\ K$.

We choose a heater based on its heat exchange surface area [22].

2.4.2 Lubrication system of the MAN B&W 7S70ME-C engine

It consists of a circulating oil system and a cylinder lubrication system. The circulating lubrication system supplies oil to the rubbing surfaces and also cools the pistons.

The system consists of oil storage tanks, waste tanks, oil circulation pumps, filters, separators, and oil coolers.

Capacity of main lube oil storage tanks for circulation system $V_{м.з.}$ is taken based on the specific consumption of circulating oil $b_{м.м.}$, which is compiled for the LSE

0.0002 kg/(kW·hour), with a 20% voyage reserve.

$V_{м.з.} = 1,2 \cdot b_{м.м} \cdot \Sigma N_e \cdot \tau_{гд} / \rho_м$

$V_{м.з.} = 1,2 \cdot 0,0002 \cdot 21700 \cdot 1200 / 867 = 7,21\ m^3$,

where $\tau_{гд}$ – duration of operation of the main engine MAN B&W 7S70ME-C in a calculated voyage, hours. Assume for the prototype: $\tau_{гд}$ = 1200 hours.

$\rho_м$ is oil density equal to 867 kg/m^3.

$V_{м.з.}$ with a 20% reserve for the voyage equals 3,4 m^3.

Cylinder oil storage tanks capacity:

$V_{ц.з} = b_{цм} \cdot \Sigma N_e \cdot \tau_{гд} / \rho_м$

$V_{ц.з} = 0,0005 \cdot 21700 \cdot 1200 / 867 = 15,0\ м^3$.

where $b_{цм}$ is pecific consumption of cylinder oil, depending on the type of engine, for МОД MAN B&W 7S70ME-C: from $0.4 \cdot 10^{-3}$ to $0.7 \cdot 10^{-3}$ kg/(kW·hour). We assume $b_{цм}$ *= 0.0005 kg/(kW·hour).*

Circulation oil pump

Circulation oil pump flow rate:

$$Q_{м.н} = \frac{q_{тр} + q_п}{c_м \cdot \rho_м \cdot \Delta T_м}$$

$Q_{м.н} = (1399650 + 7339000)/(3,0 \cdot 867 \cdot 8) = 420,0$ m^3/hour,

where $c_м$ is heat capacity of oil, can be assumed to be 3 kJ/(kg·K);

$q_{тр}$ is heat of friction removed by oil, kJ/kg;

$q_п$ is heat that oil receives from the piston, kJ/kg;

$\Delta T_м$ is difference between oil temperature at the outlet and inlet of the engine MAN B&W 7S70ME-C can be assumed 8 K.

$q_{тр} = 3,6 \cdot 10^3 \cdot a_{тр} \cdot N_e \cdot (1 - \eta_м)/\eta_м$

$q_{тр} = 3,6 \cdot 10^3 \cdot 0,43 \cdot 21700 \cdot (1 - 0,96)/0,96 = 1399650$ kJ/hour.

where $a_{тр}$ is the proportion of heat generated by friction and carried away by oil from 0.4 to 0.45. We assume $a_{тр} = 0.43$;

$\eta_м$ is the mechanical efficiency of the main engine MAN B&W 7S70ME-C is equal to $\eta_м$ = 0,96.

$q_п = a_п \cdot q$

$q_п = 0{,}05 \cdot 146780000 = 7339000$ kJ/hour.

where $a_п$ is part of the heat transferred from the piston to the oil for MAN B&W 7S70ME-C, from 0.04 to 0.06. We assume $a_п = 0.05$.

The power consumption of the circulation oil pump drive motor is determined by the formula:

$P = (420{,}0 \cdot 0{,}25)/(3{,}6 \cdot 0{,}85) = 34{,}3$ kW

We assume for the drive motor of the circulation oil pump η = 0,85.

$p_{мм}$ is pump delivery pressure, from 0.2 to 0.4 MPa.

We assume $p_{мм} = 0{,}25\ MPa$.

Lube oil volume in the system:

$V_{мс} = Q_{мс}/z$.

$V_{мс} = 420{,}0 / 10 = 42{,}0$ м^3,

where z is circulation rate, hour^{-1} when turbocharge above 40% $z = 10$.

Waste oil tank capacity

$V_{сц} = r \cdot V_{мс}$

$V_{сц} = 1{,}25 \cdot 42{,}0 = 52{,}5\ m^3$,

where r is foaming coefficient, which is from 1.2 to 1.3. We assume $r = 1.25$.

Lube oil purifier

Lube oil purifier feed

$Q_{м.с} = V_{мс}/ \tau_{см}$.

$Q_{м.с} = 42{,}0 / 8 = 5{,}25\ m^3/hour$,

where $\tau_{см}$ is time required to treat all oil in the system, $\tau_{см}$ from 4 to 8 hours. We assume $\tau_{см}$ = 8 *hours*.

We select an oil separator based on the supply rate and also install one spare of the same type [22].

Oil cooler heat exchanger surface:

$$A_м = \frac{q_{тр} + q_п}{k_м \cdot \Delta T_м}, m^2,$$

$$A_м = (1399650+7339000)/(1000 \cdot 12)=437\ m^2,$$

where $\Delta T_м$ is difference between the average temperature of oil and seawater in the cooler, К ($\Delta T_м$ = 12 К);

$k_м$ is heat transfer coefficient, from 500 kJ/ (m^2·hour·К) to 1000 kJ/ (m^2·hour·К). We assume $k_м$ = 1000 kJ/ (m^2·hour·К).

We install two coolers, each with a surface area of 60% of the total, i.e., *265* $м^2$.

Lube oil transfer pump

The oil transfer pump capacity must be sufficient to transfer oil from the main storage tanks to the circulation system within $\tau_м$ from 0.5 to 1 hour:

$Q_{м.п} = V_{мс} / \tau_м$,

$Q_{м.п}$ = 42,0 / 1 = 42,0 $м^3/год$.

Oil should be supplied from the main storage tanks to the circulation system continuously $\tau_м$ = *1 hour*.

The nominal power of the oil transfer pump drive is equal to:

P = (42,0 ·0.2)/(3,6·0.8)=2.92 kW.

$p_{мн}$ is pump delivery pressure, taken from 0.2 MPa to 0.3 MPa; We assume $H_{мн}$ = 0.2 MPa.

We assume the efficiency of the oil transfer pump η = 0.8.

2.4.3 Cooling system of the MAN B&W 7S70ME-C engine

Sea water pumps

Sea water pumps are used to pump seawater through water coolers, oil coolers, and charge air coolers. Seawater is used to dissipate frictional heat $q_{тр}$, heat transferred through liners, covers $q_ц$, heat transferred from pistons $q_п$, and the heat of the turbocharged air $q_н$.

Heat transferred through liners and covers and cooled by fresh water:

$q_ц = a_ц \cdot q$;

$q_ц = 0,11 \cdot 146780000 = 16145800$ *kJ/hour;*

where $a_ц$ is part of the heat transferred from liners and covers; the value $a_ц$ varies from 0.1 to 0.14 for LSE.

Fresh water pump delivery:

$$Q_{п.в} = \frac{q_ц}{c_{п.в} \cdot \rho_{п.в} \cdot \Delta T_{п.в}}$$

$Q_{п.в} = 16145800/(4,2 \cdot 10 \cdot 1000) = 384$ *м*^{3}*/ год,*

where $c_{п.в}$ is heat capacity of fresh water, we assume 4.2 kJ/(kg·K);

$\rho_{п.в}$ is The density of fresh water is approximately equal to 1000 kg/ m^3;

$\Delta T_{п.в}$ is the difference in temperature between the fresh water at the inlet and outlet of MAN B&W 7S70ME-C engine, which is usually in the range of 6 to 10 K.

Nominal power of the fresh water countour water pump drive:

$P=(Q_{п.в} \cdot p_{п.в})/(3,6 \cdot \eta)$,

$P=(384 \cdot 0,3)/(3,6 \cdot 0,9)=35,6$ *kW.*

where $p_{п.в}$ is delivery pressure, assumed from 0.2 to 0.4 MPa;

We assume $p_{пв} = 0.3$ *MPa;*

We assume the efficiency of the piston pump to be equal to $\eta = 0.9$.

The sea water pump delivery is determined by the formula:

$$Q_{з.в} = \frac{q_ц + q_{тр} + r \cdot q_н + q_п}{c_{з.в} \cdot \rho_{з.в} \cdot \Delta T_{з.в}},$$

$Q_{з.в} = (16145800+1399650+(0.6 \cdot 5871200)+7339000)/(4,2 \cdot 11 \cdot 1025) = 599.9$ *m*^{3}*/hour*.

where $c_{з.в}$ is heat capcity of seawater, 4.2 kJ/(kg·K);

$\rho_{з.в}$ is density of seawater, assumed 1025 kg/m^3;

$\Delta T_{з.в}$ is the difference in temperature between the fresh water at the inlet and outlet of the engine, from 10 K to 15 K; we assume $\Delta T_{з.в}$ = 11 K.

r is coefficient, assumed for turbochargers from 0.5 (with deep utilization), to 1 (without utilization). We assume *r* = 0.6.

$q_н = a_n \cdot q,$

$q_н = 0{,}04 \cdot 146780000 = 5871200$ *kJ/hour*,

where a_n is the coefficient, during cooling of the pistons with fresh water, lies in the range from 0.03 to 0.05; we assume $a_n = 0.04$.

$q_n = a_n \cdot q,$

$q_n = 0{,}05 \cdot 146780000 = 7339000$ *kJ/hour*,

where a_n is the proportion of fuel heat removed by cooling water in air coolers.

We assume p_s = 0.3 Mpa and $a_н = 0.05$.

We verify the correctness of the calculation of the sea water pump delivery using an approximate relationship:

$$\frac{Q_{з.в}}{N_e} = (0{,}035...0{,}045),$$

$$\frac{Q_{з.в}}{N_e} = 599.9\ /21700 = 0{,}0276.$$

That is, the value obtained satisfies the above dependence. The calculation of the seawater pump delivery is correct.

Nominal power of the sea water pump drive:

$P = (599.9 \cdot 0.2)/(3{,}6 \cdot 0{,}9) = 37{,}0$ kW

where $p_{зв}$ – pup delivery pressure, from 0.2 to 0.4 MPa;

We assume $p_{зв} = 0.2\ MPa$;

We assume the efficiency of the piston pump to be equal to $\eta = 0.9$.

Water cooler

The surface area of a water cooler is calculated using the formula:

$A_{охл} = q_ц/(k_ц\ \Delta T_в),$

$A_{охл} = 16145800/(5000 \cdot 15) = 215{,}3\ m^2.$

where $\Delta T_в$ is difference between the average temperature of fresh water and sea water in the cooler, K;

$k_ц$ – heat transfer coefficient, we assume $5000\ kJ/(m^2 \cdot hour \cdot K)$.

We choose a water cooler for the surface plane.

$\Delta T_в = T_{пв} - T_{зв}$, K.

$T_{пв}$ is feed water temperature, accepted from 310 K до 350 K;

We assume $T_{пв} = 320\ К$.

$T_{зв}$ is temperature of sea water, assumed $T_{зв} = 305\ К$.

$\Delta T_{в} = 320 ... 305 = 15\ К.$

2.4.4 Compressed air system

The system provides compressed air at specific pressure for starting and reversing the main engine MAN B&W 7S70ME-C and starting auxiliary diesel engines. The system includes starting air compressors and starting air cylinders.

Amount of compessed air V_B for n_n engine starts:

$V_B = n_n \cdot b_B\, \Sigma V_s,$

where n_n is minimum number of consecutive starts in forward and reverse that the system must provide; accepted for reversible motors $n_n \geq 12$.

b_B is specific consumption of free air per 1 м^3 cylinder's volume; assumed for LSE from 4 to 6, we assume $b_B = 5$.

ΣV_s is working volume of the engine's starter cylinders.

The working volume of the engine cylinders is calculated using the following formula:

$\Sigma V_s = (\pi \cdot d^2 \cdot s \cdot n_ц)/4,$

$\Sigma V_s = (3{,}14 \cdot 0{,}70 \cdot 2{,}8 \cdot 7)/4 = 10{,}8\ м^3,$

where D is cylinder's diameter, m;

S is piston stroke, m;

N is number of cylinders.

Total volume of air cylinders:

$\Sigma V_б = V_B \cdot p_B/(p_{мах} - p_{мin})$

$\Sigma V_б = 646 \cdot 0{,}1013/(3{,}0\text{-}1{,}0) = 32{,}7$ м^3,

where $p_{мах}$ is maximum air pressure in the cylinder, from 2.5 MPa to 3.0 MPa; we assume $p_{мах}$ =3.0 MPa.

$p_{мin}$ is minimum air pressure at which the engine can be started, from 1.0 MPa to 1.5 MPa; we assume $p_{мin}$ = 1.0 MPa;

p_B is free air pressure; we assume p_B =0.1013 MPa.

At least two standard air cylinders must have a total volume close to $\Sigma V_б$, we assume $\Sigma V_б = 34$ m^3.

The selection of air cylinders for a diesel generator is done in a similar manner.

