Report

Implementation of natural refrigerants on cruise ships.

A review of rules and regulations from two Classification Societies

Authors:

Ángel Álvarez Pardiñas, Cecilia Gabrielii

Report No:

2022:01435 - Unrestricted

Clients:

Teknotherm Marine AS, Ulmatec Pyro AS

SINTEF Energy Research
Postal address:
Postboks 4761 Torgarden
7465 Trondheim

Switchboard: +47 45456000

energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

Report

Implementation of natural refrigerants on cruise ships.

A review of rules and regulations from two Classification Societies

KEYWORDS
HVAC&R
Heat pump
Refrigeration
Chiller
Classification society
Regulations
Natural refrigerants

VERSION
V2

DATE
2022-12-23

AUTHOR(S)
Ángel Álvarez Pardiñas, Cecilia Gabrielii

CLIENT(S)
Teknotherm Marine AS, Ulmatec Pyro AS

CLIENT'S REFERENCE
Research Council of Norway
308779/O80

PROJECT NO.
502002540

NO. OF PAGES/APPENDICES
24

SUMMARY
This report delves into the challenge of implementing heat pumps, refrigeration systems and chillers (vapour compression systems) that use natural refrigerants, in the maritime sector. The first part gives a context, introducing the international organisations aim to reduce greenhouse gas emissions from the shipping industry, and defining the topic of refrigerant selection. The documents on safety requirements for vapour compression systems onboard, issued by the classification societies Lloyds Registers and DNV, are then summarised. The focus is on the implications for systems using natural refrigerants. It is found that a "case-to-case" evaluation of almost all these systems must be applied. In the last section the communication with the classification societies is summarised. The goal is to contribute to clearer and more standardised requirements on the use of natural refrigerants, to facilitate their safe implementation, environmental-friendly and long-term compliant maritime refrigerants.

PREPARED BY Ángel Álvarez Pardiñas, Cecilia Gabrielii	SIGNATURE Ángel Álvarez Pardiñas Cecilia Gabrielii Cecilia Gabrielii (Jan 18, 2023 08:42 GMT+1)
CHECKED BY Rune Aarlien	SIGNATURE
APPROVED BY Petter Egil Røkke	SIGNATURE Petter E. Røkke Petter E. Røkke (Jan 18, 2023 09:02 GMT+1)

REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
2022:01435	978-82-14-07902-9	Unrestricted	Unrestricted

COMPANY WITH
MANAGEMENT SYSTEM
CERTIFIED BY DNV
ISO 9001 • ISO 14001
ISO 45001

Document history

VERSION	DATE	VERSION DESCRIPTION
V1	2022-12-06	First draft for internal review.
V2	2022-12-23	Final version after internal review and QA

Table of contents

ABBREVIATIONS

A list of abbreviation used is found at the bottom of this document.

1 Context

1.1 Greenhouse gasses (GHG) emissions in the maritime sector

The maritime sector is following a roadmap which should lead to a much cleaner future on seas. The International Maritime Organization's (IMO) greenhouse gas (GHG) strategy [1] aims to reduce the carbon intensity of international shipping (i.e., emissions per transport work) with at least 40% by 2030 and towards 70% by 2050, compared to 2008. Due to the increase in maritime traffic in coming years, this will translate into a total emission reduction of 50% by 2050. The role of port-ship interaction, speed optimization, use of alternative fuels or biofuels or energy efficiency measures (in ship design and systems used) is discussed. Supporting this strategy is the ongoing project *GreenVoyage-2050* between IMO and the Norwegian Ministry of Climate and Environment, with the objective of testing and demonstrating technical solutions to reduce GHG emissions. A guide was recently published with good practices and considerations on selection of technologies for a greener maritime sector [2]. Norway has since long spearheaded development of measures to reduce GHG emissions, with high ambitions for the current decade in terms of zero-emission cruise ships in Norwegian fjords or reduced emissions at port.

The forecast documents for the maritime sector from some of the main Classification Societies point at the previous IMO strategy (to be revised in 2023) and EU initiatives and regulations, as key drivers. As indicated in the *Maritime Forecast to 2050* by DNV [3], the focus in this sector will be on fuel availability and infrastructure to implement carbon-neutral fuels. New alternatives such as hydrogen, ammonia, e-fuels, are indicated, with greater emphasis on safety. The impact of energy efficiency on decarbonization is also important, making the most out of the fuel or the electrified infrastructure (batteries) onboard. Electrification of ships is linked to lower availability of surplus heat at sufficiently high temperatures for direct use in heating systems or heat-driven cooling systems (e.g., absorption units). Thus, efficient heat pumps, chillers or integrated solutions for heating and cooling appear as crucial in this scenario, and even more in cruise ships, where the thermal needs often consume an important share of the electricity produced by engines and generators. However, there are only very generic references to "improved efficiency of machinery" in this forecast document.

1.2 Vapour compression systems and refrigerants

Heat pumps, refrigeration systems or integrated systems typically operate according to a vapor compression cycle. This means that they absorb heat from a heat source at relatively low temperature and reject heat to a heat sink at a higher temperature level. The second law of thermodynamics dictates that an energy input in the form of work is needed to sustain this process (Figure 1, left). In practice, at least four components are needed in a vapour compression system, i.e., evaporator, compressor, condenser, and expansion device (Figure 1, right). A fluid, the refrigerant, flows following a cycle. In the evaporator the refrigerant is evaporated at relatively low pressure and temperature due to heat transfer from the heat source. Then, work is transferred to the refrigerant in a compression process, in which pressure and temperature increase. Heat is then transferred from the refrigerant to the heat sink in a condensation process. Finally, the refrigerant is expanded to a lower pressure, and the cycle is repeated. Depending on the objectives with the vapour compression cycle, it should be referred to as either a heat pump (only heating needs), a refrigeration system or chiller (only cooling needs) or an integrated system (heating and cooling needs simultaneously).

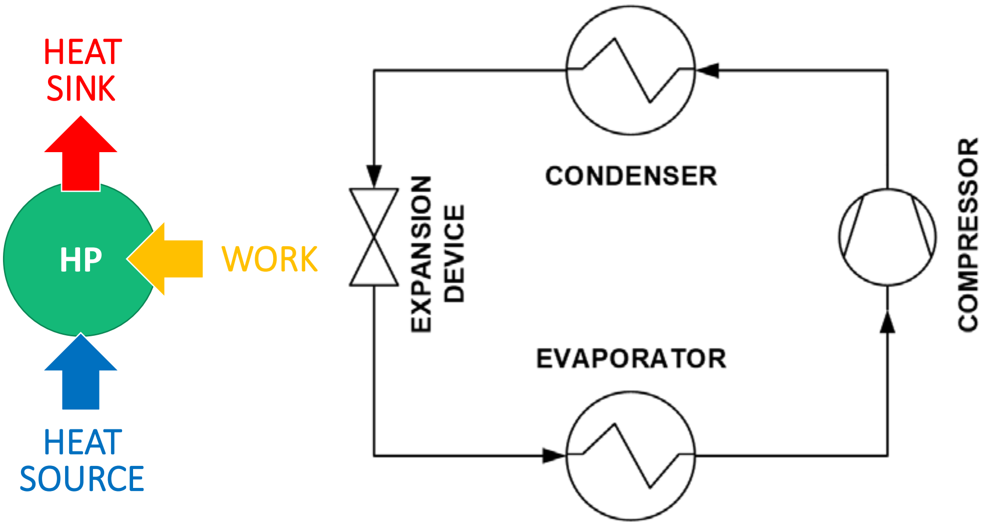

Figure 1. Basic concept (left) and cycle of a vapour compression system (right).