The total output of the compressors must ensure that the cylinders are filled in 1 hour, starting from atmospheric pressure to the pressure $p_{мах}$.

$Q_к = \Sigma V_б (p_{мах} - p_{мin})/p_B$,

$Q_к = 7{,}5 \cdot (3{,}0\text{-}1.0)/0{,}1013 = 147{,}2\ m^3/hour$.

If it is necessary to ensure that the vessel's horn operates for at least 6 minutes while maintaining the ability to perform 12 consecutive starts, the cylinder volumes are increased accordingly.

2.4.5 Gas release system

The system includes an exhaust pipe, muffler, spark arrestor, and waste heat boiler.

Amount of gases emitted from the engine:

$Q_г = 10 \cdot N_e$,

$Q_г = 10 \cdot 21700 = 2170\ м^3/год$,

where N_e is effective power of the main engine, kW.

Exhaust pipes are made separately for each engine. The diameter of the pipes is determined based on the speed of the exhaust gases.

For two-stroke internal combustion engines, the diameter of the pipes is equal to:

$d_{газ} = 12 \cdot \sqrt{N_e}$.

$d_{газ} = 12 \cdot \sqrt{21700}$ = 1768 mm.

2.5 Mechanisms and devices of general ship systems

2.5.1 Firefighting system MV NUNAVIK

The total flow rate ΣQ of stationary fire pumps must be at least:

$\Sigma Q = k \cdot m^2$,

$\Sigma Q = 0{,}008 \cdot 175.1^2 = 245{,}4\ m^3/hour.$

$$m = 1{,}68 \cdot \sqrt{L_c \cdot (B_c + H_б)} + 25,$$

$m=1{,}68\cdot\sqrt{(188.8\cdot(26.6+15.7))}+25=175.1,$

where L_c is ship length, m,

B_c is ship width, m,

$H_б$ is height of the side to the bulkhead deck at midship, m,

k – coefficient, for MV NUNAVIK, we take k = 0.008.

Nominal power of the fire pump drive:

$P=(\Sigma Q \cdot p)/(3{,}6\cdot\eta)/2,$

$P=(245{,}4 \cdot 1{,}0)/(3{,}6\cdot 0{,}93)/2= 36{,}6\ kW$

where p is pump delivery pressure, accepted in accordance with the requirements of the Register, MPa;

η is pump efficiency, we assume equal *0.93*.

There are two stationary fire pumps. The pressure at the location of any hydrant is assumed to be $p = 0.30\ MPa$.

Fire pumps can be sanitary, ballast, bilge, and seawater pumps, provided that their flow rate and pressure meet the design requirements. These pumps cannot be used to pump petroleum products, oil, or other flammable liquids.

2.5.2 Bilge system MV NUNAVIK

Bilge system pumps are used to remove water from the engine room bilges, propeller shaft corridors, cargo hold bilges, and can also be used to pump ballast from the aft peak and forepeak.

Bilge pumps can serve as ballast pumps in cases specified by the Register's Rules.

Pipeline diameter d_{oc} is calculated using the formula of Register:

$$d_{oc} = 1{,}68 \cdot \sqrt{L_c \cdot (B_c + H_б)} + 25,$$

$d_{oc} =1{,}68\cdot\sqrt{(188.8\cdot(26.6+15.7))}+25=175.1\ mm,$

where L_c is ship length, m,

B_c is ship width, m,

$H_б$ is height of the side to the bulkhead deck at midship, m,

The total flow rate of drainage pumps must be no less than the total flow rate of fire pumps.

The flow rate of drainage pumps is calculated based on the flow velocity of fluid in the pipeline. $v_{он} \geq 2$ *m/s*..

$$Q_{ос} = 3600 \cdot \frac{\pi \cdot d_{ос}^2}{4} \cdot v_{он} .$$

$$Q_{ос} = 3600 \cdot (3{,}14 \cdot 0{,}175^2)/4 \cdot 2.5 = 216.4 \ m^3/hour.$$

Nominal power of the bilge pump drive:

$$P_{ос} = (Q_{ос} \cdot p_{он})/(3{,}6 \cdot \eta),$$

$$P_{ос} = (216.4 \ \cdot 0.3)/(3{,}6 \cdot 0.9) = 20.0 \text{ kW},$$

where $p_{он}$ is the pump delivery pressure is in the range from 0.2 MPa to 0.3 MPa; we assume $p_{он}$ = 0.3 MPa;

Pump efficiency $\eta = 0.9$.

The number of pumps shall be no less than two. A ballast pump or other pump with the required flow rate may be used as one of the independent pumps.

2.5.3 Ballast water system MV NUNAVIK

The system is designed to fill and drain ballast tanks.

The ballast pump delivery must be such that all ballast tanks are drained within 4 to 10 hours, depending on the size of the vessel.

According to the Register Rules, the internal diameter of the ballast pipeline dбс is calculated using the formula:

$$d_{бс} = 18 \cdot \sqrt[3]{V_{бв}} .$$

$$d_{бс} = 18 \cdot 3\sqrt{2258} \ = 236 \ mm,$$

where $V_{бв}$ is the volume of the largest ballast compartment is determined based on the data of the prototype vessey, $V_{бв}$ = 2258 m^3.

The flow rate of ballast pumps for a given pipe diameter is determined by the speed of water flow in the pipeline $v_{бс} \geq 2$ *m/s*.

$$Q_{бн} = 3600 \cdot \frac{\pi \cdot d_{бс}^2}{4} \cdot v_{бс}$$

$$Q_{бн} = 3600 \cdot (3{,}14 \cdot 0{,}236^2)/4 \cdot 2{,}5 = 394{,}0 \ \text{m}^3\text{/hour},$$

where $v_{бс}$ is working flow speed.

For ballast water system $v_{бс} = 2.5$ *m/s*.

Nominal power of ballast pump drive:

$P_{бн} = (Q_{бн} \cdot p_{бн})/(3{,}6 \cdot \eta)$,

$P_{бн} = (394{,}0 \cdot 0{,}3)/(3{,}6 \cdot 0{,}78) = 43{,}0$ *kW*.

where $p_{бн}$ is pump delivery pressure, from 0.2 MPa to 0.3 MPa; we assume $p_{бн}$ = 0.3 MPa.

Pump efficiency equals to $\eta = 0.78$.

Reserve cooling pumps, fire pumps, and drainage pumps can be used as ballast pumps.

2.6 Ventilation system MV NUNAVIK

The supply of air blowers that provide ventilation of living quarters is calculated based on the condition of supplying each crew member or passenger with 33 m^3/hour to 50 m^3/hour of air.

The ventilation system for the engine room is designed to ensure the operation of the main engines in storm conditions with the engine room closed.

According to the prototype, the ship has 21 crew berths and 2 spare berths. Thus, to ensure full human occupancy of the ship with a total of 23 crew berths, the total air supply is equal to:

$$Q_e = 40 \cdot 23 = 920.0 \ m^3/hour.$$

Air supply required for the operation of machines and mechanisms in the engine room:

$$Q_{мо} = \alpha_g \cdot G_0 \cdot Q_e / \rho_B,$$

$$Q_{мо} = 2.5 \cdot 14 \cdot 920.0 / 1.29 = 24961 \ m^3/hour.$$

Where α_g – air residue coefficient during fuel combustion in the engine. For the MAN

B&W 7S70ME-C engine, we assume α_g = 2.5,

G_0 – mass air flow per 1 kg of fuel,

ρ_B – air density at barometric pressure.

2.7 Sanitary systems MV NUNAVIK

2.7.1 Drinking water system MV NUNAVIK

Drinking water is stored in reserve tanks located outside the double bottom. Water is pumped from the reserve tanks to the hydrophores. The volume of the pressure tank is assumed to be 0.2 times the daily consumption.

The drinking water pump supply is determined based on the calculation of consumption per person per day from 10 l to 40 l of drinking water.

Thus, based on the maximum human capacity of the vessel, the daily consumption from the drinking water tank is equal to:

$$Q_{цпв} = (23 \cdot 40) \cdot 0.2 = 1.84\ m^3.$$

Nominal power of the drinking water system pump drive:

$$P_{пв} = (Q_{цпв} \cdot p_{пв})/(3.6 \cdot \eta),$$

$$P_{пв} = (1.84 \cdot 0.7)/(3.6 \cdot 0.75) = 0.48\ kW.$$

Where $p_{пв}$ – pump delivery pressure, from 0.5 MPa to 0.7 MPa; we assume $p_{пв} = 0.7$ *MPa*.

Pump efficiency equals to $\eta = 0.75$.

2.7.2 water system for sanitary and domestic needs MV NUNAVIK

Water consumption for sanitary and domestic needs averages between 100 and 200 liters per person per day. Determining the water supply for sanitary and domestic needs is similar to the previous calculation.

$$V_{цпв} = Q_{цпв} = (200 \cdot 23) \cdot 0.2 = 9.20\ m^3.$$

Nominal power of the pump drive:

$$P_{спп} = (9.20 \cdot 0.7)/(3.6 \cdot 0.7) = 2.56\ kW,$$

where $p_{спп}$ – pump delivery pressure, from 0.5 MPa to 0.7 MPa; we assume $p_{пв}$ = 0.7

MPa;

Pump efficiency equals to $\eta = 0.7$.

Water consumption for sanitary and domestic needs averages between 100 and 200 liters per person per day. Determining the water supply for sanitary and domestic needs is similar to the previous calculation.

$$V_{цпв} = Q_{цпв} = (200 \cdot 23) \cdot 0.2 = 9.20\ m^3.$$

Nominal power of the pump drive:

$$P_{спп}=(9.20 \cdot 0.7)/(3.6 \cdot 0.7) = 2.56\ kW,$$

where $p_{спп}$ – pump delivery pressure, from 0.5 MPa to 0.7 MPa; we assume $p_{пв}$ = 0.7 MPa;

Pump efficiency equals to $\eta = 0.7$.

2.7.3 Seawater system for sanitary and technical needs MV NUNAVIK

To calculate the pump flow rate, the water consumption for sanitary and technical needs is taken as 20–30 liters per person per day. The pump flow rate is determined in the same way as in the previous calculation.

$$V_{цзв} = Q_{цзв} = (30 \cdot 23) \cdot 0.65 = 4.49\ m^3.$$

Nominal power of the pump drive:

$$P_{стп}=(4.49 \cdot 0.7)/(3.6 \cdot 0.74) = 11.78\ kW.$$

where $p_{стп}$ pump delivery pressure, from 0.5 MPa to 0.7 MPa; we assume $p_{пв}$ = 0.7 MPa;

Pump efficiency equals to $\eta = 0.74$.

3 POWER AND FUEL CONSUMPTION COMPARISON OF TWO SHIPBOARD INERT GAS GENERATION SYSTEMS

3.1 Characteristics of compared inert gas generators

3.1.1 The Nitrogen Generator of Inert Gas

The Nitrogen Generator model NCl type approved by DNV (produced by Air Products AS) was chosen for analysis. The operational principle is based on membrane separation. This PRlSM® Nitrogen system, based on PRISM® membranes, allows for continuous on-site production of pure and dry nitrogen from air that can cover various purposes [23].

Nitrogen generation is based on the following processes. Compressed air is fed to the Filter & Control Unit and passes through a filter-package which will protect the membranes from harmful particles and oil and water condensate. The air then passes through a heater (electric or heat exchanger type), which will raise the air temperature by min. 5°C to approx. 50°C. The heated air is now fed from the Filter & Control Unit to each Membrane Bank and then to each individual membrane separator. The nitrogen product exiting the membrane modules is collected in a manifold and fed back to the Filter & Control Unit. The Filter & Control Unit is equipped with an oxygen analyser that will continuously monitor the oxygen content in the nitrogen product. Should the oxygen content, for some reason, rise above the design value, an alarm will be initiated. If the nitrogen consumption is lower than the design, the backpressure in the distribution lines will build up and give a lower product flow. A lower flow in the tum will result in higher nitrogen purity, i.e. less oxygen in the product.

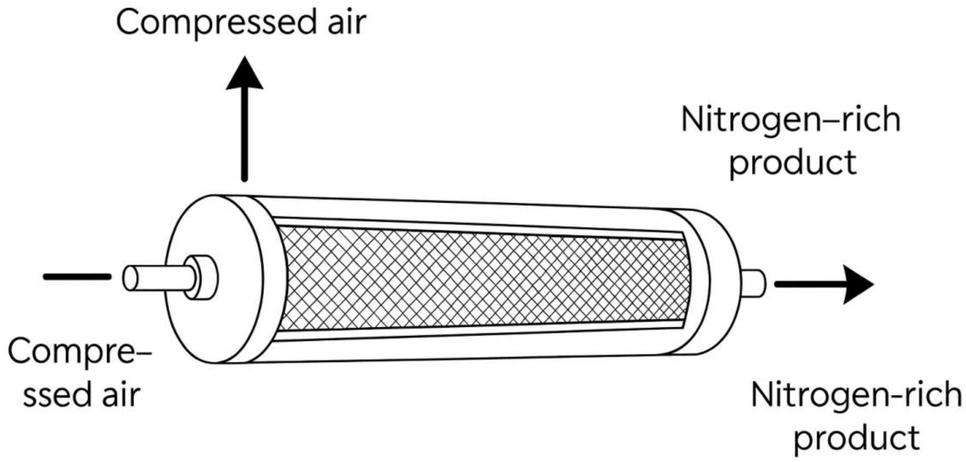

Fig. 3.1 Prism Membrane Principle

The presented scheme Figs. 3.2-3.3 illustrates a typical shipboard nitrogen generation system consisting of dual feed-air compressors supplying conditioned compressed air to a membrane-type nitrogen generator (Cabinet Model NC2.1). The system separates the wet and dry service sections, with compressed air routed through filtration, cooling, and control valves before entering the nitrogen cabinet, where oxygen-lean permeate is discharged and nitrogen product is delivered to the cargo-tank supply line or an optional nitrogen receiver. The diagram also shows recommended feed-air piping, deck-area arrangements, hazardous-zone boundaries, isolation valves, and instrumentation required for safe operation. The schematic is generic and intended to represent the principal process flow and installation considerations rather than project-specific details.

The scheme Fig. 3.4 illustrates the nitrogen distribution line, venting arrangement, DBB valves, non-return valves, deck isolation, vapor return lines, cargo hold connections, high-velocity vent head, vacuum relief valves, and operational parameters. It provides piping layout for No.3 cargo hold, Jet A tank, and slop tank with capacity data.

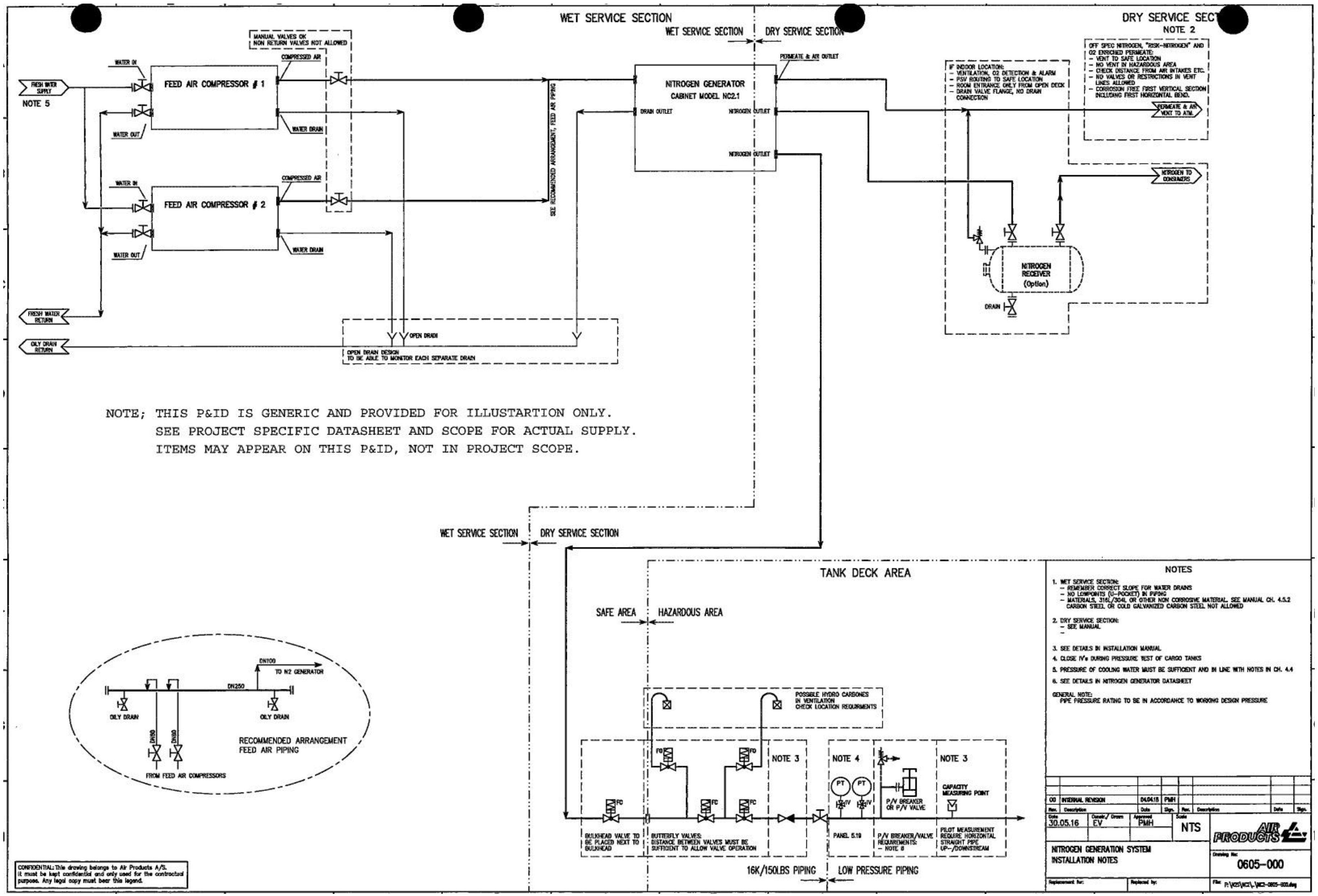

Fig. 3.2. Nitrogen generation system installation notes

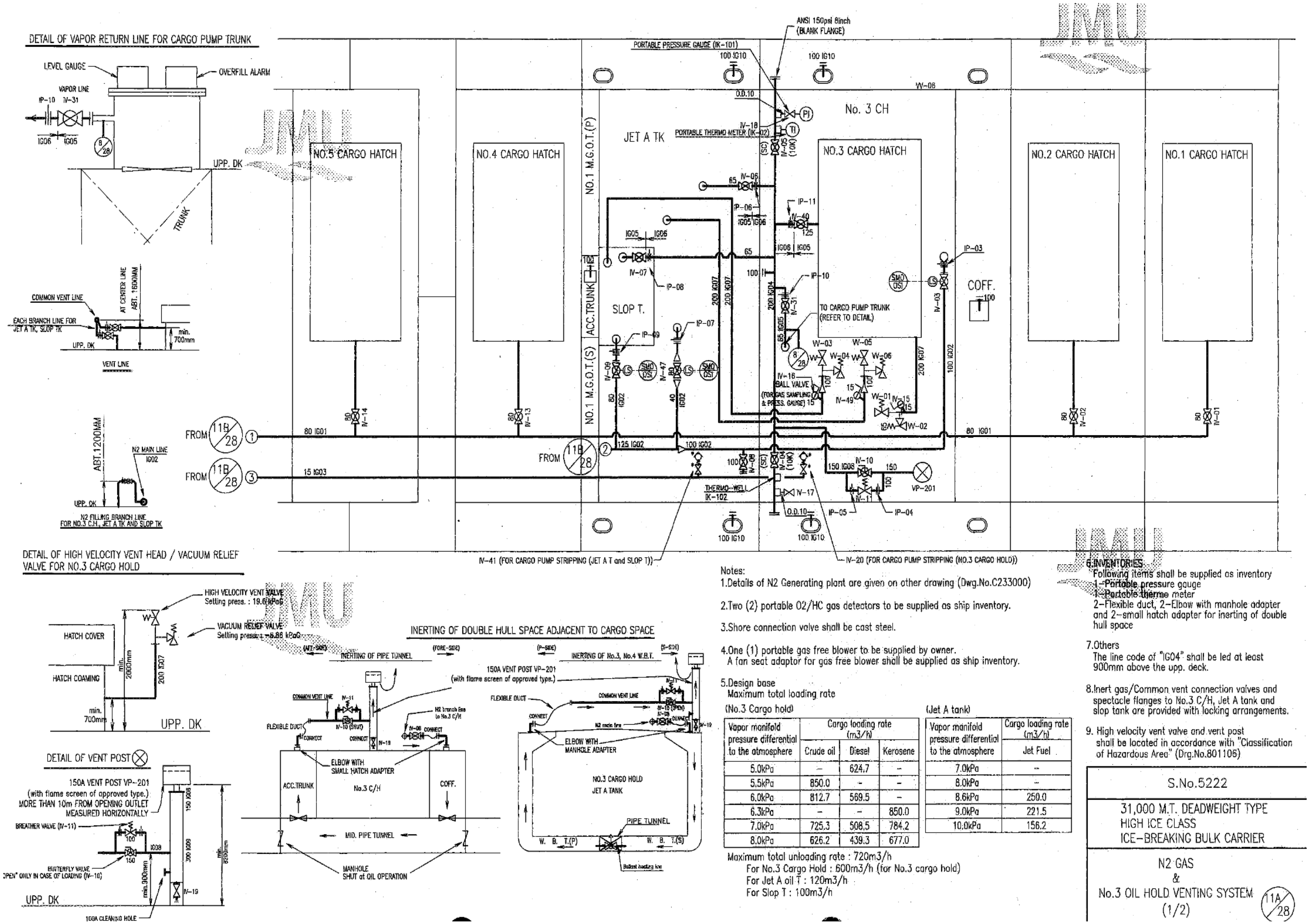

Fig. 3.3. Diagram of N2 Gas & No.3 Oil Hold Venting System

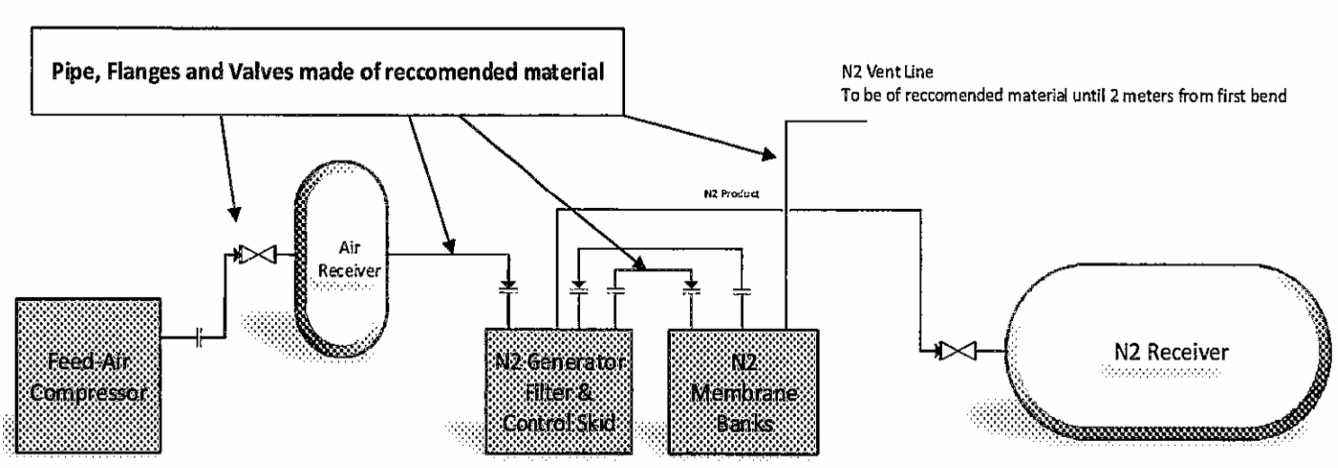

Fig.3.4 Example of correct pipe routing and material selection

Operating Modes and Working Parameters of the Nitrogen Generation System

This section provides an extended, engineering-grade description of the operating modes of the membrane-based nitrogen generation system (Air Products NC2.1). Each operating mode is characterized by nitrogen purity, delivery direction, pressure control logic, working parameters such as pressures and flow rates, and typical operational applications.

Extended characteristics of the system operation in all possible modes are given in Table 3.1. The main characteristics of the main operation modes for future analysi are presented in Table 3.2.

The nitrogen-generation system employs a KAESER DSDX 305 screw compressor. This compressor supplies compressed air to the membrane nitrogen generator. According to the manufacturer's manual (KAESER DSDX 305/14 bar, Assembly and Operating Manual), the compressor delivers compressed air at a controlled discharge pressure up to 14 bar. It operates with modulating or load/unload control modes and requires adequate cooling and ventilation.

Key compressor features include oil-injected screw compression, SIGMA CONTROL 2 onboard automation, and compatibility with external or internal modulation control. The compressor is designed for continuous operation under shipboard industrial conditions. Main Compressor Specifications presented in Table 3.3.