The efficiency of a heat pump, named Coefficient of Performance (COP), relates the amount of useful heating and/or cooling produced divided by the energy input (typically electricity) to the compressor. Higher efficiencies are attained for systems with a low temperature difference between heat source and heat sink. On the other hand, it is also beneficial with integrated systems, enabling a high COP even if this typically implies a higher temperature difference between heat source and sink, and thus, the compressor power consumption is also higher. Typically, the heat pump COP is well above one, which is the maximum achievable efficiency by an ideal electrical boiler. Thus, heat pumps require far lower power input to meet the demands onboard, leading to reduced fuel consumption, better utilization of shore power and longer operation time on batteries.

A crucial aspect related to heat pump is refrigerant selection. The specific properties of each refrigerant affect system layout, design pressures, material selection, need for safety measures, etc. Since the introduction of refrigeration technology, various fluids have been used. They can be grouped into *natural refrigerants* and *synthetic refrigerants*, where the former are substances found in nature, and the latter are chemicals created by synthesis and are foreign to nature. Refrigerants in heat pumps and refrigeration systems are ideally completely contained within the equipment, but in practice there are significant leakage rates, especially in maritime installations. Consequently, refrigerants end up in the atmosphere, and thus there are restrictions on their use depending on their environmental impact. Obviously, the use of natural refrigerants is to be preferred, as leakages would have no adverse environmental impact.

The evolution of refrigerant selection is illustrated in Figure 2, showing how the various classes of synthetic refrigerants were introduced to the market.

- At the beginning of mechanical refrigeration, only **natural refrigerants** such as ammonia, carbon dioxide and diethyl ether were used. However, many were toxic and/or flammable, and this was a concern for the people working with these fluids.
- The first synthetic refrigerants (**chlorofluorocarbons CFCs, hydrochlorofluorocarbons HCFCs**) were introduced to mitigate safety concerns in the 1930s, but it was later discovered that these fluids were causing depletion of the ozone layer and were phased out following the ratification of the Montreal Protocol (in force on Jan. 1st, 1989). Concerning the maritime sector, new installations are affected by a total ban of CFCs since 2005, and HCFCs since 2020 [4]. These refrigerants must be collected in a controlled way, and deliberate discharge to the atmosphere is prohibited.

- The next generation of synthetic refrigerants, **hydrofluorocarbons (HFCs)**, has no ozone depletion potential. However, HFCs are strong greenhouse gases and are now being phased out according to the EU F-gas regulation [5] and Montreal Protocol amendments [6]. HFCs in the maritime sector are not regulated by IMO, and this sector is not directly affected by the 2014 F-gas regulation, with some exceptions. HFC recovery and avoiding of intentional releases of refrigerant are mandatory on ships. Moreover, EU-flagged ships with systems containing relatively large charges of HFC with global warming potential (GWP) above 2500 (100-year basis) cannot have these systems serviced with new refrigerant from 2020 or recycled/recovered refrigerant from 2030. An indirect effect of the F-gas regulation will be seen on the cost of refrigerants, due to the progressive reduction in HFC import capacity. This should be considered by ship-owners.
- **Hydrofluoroolefins (HFOs)** were introduced to mitigate the challenge of global warming potential. HFOs are mildly flammable and have very low retention time in the atmosphere. However, recent studies indicate some concerns with these refrigerants on different levels, as it has been reviewed in a recent report by *ATMOsphere* [7]. First, that HFOs suffer total or partial atmospheric degradation into Trifluoroacetic acid (TFA), which is shown to accumulate in (drinking) water reservoirs. Even if there is insufficient research to confirm it, long-term exposure to TFA could damage liver and thyroid in humans. Moreover, TFAs is a subgroup within PFAs (per- and polyfluoroalkyl substances), and adverse health effects from some of these PFAs have been proven. Several European countries are trying to include some HFCs and HFOs under the REACH umbrella, a regulation governing chemicals that can be produced and used legally in EU, overriding the F-Gas regulation. However, this proposal is delayed [8]. Additionally, some of the feedstock and decomposition products have significant global warming potential (GWP) and even ozone depletion potential (ODP), and leaks have been reported in HFO production facilities. Moreover, the operational cost of using HFO could be substantial, due to the cost of the refrigerant itself. Finally, the outcome of the ongoing F-gas revision is unclear, with a potential phaseout affecting also HFOs. This is currently debated between industry and EU's Committee on the Environment, Public Health and Food Safety (ENVI) [9].
- With the questionable history of synthetic refrigerants, it is advised to focus on using **natural refrigerants** and to develop systems utilising the characteristics of these fluids [10]. The natural refrigerants, carbon dioxide (R744), ammonia (R717), hydrocarbons, have experienced increased interest and are already competitive compared to synthetic refrigerants in terms of energy efficiency in many applications.

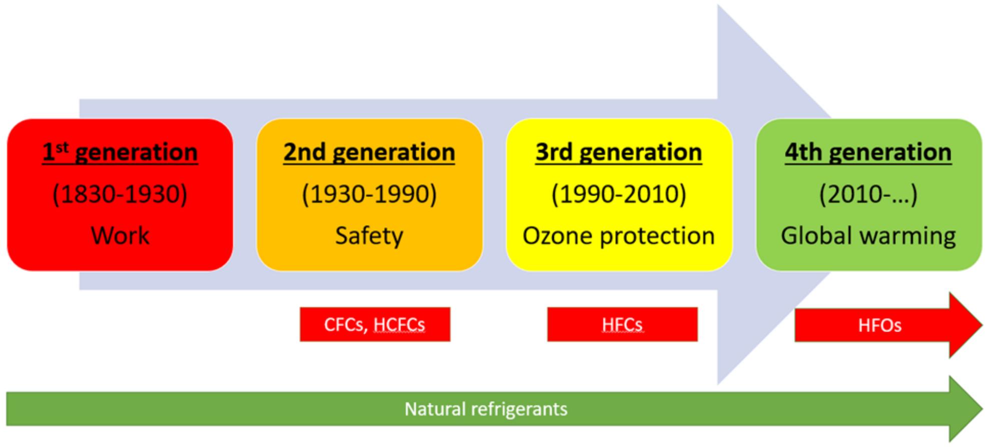

Figure 2. Evolution of refrigerants since the introduction of mechanical refrigeration technology.

Even if the maritime sector is moving away from HCFCs, and HFCs with high GWP, there are still many ships with active systems using R22, R134a or R410A. An interesting review on the current status in terms of refrigerant inventory is given in [11], with the main focus on the Nordic countries.

2 Classification societies

Ship classification societies are non-governmental organizations defining and maintaining technical standards that ships must fulfil to be registered, obtain marine insurance, enter ports and waterways, etc. Societies also perform surveys to ensure that ships comply with these standards.

The documents from Lloyds Register (LR) and Det Norske Veritas (DNV) have been screened for this report. The focus has been on those chapters and sections dealing with heating, ventilation, air conditioning and refrigeration (HVAC&R) units, and how different refrigerants are to be handled.

2.1 Lloyds Register

In the latest update from July 2022 of LR's Rules and Regulations for the Classification of Ships [12], the following sections were considered most relevant and were reviewed thoroughly:

- Part 6, Chapter 3: Refrigerated Cargo Installations. This chapter applies *to refrigerated cargo installations of refrigerated cargo ships, refrigerated container ships, fish factory ships, fishing vessels, fruit juice carriers, and the re-liquefaction/refrigerating plant of liquefied gas carriers and chemical carriers or tankers.* Here, the requirements related to the class notations "RMC" (Refrigerated cargo installations) are stated. Even though this chapter is not directly relevant to cruise ships, it is s a prerequisite for the chapters applicable to cruise ships.
- Part 7, Chapter 15: Refrigeration Systems and Equipment Serving Provision Stores and Air-Conditioning Installations. *This chapter applies to ships having centralised refrigeration systems, designed to reject heat from refrigerated stores or from the air-conditioning and ventilation arrangements fitted to both passenger and crew accommodation spaces*. The requirements stated here aim *to mitigate risks associated with the safety of refrigeration and air-conditioning machinery.* Complying ships are given the class notation "RPA" (Refrigeration Machinery for Provision Stores and Air-conditioning).
- Part 7, Chapter 11: Arrangements and Equipment for Environmental Protection (ECO Class Notation). Optional compliance for ships designed with special concern for the environment. It provides requirements *for the design and construction of ships having a reduced environmental impact during operation compared to ships designed and constructed solely in accordance with the relevant minimum statutory requirements of the MARPOL convention, and as such, the requirements in this chapter necessarily exceed the relevant minimum statutory requirements of the MARPOL convention*.

2.1.1 General requirements

Here, a summary is given of the most relevant requirements that must be fulfilled, regardless of the refrigerant used. However, it should be clarified that *the primary refrigerants ammonia, hydrocarbons or carbon dioxide shall not be used in direct expansion fan coil units (FCU) located in accommodation spaces. The use of these refrigerants in machinery spaces, such as a separate air handling unit (AHU) compartment, may be accepted subject to suitable safety arrangements being provided to the satisfaction of Lloyd's Register*. Note that no other flammable refrigerants (e.g., HFOs or HFCs) are mentioned in this context.

- **Piping**
    - The required piping class depends on the refrigerant used, e.g., Class I for ammonia and, Class II for propane.
    - Provision for expansion and contraction is to be made.
      All pipes are to be adequately supported and secured to prevent vibration.
- **Pressure relief devices**
    - Relief valves are to be adjusted, and bursting discs selected, so they relieve at a pressure not higher than the design pressure of the system.

- Relief devices are required between the discharge port of positive displacement compressors and gas delivery stop valves. Relief devices must lead to the suction side of the compressor. Servo-operated valves are accepted. They may be omitted if motive power is below 10 kW. Similar approach applies to refrigerant pumps.
- For pressure vessels with liquid that can be isolated, two pressure relief valves (or bursting discs) with a changeover valve are required. It is possible to reduce this to one valve (and no changeover) if the tank volume is below 300 litres or the relief device is connected to the low-pressure side.
- Pressure relief valves must be mounted in a way ensuring that they cannot be isolated.
- Relief devices are needed if liquid entrapment can happen between shut-off valves.
- Circumstances which could lead to an inadvertent discharge of refrigerant to the atmosphere must be avoided.
- The system is to be designed so that any pressure increase due to fire conditions will be safely relieved. A safe place is above deck, away from personnel access or air intakes.
- Discharge pipes from safety valves must be designed to preclude ingress of water, dirt, or debris.
- Discharge pipes must be dimensioned according to specified equations. As a minimum, they must have the same bore as the relief valve outlet, or as the total bores if several relief valves share the discharge pipe. The pipe must be properly supported.

- **Pressure vessels**
  - Pressure vessels must be thermally insulated to minimise condensation of moisture. Efficient vapour barriers and protection against mechanical damage must be in place. Steel surfaces must be suitably protected against corrosion prior to insulation.
  - When several pressure vessels are interconnected by pipework without valves, so that they cannot be isolated from each other, they may be regarded as a single pressure vessel, provided that the interconnecting pipework does not prevent effective venting of any of the vessels.
- **Compressors**
  - If hermetic or semi-hermetic compressors have their electric motor cooled with refrigerant, it is not allowed to have more than one of these compressors per system.
  - If several compressors operate in parallel, it must be possible to stop them individually, and to select compressor to equalise running hours.
  - The required sensors and protections for refrigeration compressors must be specified, e.g., suction pressure and discharge pressure, oil pressure, automatic shutdown with low lubricating pressure or high discharge pressure. If compressors are above 25 kW electric input, additional requirements apply.
  - New compressor types or improvements of existing types are subject to an agreed test programme to complement the design appraisal and review of documentation.
  - Check valves must be connected at compressor discharges.
  - Stop valves must be provided on suction and discharge ports.
  - Suction strainers and lubricating oil filters must be provided and so arranged that they are easily accessible for cleaning or renewal of the filter elements, without substantial loss of refrigerant or lubricating oil.
  - The correct direction of rotation is to be permanently kept visible on the compressor.
- **Oil separators**
  - Oil separators must be provided at compressor discharges and are to be fitted with a control arrangement to enable the separated oil to be returned to the compressor crankcase. Wire gauze used in separators is to be sufficiently robust and well supported.

- **Pressures**
  - The design pressure is regarded as the maximum working pressure, defined as the maximum permissible pressure in the system. The set-point of pressure relief valves or other safety devices must not be higher than the maximum working pressure.
  - The design pressure at the low-pressure side is the saturated vapour pressure at 46°C.
  - The minimum design pressure at the high-pressure side, must be at least 1.11 times higher than the compressor cut-off pressure, and the cut-off pressure must not be less than 1.11 times higher than the condenser saturation pressure at 46°C.
  - Minimum design pressures applicable to different refrigerants is given in Table 15.2.1.
- **Machinery location**
  - The machinery must be located in a properly ventilated compartment. The arrangement must allow for components to be opened and accessed for inspection and replacement (space around system is important). Alternative arrangements must be submitted to LR.
  - Mechanical ventilation systems must have at least 30 air changes per hour.
  - Systems with toxic or flammable refrigerants shall be placed outside the main machinery space, in a separate gastight compartment.
  - Refrigerating machinery using non-toxic and non-flammable refrigerants will not, in general[1], be required to be placed in a separate compartment outside the main machinery space.
  - Openings for pipes, electrical cables and other fittings in bulkheads and decks, are to be fitted with gastight seals.
  - Gas storage compartments, for the purpose of containing reserve supplies of refrigerant, must be placed in separate ventilated spaces, with at least 10 air changes per hour.
  - Access doors to refrigerated spaces is to be opened outwards. Sliding doors can be used where doors lead to an external space.
  - Access ways to the refrigerated spaces must be designed to facilitate escape in case of emergencies, and transport/removal of personnel on stretchers.
  - Access ways and refrigerated compartments must be provided with an independent lighting system. Redundancy and emergency lighting are required.
  - Means shall be provided for opening the access doors and for sounding the alarm from inside refrigerated spaces.
- **Pressure tests**
  - At location of the manufacturer (Table 15.3.1):
    - Primary loop tests are to be hydraulic or, if appropriate safety measures are taken, they may be pneumatic using dry inert gas (nitrogen). After successful pressure test, a tightness test must be performed.
    - Secondary refrigerants or cooling water loops must be hydraulic tested to 1.5x design pressure, but in no case less than to 0.35 MPa.
  - After installation:
    - Primary refrigerant piping welded on site, are to be tested to 1.5x design pressure, normally pneumatically. Tests may be omitted and substituted by non-destructive examination by approved operator.
    - Tightness tests are required after successful pressure tests and are to be performed with inert gas at the design pressure, and in presence of an inspector.
    - Secondary refrigerant piping welded on site must be hydraulically tested to 1.5x design pressure, in no case less than 0.35 MPa.

[1] The term "in general" is typically used to for not allowing CO_2 systems in the main machinery room.

- **Detection systems**
  - Fixed refrigerant detection systems must be installed in the machinery compartment, or in space and ventilation ducts when the machinery compartment ventilation system shares ventilation with other compartments.
  - As a minimum, the system is to activate at a low-level concentration to give warning of a refrigerant leak, and at a high-level concentration corresponding to the refrigerant's safe occupational level.
  - The system must be designed so that it may readily be tested and calibrated. A detector failure shall initiate an alarm.
  - Audible and visual alarms must be activated both inside and outside the affected space. The alarms should be readily identifiable, visible, and audible in all locations where the refrigeration equipment is placed.
- **Alarm system**
  - In primary refrigeration loops, alarms are to be initiated in the event of fault conditions of the compressor, such as high discharge pressure, low suction pressure, high oil pressure and temperature, high discharge temperature, motor shutdown, among others.
  - In secondary refrigeration loops, alarms are to be initiated at, for example pump failure, high cooling water temperature, fan failure, high and low refrigerated air temperatures, etc.
- **Personnel warning systems**
  - A system to monitor the well-being of crew members entering refrigerated spaces must be installed. Crew members shall receive warnings and must indicate their well-being by accepting the warning.
- **Testing and trials**
  - Tests should include:
    - Verification of control, alarm, and safety systems.
    - Simulation tests for failure of refrigeration equipment, verification of functioning of alarms and systems in service.
    - Verification of accuracy, calibration and functioning of temperature control.
  - Special tests may be required for plate heat exchangers.
  - Acceptance trials are to demonstrate that the provision store or AC system meets the design duty, at conditions as close as possible to those in service.