Table 3.1. Operating Modes and Working Parameters of the Nitrogen Generation System

Mode	N_2 Purity	Delivery Direction	Pressure Control	Working Parameters	Typical Operations
IG Mode – Cargo Tanks	≈95.4%	Cargo tanks via IG main line	Deck pressure regulation via DBB valves and PCV	$O_2 \le 5\%$ vol.; N_2 flow ≈ 925 Nm^3/h max; tank pressure ≥100 mmWG; feed air 7–10 bar; air heater ≈50°C	Main inerting, topping-up during loading/discharging, maintaining positive pressure
IG Mode – Buffer Tank / Cargo Holds	≈95.4%	Buffer tank or cargo holds	System pressure controlled via PCV-8.91	$O_2 \le 5\%$ vol.; flow rate variable 0–100%; buffer pressure 0.1–0.2 bar; automatic turndown; feed air 7–10 bar	Pre-inerting, stabilizing IG reserve, pressure buffering during operations
High-Purity Mode – Buffer Tank	≈99.9%	Buffer tank (high-purity storage)	Automatic start/stop based on pressure schedule	$O_2 \le 0.1\%$ vol.; reduced N_2 flow (≈10–35% of nominal); feed air 10–12 bar; membrane ΔP optimized for purity	Operations requiring ultra-low O_2 content, purging sensitive systems
Fresh Air Mode	Atmospheric air (≈21% O_2)	Cargo tanks for ventilation	Ventilation pressure maintained within safe limits	Flow limited by blowers; tank pressure kept near ambient; ensures <1% LFL before entry	Gas-freeing, tank preparation for inspection or maintenance

Table 3.2. Performance data of membrane nitrogen generator in main modes

	Mode 1 Inert Gas to Cargo Tanks	Mode 2 Inert Gas to Buffer Tank	Mode 3 N_2 to Buffer Tank	Mode 4 Fresh Air Mode
Capacity – Nitrogen Flow, nm^3/h	925	925	110	Fresh air flow per SetPoint ≈ 900 (from control setpoint)
N_2 purity (N_2+Argon), vol %	95.4	95.4	99.9	n/a (fresh air, ~21% O_2)
N_2 Dew Point (at atm. Pressure), ºC	-60	-60	-60	Ambient
Outlet Pressure, kPa	21	20 (PCV-8.91 regulation)	700	Controlled (cargo tank pressure regulation)
Outlet Temperature (max), ºC	50	50	50	≤50

Table 3.3 Main Compressor Specifications

Parameter	Value
Model	KAESER DSDX 305
Rated Working Pressure	14 bar
Free Air Delivery (FAD)	25.15 m^3/min (≈1509 m^3/h)
Installed Motor Power	141 kW
Cooling	Oil-injected, air-cooled or water-cooled
Control System	SIGMA CONTROL 2

3.1.2 The Alfa Laval Smit Combustion inert gas system

For comparison, the Alfa Laval Smit Combustion inert gas system was chosen, which consumes the MDO (DMB or DMC) as fuel [24]. The special burners of the Ultramizing system ensure inert gas production with low NOx emissions and no soot. Quality is further assured by sprayer systems that avoid creating salt crystals through water evaporation.

The Smit Combustion system is a low-pressure, combustion-based system for producing inert gas. Using the unique Ultramizing® system, it produces soot-free inert gas with an oxygen content of 2-4%, even when below stoichiometric conditions. To save fuel, it can also be equipped with an Alfa Laval Automatic Fuel Efficiency Module (AFEM).

Table 3.4 Main characteristics of Alfa Laval Smit Combustion inert gas system

Capacity:	1000-20,000 m3/h
Design:	Combustion
Pressure:	0.15 or 0.25 bar(g)
Typical oxygen content:	2-4% (varied by user)
Fuel type:	DMA, DMB, DMZ
Fuel atomizing:	Air
Dew point:	Saturated

On a typical product tanker, the inert gas system operates around 750 hours per year. To avoid costly delays and penalties, it must work whenever needed, despite continuous exposure to high tempera tures and seawater. This is why Alfa Laval uses durable materials and best-quality components, and why we back up our inert gas systems with proven main tenance solutions.

Fig. 3.5 The Alfa Laval Smit Combustion inert gas system: general view of the installation

Alfa Laval also values fuel efficiency, which is important for both your tanker's economy and the environment. The Smit Combustion system prevents the loss of inert gas through the water discharge, so that the fuel you burn does not go to waste. This is a unique feature among inert gas generators. Still more fuel is saved by the Automatic Fuel Efficiency Module (AFEM), which constantly adjusts the production to current needs. Only the right amount of inert gas is produced, with the AFEM regulating the fuel quantity to compensate for ambient factors and keep the oxygen percentage stable.

Inert gas quality is important as well. If the tank is dirtied by soot, you risk extra cleaning that slows you down – or rejections and claims that cost you money. This is why the patented Ultramizing® combustion system is at the heart of every Smit Combustion system. The special burners of the Ultramizing system ensure inert gas production with low NOx emissions and no soot. Quality is further assured by sprayer systems that avoid creating salt crystals through water evaporation.

3.2 Membrane Generator and Combustion Inert Gas Generator: methodology of power and fuel concumption calculation and analysis

3.2.1 Membrane Generators

This section describes how the air supply delivered by the screw compressor is related to the nitrogen production rate of the membrane-based inert gas generator. The analysis is presented in two forms:

(1) a simplified engineering model based on a membrane recovery factor,

(2) a physically grounded oxygen-balance model.

Simplified Engineering Model

Membrane nitrogen generators exhibit a direct relationship between the amount of compressed air $\dot{V}_{N_2}$ supplied and the nitrogen product flow $\dot{V}_{air}$. This relation can be approximated by introducing a membrane recovery factor φ, defined as:

$$\varphi = \frac{\dot{V}_{N_2}}{\dot{V}_{air}}.$$

Thus, the required air flow rate is:

$$\dot{V}_{air} = \frac{\dot{V}_{N_2}}{\varphi}.$$

Typical recovery values for commercial membrane systems are:

φ = 0.6…0.7 for N_2 purity ≈ 95.4%,

φ = 0.25…0.35 for N_2 purity ≈ 99.9%.

These values reflect the fact that higher nitrogen purity requires a larger purge flow and thus more air feed.

Oxygen-Balance Model (Physically Consistent). A more rigorous model can be derived from an oxygen balance across the membrane module.

Let the variables be defined as follows:

F – feed air flow (Nm^3/h);

P – nitrogen product flow (Nm^3/h);

W – oxygen-rich permeate flow (Nm^3/h);

$x_f = 0.21$ – oxygen mole fraction in feed air;

x_p – oxygen mole fraction in nitrogen product;

y_p – oxygen mole fraction in permeate (ermeate is the gas stream that passes through the membrane material due to its higher permeability), typically 0.3…0.4.

Mass balance:

$$F = P + W .$$

Oxygen balance:

$$Fx_f = Px_p + Wy_p .$$

From there we obtain:

$$F(x_f - y_p) = P(x_p - y_p) .$$

$$\frac{F}{P} = \frac{x_p - y_p}{x_f - y_p} \quad => \quad P = \frac{F}{\frac{x_p - y_p}{x_f - y_p}} .$$

This ratio directly provides the air consumption per unit of nitrogen product as a function of purity. For example, with:

$x_f = 0.21$.

$x_p = 0.046$ (95.4% N_2).

$y_p = 0.35$.

$$\frac{F}{P} \approx \frac{0.046 - 0.35}{0.21 - 0.35} \approx 2.2 .$$

Thus, the compressor must supply approximately 2.2 Nm^3 of air for each Nm^3 of nitrogen produced.

Below provides an empirical table of recovery values (φ) for membrane nitrogen generators as a function of nitrogen purity. The data are synthesized from typical performance curves published by the three major membrane module suppliers: Air Products PRISM® membranes [25], GENERON® hollow-fiber membrane systems [26], and Parker Hannifin nitrogen generators [27].

Table 3.5. Empirical Recovery vs Nitrogen Purity [25-27]

Nitrogen Purity (%)	Typical Recovery φ	Air-to-N_2 Ratio (F/P)	O_2 in Product (%)
90%	0.65–0.75	1.3–1.54	10%
95%	0.55–0.65	1.54–1.82	5%
98%	0.40–0.50	2.0–2.5	2%
99%	0.30–0.40	2.5–3.3	1%
99.5%	0.20–0.30	3.3–5.0	0.5%
99.9%	0.08–0.15	6.7–12.5	0.1%

These values reflect typical membrane behavior: recovery decreases as nitrogen purity increases, resulting in a significant rise in the required air-to-nitrogen ratio. This trend matches published performance curves from industrial membrane suppliers [25-27].

Table 3.6. Recommended Values for Engineering Calculations

Purity (%)	Recommended φ	Recommended F/P
95.4%	0.60	1.67
99.9%	0.12	8.33

These recommended values correspond closely to mid-range performance of Air Products PRISM® PA-series and GENERON® GN-series membrane nitrogen generators. They may be used in compressor sizing, power estimation, and air consumption calculations in marine nitrogen generation applications.

Compressor Power Relationship

Using the airflow relation, the compressor power can be expressed as:

$$P_{el} = P_{idle} + (P_{full} - P_{idle}) \cdot \frac{\dot{V}_{air}}{\dot{V}_{air,full}}$$

P_{idle} is idle Power (idle is the operating condition of a compressor in which the motor runs but no useful work is performed). Typically $P_{idle} \approx$ 25–30% of full-load power.

Combining the membrane model with the compressor characteristics yields a complete analytical framework for power consumption as a function of nitrogen purity and output:

$$P_{el} = P_{idle} + (P_{full} - P_{idle}) \cdot \frac{1}{\dot{V}_{air,full}} \cdot \frac{\dot{V}_{N_2}}{\varphi(C_{N_2})},$$

or, using the oxygen-balance model:

$$P_{el} = P_{idle} + (P_{full} - P_{idle}) \cdot \frac{1}{\dot{V}_{air,full}} \cdot \left(\frac{F}{P}\right)\dot{V}_{N_2}.$$

This formulation allows to construct performance curves, sensitivity analyses, and energy-efficiency comparisons between membrane nitrogen generators and combustion-type inert gas generators.

If the volumetric flow rate of air entering the compressor is known, the mass flow rate of air can be calculated from the ideal gas relation:

$$\dot{m} = \rho_1 \dot{V}_1 = \frac{p_1}{RT_1}\dot{V}_1,$$

where $\dot{m}$ is mass flow rate of air, kg/s; $\dot{V}$ is volumetric flow rate at inlet conditions m³/s; p_1 is inlet absolute pressure, Pa; T_1 is inlet temperature, K; R is specific gas constant for air; ρ_1 is air density at inlet conditions

Isentropic Work of Compression. Assuming ideal-gas behavior, the specific isentropic work required to compress air from inlet pressure p_1 to discharge p_2 is:

$$w_{is} = \frac{k}{k-1} RT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right],$$

where w_{is} is isentropic specific compression work, J/kg; k is heat capacity ratio ($k \approx 1.4$ for air); p_2 is discharge absolute pressure, Pa.

The ideal power required for compression is:

$$P_{is} = \dot{m} w_{is}$$

Real compressors require more power due to losses. The shaft power accounting for the isentropic efficiency η_{is}:

$$P_{shaft} = \frac{\dot{m}\, w_{is}}{\eta_{is}}.$$

If the mechanical efficiency of the drive train is η_{mech} and the electric motor efficiency is η_{motor}, the total electrical power consumption becomes:

$$P_{compr} = \frac{P_{shaft}}{\eta_{mech}\,\eta_{motor}} = \frac{\dot{m}\, w_{is}}{\eta_{is}\,\eta_{mech}\,\eta_{motor}}.$$

For the purposes of this study, the following typical efficiency values are adopted for a modern oil-injected screw compressor:

– isentropic efficiency η_{is}=0.80;

– mechanical efficiency of the drive train η_{mech}=0.97;

– electric motor efficiency η_{motor}=0.96.

This corresponds to an overall efficiency of approximately 0.75.

These formulas allow estimation of the power demand of the compressor for any given air flow rate and pressure ratio, and can be directly applied in the analysis of nitrogen generation systems onboard ships.

Air preheating in a membrane nitrogen generator

Air preheating in a membrane nitrogen generator is used to keep the feed gas temperature within a controlled range that is safe for the membranes and favourable for separation performance. By raising the temperature of the compressed air above its pressure dew point, the heater prevents condensation of water inside the filters, piping and membrane modules, which would otherwise damage the membrane or cause a rapid loss of capacity.

In addition, a moderate and stable feed-gas temperature improves the repeatability of the separation process. The permeability of polymeric membranes to oxygen and nitrogen is temperature dependent, so maintaining a defined temperature window upstream of the membrane bank helps to stabilise nitrogen purity and flow rate at a given feed pressure.

In practice, after the compressor, aftercooler, dryer and distribution piping, the actual air temperature just upstream of the electric heater can be significantly lower than the compressor discharge temperature. Typical values are about 10…25 °C under normal engine-room conditions, and in cold ambient or winter conditions the temperature of the air entering the heater can drop to approximately 5 °C.

The required thermal power of the air heater can be estimated from the sensible heat balance for the compressed air stream.

$$\dot{Q} = \dot{m}_{air}\, c_{p,air} \left(T_{out} - T_{in}\right),$$

where $\dot{Q}$ is the heat duty of the heater, W; $\dot{m}_{air}$ is the mass flow rate of compressed air, kg/s; $c_{p,air}$ is the specific heat capacity of air at constant pressure, J/(kg K); T_{in} and T_{out} are the air temperatures at the inlet and outlet of the heater, °C.

If the air flow rate is specified in volumetric terms at the heater inlet, the mass flow rate can be obtained from:

$$\dot{m}_{air} = \rho_{air} \dot{V}_{air},$$

where ρ_{air} is the air density at the heater inlet conditions, kg/m^3; $\dot{V}_{air}$ is the volumetric flow rate of air at the heater inlet, m^3/s.

For an electric heater, the required electrical power input can be estimated by accounting for the heater efficiency:

$$P_{heater} = \frac{\dot{Q}}{\eta_{heater}},$$

where P_{heater} is the electrical power, W; η_{heater} is the overall efficiency of the electric heater (typically in the range 0.95–0.99).