2.1.2 ECO class notation[2]:

The following requirements, must be fulfilled to obtain the ECO class notation – only applicable to installations with more than 3 kg refrigerant, not including stand-alone refrigerators, freezers, and ice makers:

- CFCs and HCFCs in existing and new refrigeration and AC installations are prohibited, in agreement with IMO.
- *Where possible, natural refrigerants, such as ammonia, carbon dioxide and hydrofluoroolefins (HFOs)[3], should be used. Where hydrofluorocarbon (HFC) refrigerants are used, they must have an Ozone Depleting Potential (ODP) rating of zero and a Global Warming Potential (GWP) of less than 1950, based on a 100-year time horizon*.
- Measures must be taken to minimize releases during maintenance and use of recovery of units.
- Refrigerants must never be mixed during evacuation of the charge.

[2] As explained above, optional compliance for ships designed with commitments to the environment.
[3] HFOs cannot be considered natural refrigerants, and this has been communicated to LR to check if there was a misconception or if it was just a typo.

- Refrigerant leakages must be minimised by leak prevention and periodic leak detection procedures (more information in Table 11.2.1). Records for demonstrating leak testing are required. After a leak is identified, repaired, and recorded, a re-check must be performed prior to resuming normal operation, and at the latest one month after repair.
- The leak detection system, appropriate to the actual refrigerant, must include alarms in permanently manned locations (e.g., 25 ppm for ammonia and 300 ppm for halogenated refrigerants). The detection systems must be checked at least every 12 months.
- Procedures for refrigerant management must be established and implemented. Refrigerant inventory and logbook records must be maintained.
- Maintenance is only to be performed by personnel with experience and proper qualifications.
- For flammable refrigerants (classification as in ISO 817:2014+A1:2017 [13]), the following requirements apply:
    - Refrigerants classified as A2L, or with higher flammability or toxicity classification, the systems must be designed specifically to consider flammability and toxicity. Systems for non-flammable refrigerants shall never be retrofitted for use with flammable refrigerants. The ventilation should be separated from ducts serving other spaces.
    - Refrigeration machinery spaces must be fitted with non-sparking mechanical ventilation, with at least 30 air changes per hour. Areas where gas accumulation may occur, are to be avoided (considering density of refrigerant vapour and potential ignition sources).
    - The leak detection equipment must be suitable for use in hazardous areas. Means must be in place for measurement of oxygen levels prior to personnel entering the space.
    - The alarm for leak detection must be activated if gas concentrations are above 30% LFL.
    - A risk assessment must be performed reviewing application [14], location, and installed refrigerant charge.
    - Personnel handling such refrigerants must hold appropriate certification.
    - Spaces containing these refrigerants must be indicated on a “hazard area plan”.

2.1.3 Ammonia (R717)

Due to its toxicity and mild flammability, there are additional requirements for ammonia systems:

- Minimum safety equipment must be positioned in accessible protected storage (locked glass fronted cabinets) located outside the machinery compartment. This must include, among others:
    - Two sets of ammonia protective clothing (including helmet, boots, and gloves).
    - Two portable battery powered hand lamps (certified as safe-type).
    - Two sets of self-contained breathing devices (compressed air).
    - Irrigation facilities or eye-wash bottles, and hand or foot-operated showers.
- Requirements related to the compartment containing ammonia machinery include:
    - An independent mechanical ventilation system installed for removing heat, keeping ammonia levels within acceptable threshold levels, and disposing of ammonia.
    - A negative pressure ventilation must be included, with 30 air changes per hour and alarm activation if fan stops.
    - Fresh air inlet shall be arranged at low level, and exhaust outlet at high levels.
    - Fixed ammonia detectors must be installed.
    - Systems with a refrigerant charge above 50 kg, shall include an emergency body shower and two access doors per compartment, unless impractical.
    - Systems with refrigerant charge below 25 kg may be located within the main machinery space.
- Additional requirements:
    - Automatic air purgers are to be provided, with their discharges being led through water before venting to atmosphere.

- The cooling water returning from seawater cooled condensers are not to be led into the main machinery spaces.
- Fresh water condenser cooling systems are to be provided with pH meters to activate audible and visual alarms in the event of a leak.
- Discharge from relief valves must be led through water before venting to the atmosphere. Vapour detectors in discharge pipes must activate audible and visual alarms in the event of ammonia leakage.

2.1.4 Carbon dioxide (R744)

Systems using carbon dioxide (CO_2) as refrigerant, operate at much higher pressures than systems with ammonia, hydrocarbons, or halogenated refrigerants. The following *additional* requirements applies to systems with CO_2:

- The maximum working pressure and maximum pressure at rest conditions, are to be maintained by fitting a supplementary refrigeration unit. It must be demonstrated that the system can operate with a local ambient temperature of 45°C (machine room).
- Pressure vessels shall be thermally insulated, to prevent operation of the relief valves within 24 hours after stopping the supplementary unit.
- Compartments housing CO_2 units need self-closing gas tight access doors between the compartment and dedicated escape routes.
- In compartments normally occupied, and where 30 changes per hour are not desirable, (e.g., production areas on fishing vessels), a negative pressure ventilation system, capable of 10 air changes per hour, must be installed. Ventilation systems must be automatically activated in the event of a leakage where the concentration of CO_2 reaches a predetermined level (5000 ppm)[4].
- Measures must be taken to avoid dry ice formation, including a method used to protect against formation of powder and choking of relief valves. Pressure relief valves shall only vent vapour.
- In cascade systems using both carbon dioxide and ammonia, the effects of carbon dioxide leaking into the ammonia side must be considered. The ammonia system must be designed to either withstand the design pressure on the carbon dioxide side or have relief arrangements to safely deal with the additional vapour produced if a leak occurs.

2.2 DNV

The latest relevant documents from DNV date from 2021 and 2022, depending on the parts and chapters. The following sections were considered most relevant and were reviewed thoroughly:

- Part 4, Systems and components, Chapter 6: Piping systems [15]. Rules in this chapter apply to piping systems for assignment to the main class notation*. A piping system is defined to include piping, as well as components in direct connection to the piping such as pumps, compressors, heat exchangers, evaporators, independent tanks, etc. with the exception of main components such as steam and gas turbines, diesel engines, reduction gears and boilers*. HVAC&R systems are part of these piping systems.
- Part 6, Additional class notations, Chapter 7: Environmental protection and pollution control [16]. Optional compliance for ships aiming to achieve the "Clean" class notations. It sets requirements *for ship's design, operation and equipment reducing the environmental impact from emissions to air, discharges to sea, and deliveries to shore from vessels. The requirements for these additional class notations are in compliance with, or more extensive than those found in international maritime regulations currently in force*.

[4] Much lower than the 1500 ppm level indicated by DNV for alarm with CO_2 systems.