Electricity and fuel consumtion during operation of the nitrogen generator

The electricity for the production of nitrogen using the Nitrogen Generator is used for the operation of the:

- compressor (the predominant part),

- electric heater for heating the airflow before the membranes,

- powering the control system (a small amount).

The Nitrogen Generator discussed has a water-cooled marine screw compressor DSDX 305 (KAESER compressor) installed.

Electricity on board a vessel is produced by burning marine fuel either in the main engine using a shaft generator or in auxiliary engines with electric generators.

The hour fuel consumption for the electricity production for the operation of the Nitrogen Generator:

$$\dot{m}_{f\,el} = g_F \cdot (P_{compr} \cdot + P_{heater}),$$

where P_{compr} and P_{heater} are the electrical power of the compressor and heater; correspondently, kW; g_F is the specific fuel consumption of a diesel generator, kg/kWh (taken 0.185 kg/kWh [2]).

3.2.2 Combustion Inert Gas Generator

This section provides a complete and rigorous methodology for determining the fuel consumption and electric-power demand of a shipboard Combustion Inert Gas Generator (C-IGG), assuming operation on marine diesel oil (MDO/MGO). The following initial data are accepted.

- Required inert gas flow rate at normal conditions (0°C, 1 bar). Represents the demanded quantity of IG delivered to the cargo tanks or deck main:

$$\dot{V}_{IG,req}\ , Nm^3/h.$$

- Safety factor allowing for leakages, operational fluctuations, control-valve malfunctions, and variations in system back-pressure:

$$k_{loss} = 1.05...1.15.$$

- Lower heating value (LHV) of MDO/MGO. Represents the available chemical energy per kilogram of fuel:

$$H_u \approx 4.27 \cdot 10^4\ kJ/kg.$$

- Excess air ratio used in combustion. $\lambda = 1$ represents stoichiometric combustion;

$\lambda > 1$ signifies air supplied in excess of stoichiometric demand, resulting in oxygen in dry flue gas:

$$\lambda = 1.05...1.15.$$

Required Final Inert Gas Flow

Final required inert gas flow:

where $\dot{V}_{IG} = k_{loss} \cdot \dot{V}_{IG,req}$,

$\dot{V}_{IG}$ is IG flow including losses;

k_{loss} is loss factor;

$\dot{V}_{IG,req}$ is base IG demand.

Mass flow of inert gas:

$$\dot{m}_{IG} = \frac{\dot{V}_{IG}}{22.414} M_{IG},$$

where M_{IG} is molar mass of inert gas mixture (≈28–30 kg/kmol);

22.414 is molar volume at NTP (Normal Temperature and Pressure - *T=0 °C=273,15 K, p=1 atm*≈) conditions.

Stoichiometric Combustion Model for Diesel Fuel

$$n_C = \frac{w_C}{12}, \quad n_H = w_H, \quad n_S = \frac{w_S}{32}$$

Moles of carbon, hydrogen and sulfur per kg of fuel.

where w_C, w_H, w_S are mass fractions of C, H, S;

12, 1, 32 are molar masses, g/mol.

Stoichiometric oxygen requirement, which reflects oxygen needed to fully oxidize carbon, hydrogen and sulfur:

$$\nu_{O_2,st} = a + \frac{b}{4} + d - \frac{c}{2},$$

where *a, b, c, d* are coefficients in empirical diesel fuel formula $C_aH_bO_cS_d$.

Stoichiometric air requirement:

$$\nu_{air,st} = \frac{\nu_{O_2,st}}{0.21},$$

where 0.21 is oxygen volume fraction in air.

Actual air supply based on excess air λ:

$$\nu_{air} = \lambda \nu_{air,st}$$

Total dry flue gas moles:

$$\nu_{FG,dry} = \nu_{CO_2} + \nu_{SO_2} + \nu_{N_2} + \nu_{O_2,excess},$$

$$\nu_{O_2,excess} = 0.21\nu_{air} - \nu_{O_2,st}$$

Dry flue gas volume at NTP (multiplies total moles by molar volume):

$$V_{FG,dry} = 22.414\nu_{FG,dry}.$$

Specific volume of dry flue gas per kg of fuel:

$$v_{FG,dry,sp} = \frac{V_{FG,dry}}{M_f},$$

where M_f is molar mass of fuel, kg/kmol.

Fuel mass flow needed to generate the required IG volume:

$$\dot{m}_f = \frac{\dot{V}_{IG}}{v_{FG,dry,sp}},$$

where $v_{FG,dry,sp}$ is m³ of dry flue gas produced per kg of fuel;

$\dot{V}_{IG}$ is inert gas flow rate.

Oxygen Content in Produced Inert Gas

Dry oxygen fraction in inert gas:

$$x_{O_2} = \frac{\nu_{O_2,excess}}{\nu_{FG,dry}},$$

Value of x_{O_2} must satisfy IMO FSS Code ≤ 5%.

Heat Supplied by Fuel (Thermal power input from fuel):

$$\dot{Q}_f = \frac{\dot{m}_f H_u}{3600}, \text{ kW},$$

where $\dot{m}_f$ is fuel mass flow, kg/h;

H_u is lower heating value (kJ/kg);

dividing by 3600 converts kJ/h → kW.

Electrical Power Requirements

The electrical power during inert gas production in a Combustion-type IGG is consumed for the operation of the:

- scrubber pumps,
- gas blower after the generator,
- power supply for the control system (a small amount).

Hydraulic power of the IG blower:

$$P_{hyd,IG} = \dot{V}_{IG,act} \Delta p_{IG},$$

where $\dot{V}_{IG,act}$ is volumetric IG flow at actual temperature and pressure;

Δp_{IG} is blower pressure rise.

Shaft power required by the blower:

$$P_{shaft,IG} = \frac{P_{hyd,IG}}{\eta_{bl}}$$

where η_{bl} is blower mechanical efficiency.

Electrical power of blower motor:

$$P_{el,IG} = \frac{P_{shaft,IG}}{\eta_{mot}}$$

where η_{mot} is motor efficiency.

Total electrical power consumption of all auxiliary equipment: IG blower, combustion-air fan, seawater/freshwater pumps.

$$P_{el,tot} = P_{el,IG} + P_{el,air} + P_{el,SW}.$$

Similar to equation for nitrigene IG generator, the hour fuel consumption for the electricity production for the operation of the Combustion-type IGG:

$$\dot{m}_{f\,el} = g_F \cdot P_{el,tot},$$

where $P_{el,tot}$ is the electrical power of the scrubber pumps and gas blower, kW.

Specific Fuel and Electricity Consumption

Specific fuel consumption per Nm³ of inert gas.

$$b_f = \frac{\dot{m}_f}{\dot{V}_{IG}}.$$

Specific electrical energy consumption per 1000 Nm³ of inert gas:

$$e_{el,sp} = \frac{P_{el,tot}}{\dot{V}_{IG}} \cdot 1000.$$

Total specific fuel consumption per Nm³ of inert gas.

$$b_{f\,tot} = \frac{\dot{m}_f + \dot{m}_{f\,el}}{\dot{V}_{IG}}.$$

All described above approaches and data is needed later to compare fuel consumption per unit of inert gas the IGGs produce.

3.3 Membrane Generator and Combustion Inert Gas Generator: results of calculation of power and fuel concumption and analysis

3.3.1 Membrane Inert Gas Generator

The graph illustrates the dependency between the inert gas (IG) flow rate and the nitrogen purity achieved by the membrane separation unit used in shipboard inert gas systems. As expected for polymeric membrane technology, the IG production rate decreases non-linearly as higher nitrogen purity is targeted – Fig. 3.6.

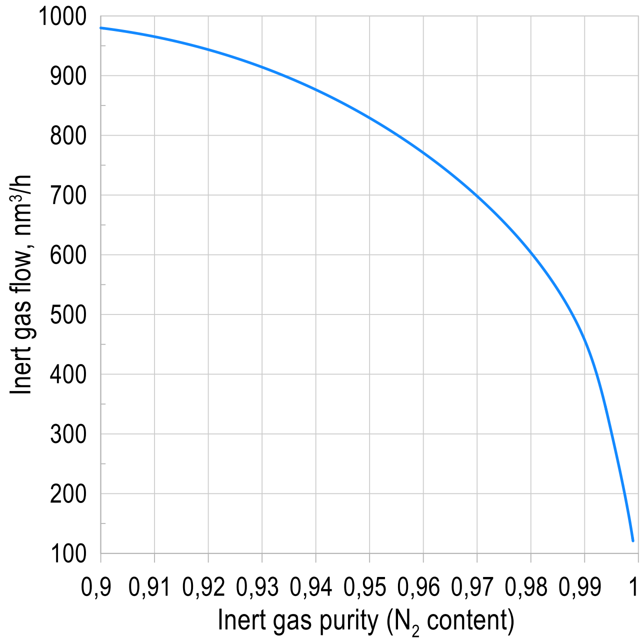

Fig. 3.6 Variation of inert gas flow rate with nitrogen purity for the membrane-type inert gas generator

At moderate purities (90–95% N_2), the reduction in flow rate is relatively gradual: the input of inert gas remains in the range of approximately 900–750 Nm^3/h. This indicates that the membrane still allows sufficiently high permeation fluxes at these driving conditions, making these operating points suitable for routine tank inerting or maintaining positive pressure in cargo tanks on product/chemical tankers.

However, as nitrogen purity increases beyond approximately 97%, the decline in flow rate becomes substantially steeper. At 98–99% N_2, the inert gas output drops to 500–200 Nm^3/h, reflecting the intrinsic selectivity–permeability trade-off of membrane materials. Achieving very high purities requires a lower stage-cut and significantly reduces the mass flow available at the retentate (nitrogen-rich) side.

Near 99.5–100% purity the IG flow approaches minimum practical values (~100 Nm^3/h), which is consistent with the known performance limits of commercial hollow-fiber membranes used in marine nitrogen generator systems. These operating regimes are typically used only for specific cargoes requiring extremely low oxygen content (e.g., certain IMO Type 1 chemicals), because the membrane unit must operate at substantially higher compressor power per unit of IG delivered.

In operational terms, the results confirm that:

- Increasing nitrogen purity significantly increases the specific energy consumption (kWh per Nm^3 IG) due to both reduced flow and higher compressor load.

- Optimal operating purity for bulk inerting is usually 95–97% N_2, balancing safety requirements and system efficiency.

- For cargoes requiring oxygen content below 1%, the membrane system must operate in a high-purity, low-flow regime, which must be considered in the sizing of compressors and backup nitrogen capacity.

The input parameters for the membrane-type inert gas generator calculation are defined as follows. The feed-air flow rate supplied to the membrane module is 1509 Nm^3/h. The feed-air pressure at the module inlet is 0 bar gauge (atmospheric), while the discharge pressure at the module outlet is 10 bar gauge. The assumed temperature increase of the air stream in heater before membranes is $\Delta T = 10$ K. These values are used as baseline conditions for sizing the compressor, evaluating the membrane separation performance, and determining the energy demand of the system.

Based on the calculations performed using the methodology described above, the following results were obtained for all operating modes of the membrane-type inert gas generator. The required compressor shaft power amounts to 188.9 kW, while the electric heater contributes an additional 5.35 kW of power demand. Thus, the total electrical energy consumption of the system reaches 194.3 kW. When converted to the equivalent fuel consumption associated with electricity generation onboard, this corresponds to approximately 35.94 kg of fuel per hour.

The results obtained for all operating modes, including the corresponding electrical power consumption and fuel demand, are summarised in Table 3.7.

The data presented in Table 3.7 clearly demonstrate the strong inverse relationship between oxygen content in the produced inert gas and the available inert gas output of the membrane generator. As the oxygen concentration decreases from 10% to 0.1%, the production rate drops from approximately 980 m^3/h to 121 m^3/h, reflecting the inherent permeability–selectivity trade-off of membrane separation. Although the total electrical power consumption of the system remains essentially constant at 194.3 kW, the corresponding specific fuel consumption increases sharply as higher nitrogen purity is required. Specifically, the specific fuel consumption rises from 0.0367 kg/Nm³ at 10% O_2 to nearly 0.298 kg/Nm³ at 0.1% O_2. This indicates that achieving very low oxygen contents becomes progressively more energy-intensive and should therefore be reserved for cargoes that strictly demand high-purity inert atmospheres. For standard inerting operations, moderate purity levels (1–5% O_2) provide a more favourable balance between inert gas output and specific energy/fuel consumption.

Table 3.7 The electrical power consumption and total fuel consumption required to generate of inert gas with oxygen contents between 0,1 % and 10% with 1509 Nm³/h air supply to generator

Oxygen content in dry inert gas, O_2, %	Total electrical power consumption, kW	Fuel consumption for electricity generation, kg/h	Inert gas output, m³/h	Specific fuel consumption, kg/Nm³
10	194.3	35.94	979.9	0.0367
5			829.1	0.0433
2			603.6	0.0595
1			457.3	0.0786
0.5			301.8	0.1191
0.1			120.7	0.2977

3.3.2 Combustion Inert Gas Generator

Detailed Numerical Results were obtained for 829.1 Nm³/h IG Production.