2.2.1 General aspects

Here, a summary is given of the most relevant requirements included in DNV rules and regulations:

- **Piping**
  - For permanently installed pipes and fitting, the weight must not affect machinery or cause additional stresses in pipes.
  - Materials must be chosen based on refrigerant and application. For example, copper or zinc must never be used together with ammonia, and magnesium or zinc are not allowed together with fluorinated refrigerants.
  - Installation of pipes for water or steam above electric switchboards must be avoided.
  - Avoid installations of water pipes, air pipes and sounding pipes through freezing chambers.
  - Piping located in areas where exposure to high humidity or water splashing is expected, e.g., fish processing spaces, shall be of corrosion resistant material, e.g., stainless steel.
  - Piping system must be easy identified, with valves permanently and clearly marked.
  - Condenser cooling water tubes must be of materials with high resistance to corrosion and erosion. The water velocity should not exceed 2.5 m/s for aluminum or brass pipes and 90/10 copper/nickel pipes, while the maximum velocity for steel pipes is 1.5 m/s.
- **Refrigerants**
  - The refrigerants are divided in two groups, where Group 1 include HCFCs, HFCs and R744, and Group 2 only includes R717. In Group 1, R744 and R32 are treated differently due to high operating pressures and flammability, respectively.
  - For systems with Group 2 refrigerant (R717), R744 or R32, the requirements apply to plants with a motor effect of 3 kW and above, while for the remaining Group 1 refrigerants, they only apply above 100 kW.
  - Other refrigerants, i.e., not belonging to Group 1 or 2, shall be given special consideration[5].
  - Design pressure corresponds to the vapour saturation temperatures at 55°C for the high-pressure (HP) side and 45°C for the low-pressure (LP) side. Any parts of the LP side that can be subjected to high pressures, e.g., during defrosting, are to be designed as a HP side.
- **Safety valves**
  - One safety valve per compressor stage must be included, with set pressure equal to design pressure. It is possible to have an overflow valve to lead gas from discharge to suction.
  - Pressure gauges for each compressor stage are needed, indicating the maximum working pressure. A pressure transmitter may also be accepted.
  - Safety valves shall be located ahead of the shut-off valve at the discharge side of the compressor, and the outlet shall lead back to suction side.
  - If there is a shut-off valve between a pressure vessel and a safety valve, it shall be sealed in an open position. Connections to the safety valve shall be above liquid level.
  - Safety valves must open at a pressure not lower than design pressure and must be fully effective at a pressure which is maximum 10% higher.
  - Discharge piping shall be calculated to have sufficient capacity (equations in document).
  - Safety valve outlets are to be routed to a safe position on open deck. If R32 and R717 are used, the outlets shall be at the highest level possible.
- **Machine rooms**
  - Spaces where flammable or toxic gases/vapours may accumulate, or where low oxygen atmosphere may occur, shall be provided with adequate ventilation under all conditions.
- **Shut-off valves**
  - These are to be provided at the inlet and outlet of all heat exchangers and shall be equipped with a vent and a drain. There could be exceptions in case of small capacity.

[5] Hydrocarbons would be in this category

- **Manual override**
    - The automatic control must be equipped with a manual override function, so that if part of the system fails, manual operation is always possible.
- **Pressure vessels**
    - For refrigerants in Group 2 (R717), pressure vessels shall comply with Class I requirements (as for piping) and shall be delivered with compliance documents.
    - In closed refrigerating circuits, pressure vessels without inspection openings may be accepted.
    - Liquid level indicators of glass tubes are not permitted, except for long glass plates, and if self-closing valves in both connections are implemented.
- **Testing and inspections**
    - Function testing of compressors shall be performed in the presence of a surveyor, and shall include safety functions (operating pressures), capacity test (running at design conditions) and alarm activation.
    - Hydraulic pressure testing shall be made at 1.5x design pressure, but not exceeding design pressure by more than 70 bar.
    - Monitoring shall include pressure indication of, e.g., lubricating oil and compressed refrigerant, and with alarm for low and high values.
    - Installation inspections shall be witnessed by a surveyor (unless DNV accepts a different procedure), to confirm correct setting of control, monitoring, and safety devices, as well as function test under working conditions and vibrations, if applicable.
    - Hydrostatic tests of piping must be performed for all Class I and Class II pipes and integral fittings, at a pressure of 1.5x design pressure. The tests shall be made after completion of manufacturing but before insulation and coating, and in the presence of a DNV surveyor.
    - If hydraulic tests on board have an unfavourable effect on the refrigerant, it can be substituted by pneumatic pressure testing with N_2, CO_2, or air.
    - Secondary fluid tests are to be performed at a pressure of minimum 4 bar.
    - If a 100% radiographic examination and heat treatment after welding is carried out, DNV may refrain from the hydraulic test.
    - All piping systems shall be properly flushed, checked for leakage, and functionally tested under realistic working conditions.
    - For refrigeration systems the safety instrumentation, including automatic stop functions, refrigerant leakage detection, emergency stops, alarm call buttons etc., shall be tested.
- **Refrigerant detection**
    - This is addressed in the following subsection (2.2.2) because it mostly focuses on natural refrigerants and R32.

2.2.2 Class notation Clean

To achieve the class notation "Clean", DNV sets the following requirements concerning refrigerant utilization, which applies to refrigeration systems having more than 10 kg initial charge. Domestic type stand-alone air conditioning units and refrigerators are not included [16]):

- Use of ozone depleting substances is not permitted (in line with IMO/MARPOL).
- Refrigerant shall be natural refrigerants such as NH_3 or CO_2, or a HFC with GWP ≤ 2000[6].
- Refrigerant systems must be listed and included in the refrigerant management plan.
- Annual refrigerant leakage shall be as small as possible, but not more than 10% of the total charge for each system. Any leakage must be documented, as well as any topping up of refrigerant.

[6] No reference, in principle, to HFOs.

- If leakages are observed, corrective measures according to detailed procedures shall be implemented.
- The method for leakage detection and control is to be described and justified in the refrigerant management plan, and consist of one or more of the following:
    - automatic detections (considering the specific refrigerant type),
    - logging of refrigerant volumes at regular intervals (minimum once per week), or
    - weekly control of leakage by portable refrigerant detector.
- Mixing of refrigerants shall be avoided though proper labelling and colour coding of containers.
- To ensure proper refrigerant recovery, compressors shall be capable of evacuating the system charge into a liquid receiver. Recovery units shall be provided to facilitate evacuation. This does not apply to ammonia systems.
- Refrigerant systems are to be built with suitable means of insulation. Maintenance shall be performed with minimum release of refrigerant (unavoidable releases are acceptable). Isolating valves shall be installed for compressor removal and replacement. Suitable permanent valves for recovery connections should be implemented.

2.2.3 Refrigeration systems with R32, R717 or R744

Natural refrigerants and R32 are given special attention due to safety aspects, including R717's toxicity and mild flammability, R744's high operating pressures, and R32's flammability. R32 was included in the latest document from DNV (2022), but with no restrictions or requirements for units below 3 kW capacity *as the refrigerant charge is too small to be particularly hazardous*.

Some of the special requirements are listed below:

- **Machine room**
    - The complete refrigerant circuit shall be located in a separate machine room with the following characteristics:
        - Surrounded by steel decks and bulkheads (for R744, other materials could be accepted upon special considerations)
        - Fitted with self-closing gas-tight door opening outwards (two access doors except for small refrigerating machinery room).
        - Room height must be above 300 mm.
        - Decks and bulkheads must be without openings and pipe and cable penetrations.
        - Located as high as reasonably possible within the ship, subjected to approval regarding accesses and emergency exits.
    - For ships with a maximum length of 65 m[7], systems using less than 25 kg R717 or R744 may be located in the engine room or another suitable space (not accommodation spaces). All parts of the refrigerating system shall be located together. A secondary refrigerant, or heat transfer fluid, must be used in air coolers for provision stores or AC systems. The area where the refrigeration system is located, must be fitted with a hood, negative ventilation system, and a water spray system. R744 units with more than 25 kg may be accepted if a complete release of refrigerant due to leakage will not result in oxygen concentration below 19% by volume.
    - **Ventilation**
        - For R717 and R32, ventilation inlets and outlets must be located sufficiently high.
        - Thin plate ventilation ducts used in other spaces shall not be lead through refrigeration machinery rooms. Air coolers for AC plants are not to be located within refrigeration machinery room.

[7] The document also states that systems with less than 25 kg of R717 can be specially considered, without referring to the ship length.

- A separate ventilation system is required for the refrigeration machinery room, with a minimum of 30 air changes per hour.
- The required position for ventilation exhaust depends on the refrigerant (R717 on top, R32 on floor).
- Avoid that under-pressure could complicate opening of doors. A temporary stop of ventilation with a button (inside the room) shall be installed to allow easy opening.
- Alarm activation buttons shall be available in rooms.
- Mechanical catastrophe ventilation must be installed for refrigerants R717 and R32.
  - R717: the air flow shall be calculated as the largest of the following values:
    - 7.2 m^3/h per kg refrigerant for charges up to 500 kg, and 3 m^3/h above 500 kg. If several independent loops with primary refrigerant are installed, the circuit with the largest charge are considered.
    - 300 m^3/h per m^2 deck area of refrigeration machinery room.
  - For R32, this calculation shall be corrected according to evaporating heat at atmospheric pressure and acceptable concentration in ventilation exhaust air.
- Areas on open deck within 1 m from inlet ventilation openings and 3 m from outlet ventilation of refrigerating machinery rooms with R32 and R717, are classified as hazardous Zone 2.
- For R717 and R32:
  - All non-Ex protected electrical equipment in refrigerating machinery rooms shall be de-energized automatically in case a refrigerant concentration above 5000 ppm is detected. It shall also be possible to de-energize this equipment with a central switch outside the room.
  - Normal and catastrophe ventilation system shall be arranged with Ex-protected motors and non-sparking fans.
  - Ex-protected emergency lighting fixtures are required in the refrigeration machinery room.
  - Access doors and emergency escape routes must have external waters screen and eye washers, with constantly available water (not necessary for R32).
- R32 machine rooms should be accessed only from the top. Access from open deck could also be accepted.

- **Refrigerant circuit**
  - R717 and R744 may be used for direct expansion in cooling/freezing equipment located outside the refrigerating machinery room and within normally manned spaces, such as on fishing vessels and fish factory ships. Refrigerant piping is not to be located within crew accommodation spaces, the navigating bridge and the main engine room, or such that all access to the main engine room will be blocked in case of pipe rupture.
  - A quick closing valve must be installed in the delivery line (liquid and hot gas) and return to the machinery room. Non return function to the LP side of the system is required. Activation shall be possible from the refrigerating machinery room, production area, or suitably located emergency room outside these rooms. The return line valves shall provide a non-return function allowing activation from the refrigerating machinery room, other relevant rooms, and from a suitably located emergency station outside these rooms.
  - Bottles with spare refrigerant should be stored in well ventilated spaces prepared for the purpose. Storage in refrigerating machinery spaces may be accepted.
- **Piping**
  - Piping Class II applies for R32, and for R744 below 40 bar (design pressure), while for R717 and for R744 systems operating above 40 bar, piping Class I is required. For R717, soldered connections shall withstand temperatures of at least 425°C.

- **Leakage detection**
  - A system for refrigerant leak detection, including alarm functions, are required for: i) spaces with refrigerating machinery, ii) discharge piping for safety relief valves in case of R717 or R32, iii) and, if direct expansion is applied, in any refrigerated chamber.
  - For R744, an alarm shall be activated if the concentration exceeds 1500 ppm.
  - For R134a, a detector for oxygen deficiency is acceptable (18 or 19% volume).
  - For R717, there are various detection levels (Figure 3[8]):
    - 150 ppm: initial detection
    - 350 ppm: automatic shutdown of refrigerant circulation pump
    - 5000 ppm: de-energizing of non-EX protected equipment and start of mechanical catastrophe ventilation
  - Detectors shall be located considering the refrigerant's relative density compared to air.
  - Acoustic and optical signals shall be given at locations outside spaces that could be filled with refrigerant. For R32 or R717, an audible alarm is required within the compartments.
  - For provision rooms and AC refrigeration plants using Group 1 refrigerants[9] (except R32) and are located in the engine room, a leakage detection system is not required, given that the ventilation arrangement is considered sufficient to eliminate the risk of suffocation.
- **Low pressure alarm**
  - For R744, an alarm shall be activated before the pressure decreases to the triple point pressure, to avoid dry ice issues.
- **Personnel protective equipment**
  - At least two sets of air breathing apparatuses, with spare air bottles, are required independent of the refrigerant.
  - For R717, additional equipment shall be placed immediately outside each entrance to spaces with refrigerating machinery: for example, refrigerant masks and hermetically sealed filters, at least two sets of protective clothing, with gloves and boots. There are special requirements if refrigerant circuit(s) have more than 25 kg.

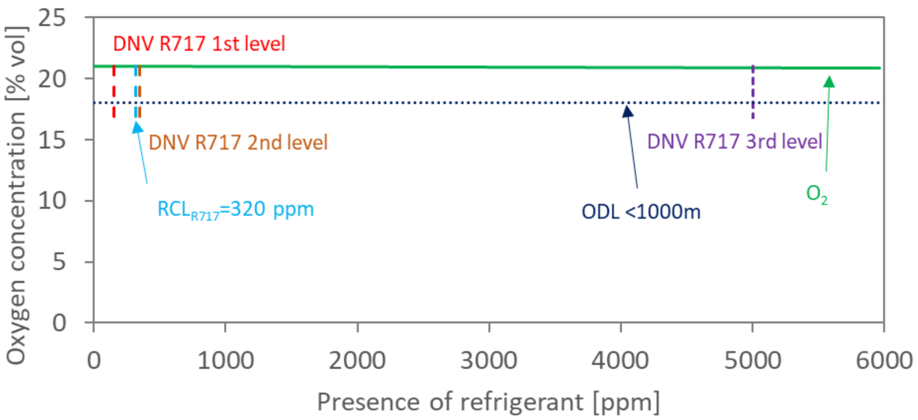

Figure 3. Detection levels for R717 according to DNV document.

[8] RCL = Refrigerant concentration limit according to ISO 817:2014+A1:2017.
[9] From this, it is understood that R744 systems that can be placed in the engine room (rather small systems) may not need detection systems if there is sufficient ventilation.

3 Communication with Classification Societies

Based on the in-depth analysis of the rules and regulations summarised above, several aspects were identified as relevant for applying natural refrigerants in HVAC&R systems onboard ships, in general, and for cruise/passenger ships, in particular. Thus, a communication channel has been established with LR and DNV. The purpose is to discuss these aspects, and to evaluate how the rules and regulations could be adapted, keeping safety as the main focus, to prepare for a scenario where natural refrigerants may be the only feasible solution. The full e-mail communication is kept on file and is available for interested parties.

3.1 Lloyds Register (LR)

This section provides a summary of the questions raised, and the answers from LR. In the communication with LR they also opened up for discussing their points of view and for participation in projects of this type.

3.1.1 Definition of HFOs

The uncertainty concerning refrigerant selection needs to be addressed. As discussed in Section 1.2, natural refrigerants are probably the only feasible solution for the mid- to long-term. Any other alternatives such as HFCs (hydrofluorocarbons) or HFOs (hydrofluoroolefins) will most likely be subject to future phase-out, they are costly, and in some cases, they are flammable and pose health risks.

We maintain that HFOs are, incorrectly, defined in Pt 7, Ch 11, 2.4.3, as natural refrigerants. Quoting the paragraph: *Where possible, natural refrigerants, such as ammonia, carbon dioxide and hydrofluoroolefins (HFOs), should be used.*

One reply has been received so far:

- LR1: *Please note that 'natural refrigerant' means natural substance such as ammonia. For using HFC, special requirement is stated in 2.4.3.*

Following this answer, we proposed to LR that 2.4.3 should be revised to avoid that HFOs are confused with natural refrigerants.