For scrubbers in a Combustion-type IGG system, typical power consumption is no more than 7 kW per 1000 Nm^3 of gas being cleaned.

The calculation of compressor power were performed for compressing 829.1 Nm³/h of inert gas from a pressure of 0.15 bar after the Combustion-type IGG to 0.5 bar (for supply to cargo tanks) with an efficiency of 0.75.

The following table 3.8 summarizes fuel consumption and electrical power consumption required to generate 829.1 Nm³/h of inert gas with oxygen contents between 2% and 5%.

Table 3.8 The fuel consumption to generate 829.1 Nm^3/h of inert gas with oxygen contents between 2% and 5%

Oxygen content in dry inert gas, O_2, %	Excess air ratio, λ	Specific dry flue-gas volume per kg of fue, v_{FG}, Nm^3/kg	Fuel mass flow required, m_f, kg/h	Specific fuel consumption, b_f, kg/Nm^3	Thermal power supplied by fuel, Q_f, kW
2%	1.098	11.52	71.97	0.0868	854
3%	1.156	12.16	68.18	0.0822	809
4%	1.220	12.88	64.39	0.0777	764
5%	1.292	13.68	60.61	0.0731	719

Fuel consumption for producing 1000 nm^3 of inert gas depends on many factors (fuel type, oxygen content in the inert gas, and others). According to the analysis of information provided by various manufacturers of Combustion-type IGG, the specific fuel consumption is 0.075…0.084 kg of MDO per 1 m^3 of inert gas.

As the oxygen content in dry inert gas increases (i.e., required purity becomes less strict), the combustion process requires a progressively higher excess-air ratio λ (from 1.098 at 2% O_2 to 1.292 at 5% O_2). This trend reflects the operational characteristic of combustion-based IGGs: achieving lower oxygen content in the flue gas requires tighter control of air–fuel mixing and a lower λ, while allowing higher O_2 levels permits more air addition.

The specific dry flue-gas volume per kilogram of fuel increases correspondingly, rising from 11.52 to 13.68 Nm^3/kg, due to greater nitrogen dilution at higher λ. As a result, the thermal power supplied by fuel decreases from 854 kW at 2% O_2 to 719 kW at 5% O_2, because less fuel is required when operating at higher excess-air levels.

A key indicator—specific fuel consumption, kg/Nm^3 of inert gas—shows a clear downward trend: 0.0868 kg/Nm^3 at 2% O_2 and 0.0731 kg/Nm^3 at 5% O_2.

This confirms that stricter IG purity (lower O_2 content) is more fuel-intensive, whereas relaxed purity requirements reduce the energy demand of the generator.

The electrical power consumption and total fuel consumption required to generate 829.1 Nm³/h of inert gas with oxygen contents between 2% and 5% are presented in Table 3.9.

Table 3.9 The electrical power consumption and total fuel consumption required to generate 829.1 Nm³/h of inert gas with oxygen contents between 2% and 5%

Oxygen content in dry inert gas, O_2, %	Electrical power consumption (compressor+scruber), P_{el}, *kW*	Fuel mass flow required for electricity generation, $m_{f\,el}$, *kg/h*	Total fuel mass flow required, $m_{f\,tot}$, *kg/h*	Total specific fuel consumption, $b_{f\,tot}$, *kg/Nm³*
2%	16.7	3.090	88.67	0.1069
3%	16.7	3.090	84.88	0.1024
4%	16.7	3.090	81.09	0.0978
5%	16.7	3.090	77.31	0.0932

Table 3.9 integrates the electrical power demand of the compressor–scrubber system (16.7 kW, assumed constant) with the fuel required to produce that electricity onboard. The fuel consumption for electricity generation remains fixed at 3.090 kg/h, regardless of IG purity, since electrical power demand does not vary between regimes.

Thus, the total fuel mass flow required for each operating point is the sum of fuel for thermal generation (IGG burner) and for electrical energy production. This combined fuel consumption decreases from 88.67 kg/h at 2% O_2 to 77.31 kg/h at 5% O_2, fully consistent with the lower thermal load identified in Table 3.1.

The total specific fuel consumption decreases from 0.1069 kg/Nm³ at 2% O_2 to 0.0932 kg/Nm³ at 5% O_2. This metric incorporates both the firing demand and electrical energy consumption, providing a holistic measure of generator efficiency.

Achieving 2% O_2 requires approximately 15% more total fuel than operating at 5% O_2 for the same IG flow rate.

The excess-air ratio is the key driver of fuel consumption in a combustion-type IGG.

Lower oxygen content requires tighter λ-control and more efficient combustion, increasing fuel demand.

Electrical energy consumption contributes a smaller but fixed share of total fuel consumption, remaining constant across all regimes.

Total specific fuel consumption decreases as permitted O_2 concentration increases, improving overall operational efficiency.

For most marine applications – excluding cargoes requiring very low oxygen limits – operating in the 3–5% O_2 range offers the best balance between fuel economy and safety.

3.3.3 Comparison of Fuel Consumption of Membrane Generator and Combustion Inert Gas Generator

Figure 3.7 presents a direct comparison of the specific fuel consumption of two fundamentally different inert gas generation technologies—membrane-based IGG and combustion-type IGG – over a wide range of inert gas purities expressed via residual oxygen content in the product gas. For the membrane system, oxygen content varies from 10 % down to 0.1 % (corresponding to nitrogen purity from 90 % to 99.9 % N_2), while for the combustion-type IGG the range of 2–5 % O_2 corresponds to the normal operating window defined by the FSS Code and manufacturer recommendations.

For the membrane generator, Fig. 3.7 shows that at relatively low nitrogen purities (10 % O_2, i.e. 90 % N_2) the specific fuel consumption is as low as 0.0367 kg/Nm^3. As nitrogen purity increases, the inert gas production rate decreases sharply, whereas the total electrical power of the compressor and heater remains essentially constant at P_{el}≈194.3 kW.

As a result, the specific fuel consumption rises significantly and reaches approximately 0.298 kg/Nm^3 at 0.1 % O_2 (≈ 99.9 % N_2).

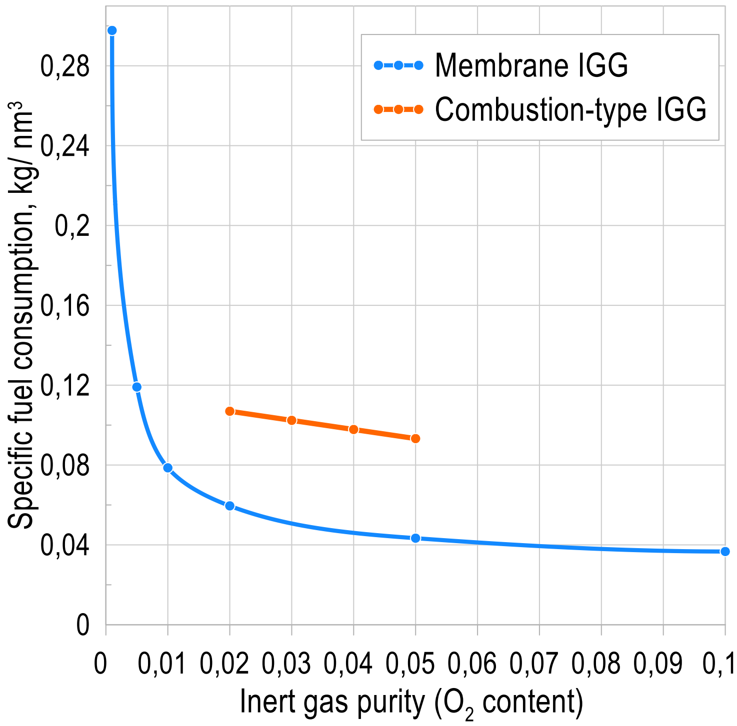

Fig. 3.7 Comparison of specific fuel consumption for membrane and combustion-type inert gas generators at different inert gas purities

In contrast, the combustion-type IGG demonstrates a much narrower variation of specific fuel consumption over the practical range of 2–5 % O_2. According to Fig. 3.7, the specific fuel consumption decreases from 0.0868 kg/Nm^3 at 2 % O_2 to 0.0731 kg/Nm^3 at 5 % O_2. This trend is associated with an increase in the excess air ratio λ and, consequently, a higher dry flue-gas volume per unit of fuel, which allows the generator to produce more inert gas at slightly higher oxygen content.

Based on the data presented in Fig. 3.1, the following key conclusions can be drawn:

– At moderate purity levels (2–5 % O_2), the membrane IGG is significantly more fuel-efficient than the combustion-type IGG, requiring approximately 30–60 % less fuel per Nm^3 of inert gas.

– At high and ultra-high purities (< 1 % O_2), the membrane system becomes progressively less efficient due to the sharp increase in specific energy demand, and its specific fuel consumption may exceed that of the combustion-type IGG by a large margin.

– Combustion-type IGGs maintain relatively stable efficiency but are inherently limited to low and medium purity levels, while membrane systems provide high operational flexibility, enabling ultra-high purity nitrogen generation at the cost of a substantial fuel penalty.

This behaviour has a direct impact on greenhouse gas emissions, since both systems ultimately consume marine fuel either directly (combustion IGG) or indirectly via shipboard diesel generators (membrane system).

4 ECOLOGICAL COMPARISON OF TWO SHIPBOARD INERT GAS GENERATION SYSTEMS

4.1 Ecological Impact of Shipboard Inert Gas Generation Systems

The ecological impact of shipboard inert gas generation systems is directly linked to their energy consumption characteristics and the physical principles by which inert gas is produced. As demonstrated in Chapter 3, the combustion-type inert gas generator (IGG) and the membrane-based nitrogen generation system exhibit fundamentally different patterns of fuel and electrical energy use. These differences predetermine not only their operational efficiency, but also the nature and magnitude of their environmental footprint.

In combustion-type IGG systems, inert gas is produced through the controlled combustion of liquid fuel, which inevitably leads to direct emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and water vapor. In addition to their contribution to global greenhouse gas emissions, these combustion products may increase corrosion intensity in the inert gas main and cargo tanks and pose a potential risk of cargo contamination, especially for chemical and high-value product tankers. Furthermore, such systems contribute locally to atmospheric pollution in port and coastal areas.

In contrast, membrane-based nitrogen generation systems do not involve any onboard combustion process. Their environmental impact is therefore indirect and is associated exclusively with the electrical power demand of air compressors and auxiliary equipment. The resulting carbon footprint depends on the efficiency of the ship's diesel generators and the overall energy balance of the vessel. At the same time, membrane systems supply high-purity, dry nitrogen, which significantly reduces the risks of corrosion, moisture ingress and chemical interaction with sensitive cargoes.

In the context of increasingly stringent international environmental regulations, including MARPOL Annex VI and the IMO strategy on the reduction of greenhouse gas emissions from ships, the environmental performance of auxiliary ship systems has become a critical factor in technical decision-making. Therefore, a comparative ecological assessment of combustion-type and membrane-based inert gas generation systems is an essential complement to the energetic analysis presented in Chapter 3.

This chapter is devoted to a quantitative and qualitative comparison of the ecological performance of the two inert gas generation concepts. The analysis focuses on the formation of greenhouse gas emissions, the presence of toxic combustion products, their potential impact on cargo safety and ship structures, and the overall conformity of both systems with current and future environmental requirements of the IMO.

4.2 Methodology of Assessment of CO_2 Emissions

A quantitative assessment of carbon dioxide emissions is a key element of the ecological comparison of the two shipboard inert gas generation systems, since CO_2 represents the dominant greenhouse gas associated with ship energy conversion processes. The formation mechanisms of CO_2 emissions for the two systems differ fundamentally and follow directly from their respective energy consumption patterns, as established in Chapter 3.

4.2.1 CO_2 Emissions of the Combustion-Type Inert Gas Generator

In combustion-type IGG systems, inert gas is produced by direct combustion of marine liquid fuel in the generator burner. Consequently, carbon dioxide is formed as an unavoidable product of the oxidation of hydrocarbon fuel. The mass flow rate of CO_2 emissions is directly proportional to the hourly fuel consumption of the inert gas generator and can be evaluated using the standard carbon conversion factor recommended in maritime emission calculations:

$$\dot{m}_{CO_2,IGG} = \dot{m}_f \cdot K_{CO_2}$$

where: $\dot{m}_{CO_2,IGG}$ is mass flow rate of CO_2 emissions from the combustion-type IGG, kg/h;

$\dot{m}_f$ is fuel mass flow rate of the IGG, kg/h;

K_{CO_2} = 3.114 kg CO_2/kg fuel.

Using the specific fuel consumption values obtained in Chapter 3, the corresponding CO_2 emissions per unit volume of produced inert gas can be determined as:

$$e_{CO_2,IGG} = g_f \cdot K_{CO_2}$$

where: $e_{CO_2,IGG}$ is specific CO_2 emission per unit volume of inert gas, kg CO_2/Nm^3;

g_f is specific fuel consumption of the IGG, kg/Nm^3.