- LR2*: Well noted with thanks. However, please understand that natural refrigerants and HFOs should be used for a refrigerant if ECO notation will be assigned and HFC, if used, are to have an Ozone Depleting Potential (ODP) rating of zero and a Global Warming Potential (GWP) of less than 1950, based on a 100-year time.*

3.1.2 CO_2 compared to other non-toxic refrigerants

CO_2 is a non-toxic and non-flammable refrigerant. Its Refrigerant Concentration Limits (RCL) of 30.000 ppm, is not very different from that of HFC R134a, which is 50.000 ppm. The main concern with using CO_2 is its high operating pressure, which technically is a resolved topic nowadays with the development of trans-critical systems and components for land-based applications. According to LR's document, in Pt 7, Ch 15, 3.1.2, only toxic and/or flammable refrigerants shall be located outside the main machinery space. However, in practice, we interpret that LR indicates that R744 systems should also be located in a separate room (Pt 6, Ch 3, 3.4.1). We asked for the reason for such a different approach, and received two very different answers:

- LR1: *Please also find Part 6, Chapter 3, 3.1.4 of the Rules. Refrigerating machinery using non-toxic and non-flammable refrigerants will not, in general, be required to be located in a separate compartment outside the main machinery space. The main machinery space is normally well ventilated but toxic and flammable products shall specially be considered for handling in this space. Therefore, Rules generally states the restriction of operation for toxic and flammable refrigerants only.*

- LR2: *CO_2 may not be considered flammable; however, it could be considered toxic at higher concentrations; in higher concentrations is recognized as a hazard and classed as such by regulatory HSE agencies; higher concentrations cause different issues to the people inclusive of fatalities as it is asphyxiant; it could displace the oxygen in the room depending on the leak size, volume and operation of the ventilation system. This is the reason that CO_2 containing equipment is considered to be in a separate room; however, and similar to Ammonia when the machinery room is complying with certain requirements and the CO_2 charge is within certain volume an assessment could be performed in a case by case basis and it may be allowed within the machinery room (refer to Part 6, Ch. 3 section 3.4.2)*
- LR3*: Please note that IMO is now trying to change CO_2 as a Toxic cargo for the carriage in Liquefied Bulk so if Code is amended, we will consider further action whether Rules need to be amended or not for CO2 as a refrigerant*

Thus, even if it is not clearly stated in the documents, it appears that LR currently deals with CO_2 differently than HFCs, even though HFCs also could displace oxygen and cause similar safety issues. However, it is also indicated that the rules might be revised in the future.

3.1.3 Ventilated enclosure and flammables/toxic refrigerants

Ventilated enclosures are a common option to handle safely refrigeration systems and heat pumps with flammable and/or toxic refrigerants, but with some limitations in terms of charge. Ventilated enclosures are supplied with separate ventilation, detection devices, ATEX components and deactivation of electric supply when a dangerous leakage concentration is reached, e.g., 20%*LFL (lower flammability limit) in the case of flammable refrigerants. According to the standard EN 378-1 [17], charges of up to 5 kg propane (R290) and 20 kg of ammonia (depending on the location of the ventilated enclosure and due to ammonia's toxicity) could be placed within the ventilated enclosure.

Thus, LR was asked to give their opinion on the use of ventilated enclosures, and how they could be applied to ships' main engine rooms. The reply received was:

- LR1: *Please note that the prescriptive requirements by Classification is to require the minimum provisions for safety aspects if particular Class notation will be assigned. Surely, it would be the manufacturer's responsibility to design the systems in accordance with applicable National or International Standards but the requirements of Classification are to cover ship's safety, not the design standards.*
- LR2: *Necessary notation (e.g., RMC, ECO and RPA) will be assigned when the proposed installations are approved, installed and tested in accordance with necessary requirements in LR Rules under LR's Plan Approval and Survey work. Classification is maintained subject to satisfaction of the Class Periodical Survey.*

From the answers, an indicative conclusion is that units in ventilated enclosures *could* be placed within the main (engine) machinery room, provided that the refrigerant charge is limited (25 kg for ammonia, as indicated in LR's document).

LR's perspective on the use of hydrocarbons as refrigerants was also requested, especially related to reduced charges with indirect systems, ventilated enclosures, detection, ATEX components, etc. The replies received were:

- LR1: *Please note that Pt 7, Ch 11 can cover for refrigeration systems considering ECO notation. Please note that Rules of particular paragraphs are applicable for specific notations such as Pt 6, Ch 3 is for +Lloyd's RMC, Pt 7, Ch 11 is for ECO notation and Pt 7, Ch 15 is for RPA notation.*

- LR2: *Refrigerants different to those indicated on Table 3.2.1 of the LR Rules and Regulations for the Classification of Ships, July 2019, Part 6, Chapter 3 Refrigerated Cargo Installations – Section 2 Design Criteria could be assessed on the basis of not been included within a banned substance either by MARPOL Annex VI, the Montreal Protocol or any other applicable legislation in regard to ODP and GWP. The main requirements are related to safety issues when used on board such as Flammability, Toxicity, Stability, operating conditions; however, it should be noted that R-290 and R-600a are already cover by our Rules and a similar approach in regards to requirements should be taken for any other one not listed there (our Rules allow the use of other refrigerant that may not be listed on that table) The Rules provide specific requirements in Part 6, Chapter 3 which cover the specific of refrigeration equipment such as compressors, heat exchangers, piping systems and its compartments/rooms which are still applicable to any non-listed refrigerant. At the end, the selection of any refrigerant is based on the required thermal requirement of the system and this may limit their use in large refrigeration plants or in existing plants as the thermal performance will be different.*

Even if the first answer gives no clarity to the topic, it is concluded from the second answer that LR is open to the use of hydrocarbons (given the examples of R290 and R600a). It would be very useful if future releases of LR's document clearly states requirements regarding hydrocarbon systems, e.g., maximum charge per circuit that could be placed in the main (engine) machine room, in a similar way as it appears for CO_2 and ammonia. Thus, the situation would evolve from a "case-to-case" approach to something more standardised.

3.1.4 Other topics

Another question asked to LR was concerning the impossibility to use more than one hermetic or semi-hermetic compressor per refrigeration circuit with the motor cooled by the refrigerant (Pt 6, Ch 3, 4.1.10). This is of special importance related to use of R744, since most R744 systems of a certain capacity have several such units. Standard booster systems for provision of cooling and freezing, for instance, will have at least two compressors. Both LR answers suggest a "case-to-case" evaluation:

- LR 1: *As stated, LR Rules allow no more than one hermetic or semi-hermetic compressor in the circuit. However, alternative design can be considered and detail will be discussed for real cases.*
- LR 2: *other arrangements could be considered by LR in a case by case basis.*

A topic which has not been discussed so far, but should be investigated in the future, is linked to the use of direct expansion (DX) fan coil units (FCUs) with different refrigerants. It is clearly stated in the document that R717, R744 or hydrocarbons are not to be used in DX FCUs in accommodation spaces. It seems, however, that there are no clear restrictions to HFOs or R32 (flammable HFC).

3.2 DNV

Even if there are differences between LR and DNV documents, a majority of the rules and regulations are similar. Thus, several of the topics discussed in the previous section are also raised here.

3.2.1 HFOs and notation Clean

HFOs are not mentioned in DNV's document, which is surprising considering the relevance they currently have in the HVAC&R sector. Thus, there is a question if HFOs are included in the HFC family. For instance, in the definition of Class notation Clean, it is stated that refrigerants shall be natural refrigerants, such as NH_3 or CO_2, or HFCs (below GWP ≤ 2000).

3.2.2 CO_2 compared to other refrigerants

As for LR, an "unfair" treatment of CO_2 is also found in the DNV document, when comparing requirements for other Group 1 refrigerants concerning the need for a separate machinery room, detection and alarms, etc. Figure 4 shows the different limits for activation of the alarm in the case of leakage of CO_2 (top) and R134a (bottom), based on DNV's rules and regulations. In the case of CO_2, the alarm shall be activated at 1500 ppm, well below the RCL according to ISO 817:2014+A1:2017 [13]. For a HFC, such as R134a, the alarm is activated based on the oxygen deprivation limit (ODL), which could be set at 18% or 19%. If the 19% limit is considered, the concentration of R134a would be close to 100.000 ppm, thus almost twice the RCL according to the ISO standard.