4.2.2 CO_2 Emissions of the Membrane-Based Nitrogen Generation System

Membrane-based nitrogen generation systems do not involve any onboard combustion process. Therefore, direct CO_2 emissions at the point of inert gas production are equal to zero. However, the production of nitrogen requires electrical energy to drive air compressors, dryers, and control systems. As a result, CO_2 emissions are formed indirectly through the operation of the ship's diesel generators supplying electrical power to the nitrogen system.

$$\dot{m}_{CO_2,N_2} = P_{el} \cdot SFC_{DG} \cdot K_{CO_2}$$

where: $\dot{m}_{CO_2,N_2}$ is indirect CO_2 emission rate associated with nitrogen generation, kg/h;

P_{el} is electrical power demand of the nitrogen system, kW;

SFC_{DG} is specific fuel consumption of the diesel generator, kg/(kWh);

K_{CO_2} is carbon-to-CO_2 conversion factor.

On a specific basis, the CO_2 emissions per unit volume of produced nitrogen can be expressed as:

$$e_{CO_2,N_2} = e_{el} \cdot SFC_{DG} \cdot K_{CO_2}$$

where: e_{el} is specific electrical energy consumption of the nitrogen system, kWh/Nm^3.

4.3 Calculation of greenhouse gas emissions from two shipboard inert gas generation systems

Volumetric inert gas flow rate:

$\dot{V}_{IG}$ *= 5000 Nm³/h* – typical value for product and crude oil tankers (Alfa Laval IGG documentation).

Annual operating time:

t_{IG} *= 750 h/year* – typical annual inert gas system operation time for medium-size tankers.

Specific fuel consumption of the ship's diesel generator (for electricity production):

$g_{DG} = 0.195\, kg/kWh.$

CO_2 emission factor for marine diesel fuel (MDO/MGO), based on IPCC 2006 Guidelines [29]:

$EF_{CO2,\,fuel} = 3.15\, kg\ CO_2\ /\ kg\ fuel.$

Thus, the specific CO_2 emissions per unit of electric energy produced by the diesel generator equal:

$e_{CO2,el} = g_{DG} \cdot EF_{CO2,\,fuel} = 0.195 \cdot 3.15 \approx 0.61 kg\ CO_2\ /\ kWh.$

This value is used to convert the electrical energy demand of the membrane-type system into fuel consumption and CO_2 emissions.

Typical specific fuel consumption of the combustion-type IGG as a function of oxygen content in the inert gas is taken from the detailed calculations and manufacturer data summarised in Table 4.1

Table 4.1 Typical specific fuel consumption of the combustion-type IGG as a function of oxygen content in the inert gas

$b_f\left(\chi_{O_2}\right)$, kg/Nm^3	χ_{O_2}, %
0.0868	2
0.0822	3
0.0777	4
0.0731	5

For the membrane system, specific fuel consumption per unit of inert gas (equivalent fuel for electricity generation) is taken from Table 4.2, which summarises the power demand of the compressor and heater and the resulting inert gas flow for different oxygen contents in the product gas.

Table 4.2 Typical specific fuel consumption of the membrane-type IGG as a function of oxygen content in the inert gas

$b_f\left(\chi_{O_2}\right)$, kg/Nm^3	χ_{O_2}, %
0.0367	10
0.0433	5
0.0595	2
0.0786	1
0.201	0.5
0.298	0.1

These values correspond to nitrogen purities from 90 % N_2 (10 % O_2) up to 99.9 % N_2 (0.1 % O_2).

Combustion-type inert gas generator: CO_2 emission calculation

For the combustion-type IGG, fuel is burnt directly for inert gas production. The specific CO_2 emissions per unit of inert gas volume at a given oxygen content χ_{O_2} are

$$e_{CO2,IGG}(\chi_{O_2}) = b_f(\chi_{O_2}) \cdot EF_{CO2,fuel},$$

where $b_f(\chi_{O_2})$ is the specific fuel consumption of the IGG, kg/Nm^3;

$EF_{CO2,fuel}$ is the emission factor, kg CO_2/kg fuel.

The corresponding annual CO_2 emissions at this operating point are:

$$M_{CO2,IGG}(\chi_{O_2}) = e_{CO2,IGG}(\chi_{O_2}) \cdot \dot{V}_{IG} \cdot t_{IG}.$$

Example for χ_{O_2} = 3%.

From Table 3.8 for the combustion-type IGG:

$b_f(3\ \%) = 0.0822\, kg/Nm^3.$

Specific CO_2 emissions:

$e_{CO2,IGG}(3\ \%)\ 0.0822 \cdot 3.15 \approx 0.259\, kg\ CO_2\ /\ Nm^3.$

Annual CO_2 emissions:

$$M_{CO2,IGG}(3\ \%)0.259 \cdot 5000 \cdot 750 = 971250\, kg\ CO_2\ /\ year \approx$$
$$\approx 971.0\, t\ CO_2\ /\ year.$$

Analogous substitutions are performed for $\chi_{O_2} = 2\ \%, 4\ \%, 5\ \%$.

Specific fuel consumption for operation the combustion-type inert gas generator

If it is necessary to analyze the influence of oxygen concentration in inert gas on the specific fuel consumption of a combustion-type inert gas generator, this dependence must be clearly defined as an assumed (scenario-based) correlation rather than as manufacturer data.

Since no explicit manufacturer-provided functional dependence of the specific fuel consumption on the oxygen concentration is available in open literature, the following linear correlation around the reference oxygen concentration of 3 % is introduced for sensitivity analysis:

$$SFC_{IGG}(\chi_{O_2}) = SFC_{IGG,ref}\left[1 + a\left(3 - \chi_{O_2}\right)\right]$$

where $SFC_{IGG,ref}$ is the nominal specific fuel consumption at $\chi_{O_2} = 3\%$ (for example, $SFC_{IGG,ref} = 0.084\, kg/Nm^3$ according to typical Moss inert gas generator data [28]);

a is the assumed sensitivity coefficient, adopted as $a = 0.03$ per 1 % O_2.

Using this assumed linear correlation, the specific fuel consumption values at different oxygen concentrations are obtained as follows.

For example, for 2 % O_2

$$SFC_{IGG}(2\%) = 0.084 \cdot \left[1 + 0.03 \cdot (3 - 2)\right] \approx 0.0865\, kg/Nm^3$$

It must be emphasized that the above dependence represents an engineering assumption adopted exclusively for scenario and sensitivity analysis. It does not represent direct manufacturer performance data and is used only to evaluate the potential influence of oxygen content on the specific fuel consumption and corresponding greenhouse gas emissions.

Table 4.3 Dependences of SFC_{IGG} of inert gas purity

χ_{O_2}, %	SFC_{IGG}, kg/Nm^3
2	0.0865
3	0.084
4	0.0815
5	0.0764

Membrane-type nitrogen system: CO_2 emission calculation

For the membrane nitrogen system, the inert gas generator itself does not burn fuel; instead, it consumes electrical power produced by the ship's diesel-generator sets. The total electrical power demand (compressor + heater) is essentially constant, $P_{el} = 194.3$ kW, whereas the inert gas flow rate decreases with increasing nitrogen purity.

The equivalent specific fuel consumption per Nm_3 of inert gas is taken from the detailed membrane calculations) as $b_{mem}(\chi_{O_2})$, kg fuel/Nm^3 of product gas. The specific CO_2 emissions per unit inert gas volume are therefore

$$e_{CO2,mem}(\chi_{O_2}) = b_{mem}(\chi_{O_2}) \cdot EF_{CO2,fuel}.$$

Annual CO_2 emissions are calculated as

$$M_{CO2,mem}(\chi_{O_2}) = e_{CO2,mem}(\chi_{O_2}) \cdot \dot{V}_{IG} \cdot t_{IG}.$$

Example for $\chi_{O_2} = 2$ % (≈ 98 % N_2).

From the membrane IGG table 3.7:

$$b_{mem}(2\ \%) = 0.0595\, kg/Nm^3.$$

Specific CO_2 emissions:

$$e_{CO2,mem}(2\ \%) = 0.0595 \cdot 3.15 \approx 0.187\, kg\ CO_2 / Nm^3.$$

Annual CO_2 emissions:

$$M_{CO2,mem}(2\ \%) = 0.187 \cdot 5000 \cdot 750 = 702750\,kg\ CO_2\ /\ year \approx$$
$$\approx 702.8t\ CO_2\ /\ year.$$

For other purity levels (10 %, 5 %, 1 %, 0.1 % O_2) the procedure is identical, with $b_{mem}(\chi_{O_2})$ taken from Table 3.7.

Results: specific and annual CO_2 emissions

Using the methodology above, the specific and annual CO_2 emissions are calculated for all operating regimes. The results are summarised in Tables 4.4 and 4.5.

Table 4.4 – CO_2 emissions of combustion-type IGG at different oxygen contents

($EF_{CO2,fuel} = 3.15\,kg\ CO_2\ /\ kg\ fuel,\quad \dot{V}_{IG} = 5000\,Nm^3\ /\ h,\quad t_{IG} = 750\,h/year$)

O_2 in dry IG, %	b_f, kg/Nm^3	$e_{CO2,IGG}$, kg CO_2/Nm^3	$M_{CO2,IGG}$, t/year
2	0.0868	0.273	1025.3
3	0.0822	0.259	971.0
4	0.0777	0.245	917.8
5	0.0731	0.230	863.5

Table 4.5 – CO_2 emissions of membrane nitrogen system at different oxygen contents / nitrogen purities

O_2 in dry IG, %	N_2 purity, %	b_{mem}, kg/Nm^3	$e_{CO2,mem}$, kg CO_2/Nm^3	$M_{CO2,mem}$, t/year
10	90	0.0367	0.116	433.5
5	95	0.0433	0.136	511.5
2	98	0.0595	0.187	702.8
1	99	0.0786	0.248	928.5
0.5	99.5	0.201	0.633	2373.8
0.1	99.9	0.298	0.939	3520.1

The table shows that relaxing the oxygen limit from 2 % to 5 % reduces annual CO_2 emissions of the combustion-type IGG by approximately 16 % at the same inert gas demand. In Table 4.5 χ_{O_2} is the residual oxygen content; nitrogen purity is approximately 100 - χ_{O_2}. The same $\dot{V}_{IG}$ and t_{IG} are used for comparison.

These results highlight the strong non-linearity of CO_2 emissions for the membrane system:

– moving from 10 % to 2 % O_2 (90 % → 98 % N_2) roughly doubles specific CO_2 emissions per Nm^3 of inert gas;

– further tightening to 0.1 % O_2 (≈ 99.9 % N_2) increases specific emissions by almost a factor of eight relative to 10 % O_2, and more than triples annual CO_2 emissions compared with the 2 % O_2 case at the same inert gas demand.

Comparative discussion

At moderate purity levels (for example, 2–5 % O_2), the membrane-type system exhibits lower specific and annual CO_2 emissions than the combustion-type IGG, owing to its lower specific fuel consumption per Nm^3 of inert gas. For instance, at 2 % O_2 (≈ 98 % N_2), the membrane system emits about 703 t CO_2/year, whereas the combustion-type IGG at the same oxygen content emits approximately 1025 t CO_2/year (difference ≈ 32 %).

However, when ultra-high nitrogen purity is required (e.g. 0.1 % O_2 ≈ 99.9 % N_2), the membrane system’s fuel demand per unit of inert gas volume becomes so large that its CO_2 emissions exceed those of the combustion-type IGG operating at 2–3 % O_2. In practice, such high-purity regimes should therefore be limited to cargoes that strictly require them, while for routine inerting operations moderate purity (2–5 % O_2) ensures a better balance between safety and greenhouse gas emissions.

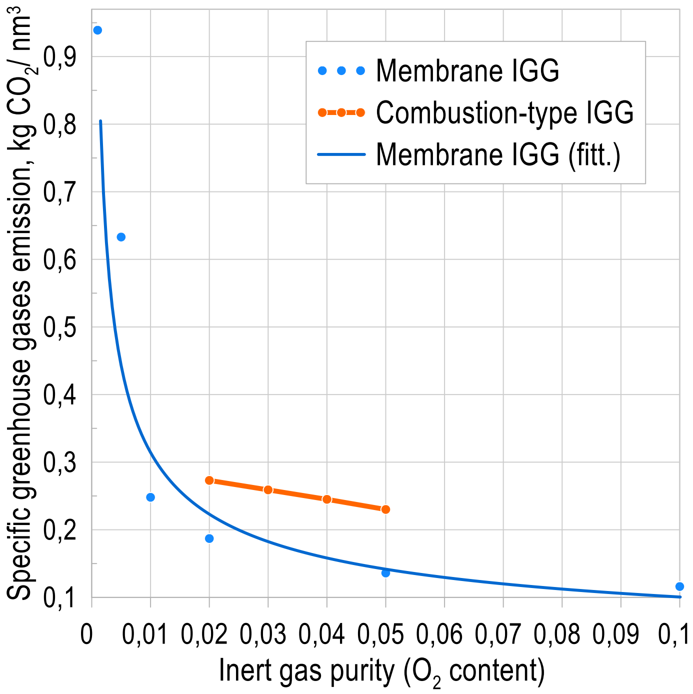

Fig. 4.1. Specific greenhouse gas (CO_2) emissions as a function of inert gas purity for membrane and combustion-type inert gas generators

4.4 Assessment of NO_x and SO_x Emissions

The purpose of this subsection is to extend the CO_2-based comparison of the two inert gas generation technologies by quantifying their emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x) and other toxic combustion-related components under the framework of MARPOL Annex VI. The analysis is carried out for the practical operating ranges of oxygen concentration in inert gas typical for tanker operation:

– for the combustion-type inert gas generator (IGG) χ_{O_2} = 2–5 % in dry inert gas;

– for the membrane nitrogen generator: χ_{O_2} = 10–0.1 % in the product nitrogen.

The same inert gas production rate and operating profiles as in the CO_2 emission assessment are adopted to ensure full consistency between energetic and ecological comparisons.

4.4.1 Methodology

For the combustion-type IGG, pollutant emission rates are proportional to fuel consumption:

$$\dot{m}_{NO_x,IGG} = \dot{m}_{f,IGG} \cdot EF_{NO_x}$$

$$\dot{m}_{SO_x,IGG} = \dot{m}_{f,IGG} \cdot S_{IGG} \cdot \kappa_{SO_2}$$

where: $\dot{m}_{f,IGG}$ - fuel mass flow rate, kg/h;

EF_{NO_x} - NO_x emission factor, kg NO_x/kg fuel;

S_{IGG} - sulfur mass fraction in fuel;

κ_{SO_2} = 2.0 — sulfur-to-SO_2 conversion factor.

For marine fuel in compliance with MARPOL Annex VI outside ECAs, the following conservative values are adopted:

$EF_{NO_x}^{IGG} = 0.087\ kg/kg, \quad S_{IGG} = 0.005$ (0.5 % sulfur fuel).

Specific pollutant emissions per unit of inert gas:

$$e_{NO_x,IGG} = \frac{\dot{m}_{NO_x,IGG}}{\dot{V}_{IG}},$$

$$e_{SO_x,IGG} = \frac{\dot{m}_{SO_x,IGG}}{\dot{V}_{IG}}.$$

For the membrane nitrogen system, emissions are indirect and originate from the diesel generator:

$$\dot{m}_{f,DG} = P_{el} \cdot SFC_{DG},$$

$$\dot{m}_{NO_x,N_2} = \dot{m}_{f,DG} \cdot EF_{NO_x,DG}$$

$$\dot{m}_{SO_x,N_2} = \dot{m}_{f,DG} \cdot S_{DG} \cdot \kappa_{SO_2}$$

Specific emissions per unit volume of nitrogen:

$$e_{NO_x,N_2} = e_{el} \cdot SFC_{DG} \cdot EF_{NO_x,DG}$$

$$e_{SO_x,N_2} = e_{el} \cdot SFC_{DG} \cdot S_{DG} \cdot \kappa_{SO_2}$$

For modern auxiliary diesel generators:

$SFC_{DG} = 0.19, \quad EF_{NO_x,DG} = 0.065, \quad S_{DG} = 0.001$ (0.1 % sulfur MGO)

4.4.2 Specific Fuel and Energy Consumption at Different O_2 Concentrations

Combustion-Type IGG:

χ_{O_2} = 2 % → 0.0868 kg/Nm³

χ_{O_2} = 3 % → 0.0822 kg/Nm³

χ_{O_2} = 4 % → 0.0777 kg/Nm³

χ_{O_2} = 5 % → 0.0731 kg/Nm³

Membrane Nitrogen Generator:

χ_{O_2} = 10 % → 0.0367 kg/Nm³

χ_{O_2} = 5 % → 0.0433 kg/Nm³

χ_{O_2} = 2 % → 0.0595 kg/Nm³

χ_{O_2} = 1 % → 0.0786 kg/Nm³

χ_{O_2} = 0.5 % → 0.201 kg/Nm³

χ_{O_2} = 0.1 % → 0.298 kg/Nm³

Table 4.6 – Specific NO_x and SO_x emissions for combustion-type IGG

O_2, %	Fuel, kg/Nm³	NO_x, kg/Nm³	SO_x, kg/Nm³
2	0.0868	0.00755	8.68×10^{-4}
3	0.0822	0.00715	8.22×10^{-4}
4	0.0777	0.00676	7.77×10^{-4}
5	0.0731	0.00636	7.31×10^{-4}

Table 4.7 – Specific NO_x and SO_x emissions for membrane nitrogen generator

O_2, %	Fuel, kg/Nm³	NO_x, kg/Nm³	SO_x, kg/Nm³
10	0.0367	0.00239	7.3×10^{-5}
5	0.0433	0.00281	8.7×10^{-5}
2	0.0595	0.00387	1.19×10^{-4}
1	0.0786	0.00511	1.57×10^{-4}
0.5	0.201	0.0131	4.02×10^{-4}
0.1	0.298	0.0194	5.96×10^{-4}

4.4.3 Discussion and Ecological Interpretation

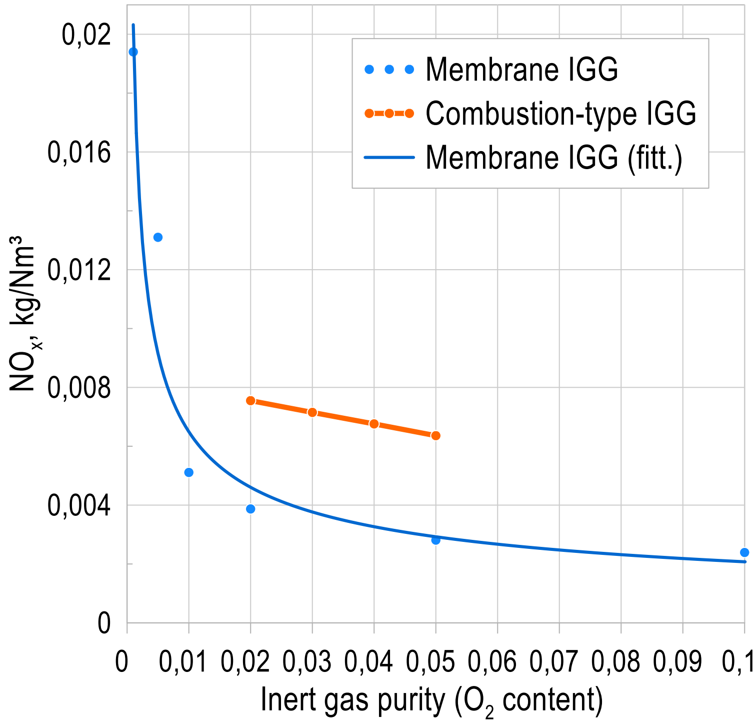

Fig. 4.2. Specific NO_x emissions as a function of inert gas purity for membrane and combustion-type inert gas generators.

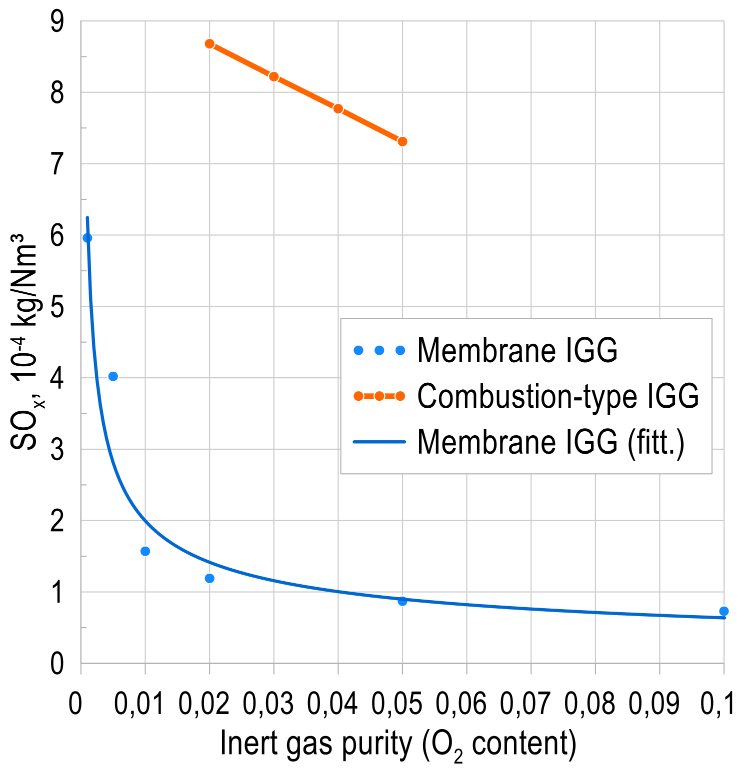

Fig. 4.3. Specific SO_x emissions as a function of inert gas purity for membrane and combustion-type inert gas generators.

The comparison shows that at practical operational oxygen levels of 2–5 %, the membrane nitrogen generator exhibits 2–3 times lower specific NO_x emissions and 7–9 times lower SO_x emissions than the combustion-type IGG. This difference is primarily caused by the lower sulphur content of diesel-generator fuel and the stricter combustion control of marine diesel engines.

At ultra-high nitrogen purities ($\chi_{O_2} \leq 1$ %), the membrane system experiences a steep rise in specific fuel equivalent consumption, which results in a strong increase in NO_x and SO_x emissions. At $\chi_{O_2} = 0.1$ %, specific NO_x emissions of the membrane system exceed the values of the combustion IGG at moderate oxygen levels.

From the standpoint of MARPOL Annex VI compliance, membrane nitrogen generators are clearly superior for standard tanker operation, while combustion-type IGG remain disadvantageous due to direct high-temperature fuel combustion and higher sulphur exposure.

CONCLUSION

1. As a result of the performed analysis, it has been established that shipboard inert gas generation systems are a critical component of explosion and fire safety on tanker vessels, and that their operating parameters have a direct impact on the energy efficiency of the ship's power plant, environmental performance, and operating costs. The requirements for such systems are strictly regulated by SOLAS, the FSS Code, ISGOTT, and the IGC and IBC Codes, according to which the oxygen content in the inert gas shall not exceed 5% by volume in the inert gas main and 8% by volume in cargo tanks, while maintaining a positive pressure at all times.

2. The review of scientific publications has confirmed that there is no universal solution for selecting an inert gas generator type, and that the optimal choice is determined by a combination of factors, including vessel type, cargo characteristics, availability of a boiler plant, installed electrical power, required inert gas purity, and environmental constraints. For large crude oil tankers, combustion-based inert gas systems remain economically justified, whereas nitrogen membrane systems are predominantly used on chemical tankers and gas carriers.

3. Based on the analysis of energy performance characteristics, it has been determined that the specific fuel consumption of combustion-type inert gas generators ranges from 0.07 to 0.09 kg/Nm^3 within an oxygen content range of 2–5% by volume. For membrane-based nitrogen systems, the specific electrical energy consumption amounts to 0.22–0.28 kWh/Nm^3 at a nitrogen purity of 95–98% and increases to 0.35–0.45 kWh/Nm^3 at a purity level of 99–99.5%.

4. It has been established that increasing nitrogen purity from 95% to 99% reduces the capacity of membrane systems by 30–60%, resulting in a significant increase in compressor load and overall electrical power consumption. At the same time, 80–90% of the total electrical energy consumed by a nitrogen system is attributable to the air compressor.

5. Combustion-based inert gas generators are characterised by stable performance at high gas flow rates; however, their operation is accompanied by:

- additional emissions of CO_2, NO_x, and SO_x;

- increased water consumption by the scrubber;

- intensive corrosion of heat-exchange surfaces and pipeline equipment;

- increased operating costs for maintenance of burners and gas-cleaning systems.

6. Membrane-based nitrogen systems, in contrast, are characterised by:

- high inert gas purity (up to 99.5% N_2);

- complete absence of combustion products in the generated gas;

- reduced corrosion risks for cargo tanks;

- lower environmental emissions;

-increased dependence on the operating режим of the ship's electrical power plant.

7. It has been determined that the use of a membrane nitrogen generation system leads to a significant increase in electrical load, especially at high nitrogen purity levels, which necessitates:

- redundancy of compressor equipment;

- verification of the adequacy of installed diesel-generator capacity.

8. Combustion-based inert gas generators, in turn, reduce the load on the ship's electrical network but increase fuel consumption, emissions of harmful substances, and operating costs associated with gas-cleaning systems.

9. Comparative analysis has shown that at an oxygen content of 5% in the inert gas, membrane nitrogen systems demonstrate advantages in both environmental and energy performance compared to combustion-type inert gas generators: the specific CO_2 emissions of membrane systems are approximately 30–35% lower than those of combustion-type IGGs, while the total energy consumption for inert gas generation is approximately 50% lower than that of combustion-based generators.

10. Comparative analysis has shown that:

- inert gas generators based on combustion are advisable for large crude oil tankers already equipped with powerful boiler plants and operating under stable cargo-handling regimes;

- membrane nitrogen generation systems are optimal for chemical tankers, gas carriers, and product tankers, where inert gas purity, environmental safety, and operational flexibility are critical.

11. For vessels transporting chemical cargoes and liquefied gases, the use of combustion-based inert gas generators is technically undesirable, since the presence of CO_2, moisture, and combustion by-products may cause:

- cargo degradation;
- corrosive damage to cargo tanks;
- non-compliance with cargo safety requirements.

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