DNV appreciated the question raised:

- DNV1: *An excellent question. I honestly only know that it is treated differently due to the much higher pressures and associated added risk, because the suffocation risk is as you say similar, even if the gases behave differently due to density. I would very much like to know more about how the high-pressure aspect can be considered resolved.*

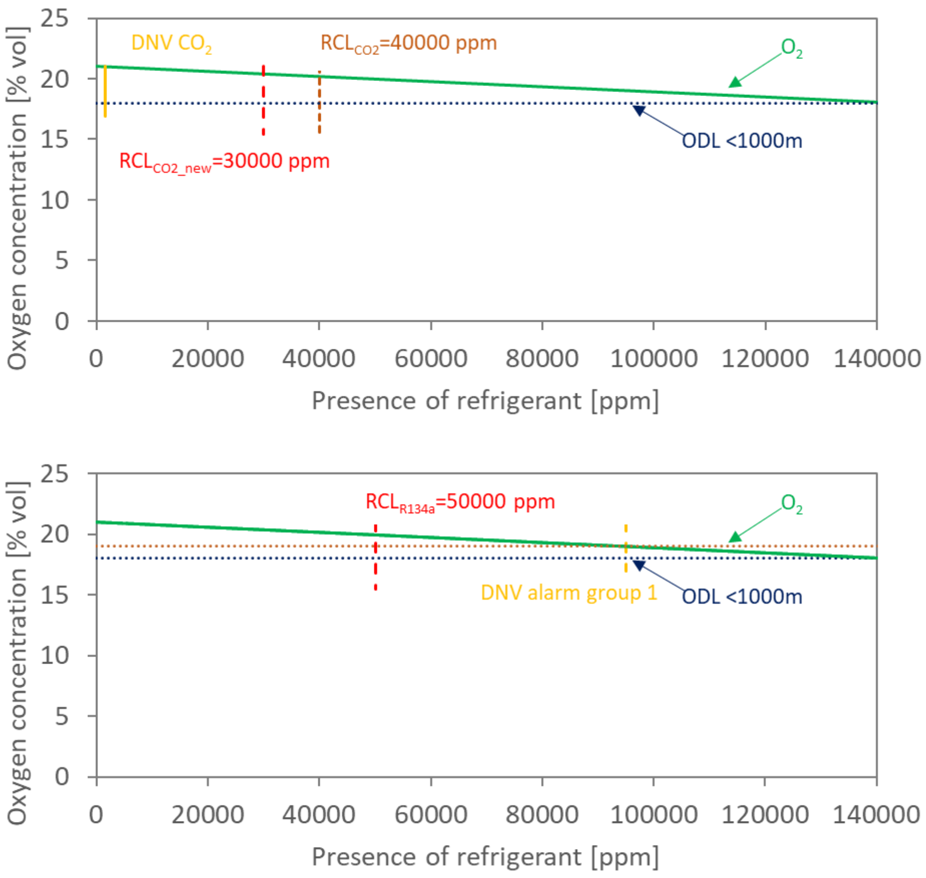

Figure 4. Oxygen concentration vs. presence of refrigerant in case of CO_2

3.2.3 Ventilated enclosures

As for LR, the possibility for applying ventilated enclosures for flammable and/or toxic refrigerants in main (engine) machine rooms was also raised to DNV, who gave the following answer:

- DNV1: T*his has been considered before and can in theory be accepted but how to do maintenance on the unit has to be considered in the design of the enclosure and system, as the enclosure cannot be opened with the system charged if it is located in the engine room (room has to be de-energized).*

In addition, it was questioned why the installation of R717 and R744 systems in the main machine room is based not only on refrigerant charge, but also on ship length. DNV agreed that the ship length should not be a criterion:

- DNV1: *We are actually removing the ship length criteria next year, fully agree with your comment*

A significant difference between the documentation provided by DNV and LR is that, in the latest version from DNV, clear requirements for the use of R32, a mildly flammable (A2L) HFC refrigerant, are included. DNV was therefore asked to give their view of developing such standardised requirements for hydrocarbons (A3), considering their much lower LFL and minimum ignition energy. That should include stringent requirements on, for example, detection levels, alarms activation, deactivation of electric components, maximum charge allowed per circuit. According to DNV's reply they may open up for including A3 refrigerants in coming regulations:

- DNV1: *We are currently only allowing A2L refrigerants under same requirements as R32 (actually the rules will be updated to refer to flammable group 1 refrigerants instead of only R32, because we will introduce R448, R1234ze and R1234yf*[10] *in the tables. Next year I hope to be able to overhaul our rules to allow A3 refrigerants, but the requirements for such installations will in any case be quite strict based on LPG fuel rules. We will not allow A3 on case by case basis in the meantime.*

Another important outcome of the correspondence with DNV is that SINTEF is invited to participate in their rule hearing process:

- *DNV1: We can arrange by you participating in the rule hearing process, so I suggest I add you to the hearing list for the next rule revision, so you can bring input on the rules directly in the formal system. This will ensure follow up and enable funding on my side for further discussions on rule development.*

[10] R1234ze and R1234yf are HFO refrigerants

4 Concluding remarks

From the thorough review of classification requirements related to natural refrigerants, and based on the communication with DNV and LR, the following indicative conclusion are drawn:

- In addition to general requirements on refrigerants, both DNV and LR have specific requirements related to R717 and R744, while DNV also have requirements for R32. Hydrocarbons are included in the LRs documents, while they are not in DNV's.
- The ECO class notation from LR requires the use of natural refrigerants, HFOs, or HFCs with GWP<1950 in systems with more than 3 kg refrigerant charge. DNV's class notation Clean, applying to systems with more than 10 kg charge, states that natural refrigerants or HFCs with GWP<2000 shall be used, thus, not mentioning HFOs.
- There are several questionable and/or unclear requirements related to R717 and/or R744. For example:
    - R744, a non-toxic refrigerant, is treated more stringent than HFCs, which also could displace oxygen and cause similar issues as R744.
    - Installation of R717 and R744 in the main machine room is, by DNV, based not only on refrigerant charge, but also on ship length.
    - LR states that R717, R744 or hydrocarbons are not to be used in direct expansion fan coil units in accommodation spaces, but there are no clear restrictions on flammable fluids like HFOs or R32.
    - LR allows for no more than one hermetic or semi-hermetic compressor with an electric motor cooled by the refrigerant.
    - Even though not clearly stated in the documents, it may be possibility to apply ventilated enclosures in main machinery room, both for R717 and R744, but with refrigerant charge limitations.
- Alternative designs and arrangements for natural refrigerants can be considered by both DNV and LR, on a case-by-case basis. However, DNV does not allow A3 refrigerants.
- Both DNV and LR gave indications on possible future revisions, for example related to proper definition of HFOs, removal of ship length criteria, changing the "unfair" treatment of CO_2 in relation to HFCs, and introduction of specific requirements for A3 refrigerants (hydrocarbons).

In conclusion, to facilitate the use of natural refrigerants, there is a need for more standardised requirements, replacing the case-to-case evaluations.

5 References

[1] IMO, 'Adoption of the Initial IMO Strategy on Reduction of GHG Emissions from Ships and Existing IMO Activity Related to Reducing GHG Emissions in the Shipping Sector', 2018. [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

[2] Arcsilea Ltd, 'A practical guide to the selection of energy efficiency technologies for ships', 2022. [Online]. Available: https://greenvoyage2050.imo.org/practical-guide-to-the-selection-of-energy-efficiency-technologies-for-ships/

[3] DNV, 'MARITIME FORECAST TO 2050. Energy Transition Outlook 2022', 2022.

[4] Z. Bazari, 'MARPOL Annex VI - Prevention of Air Pollution from Ships Chapter 3', presented at the National Workshop (virtual) on Ratification and Effective Implementation of MARPOL Annex VI for Egypt, Nov. 20, 2020.

[5] European Commission, *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16th April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006*. 2014.

[6] UNIDO, 'The Montreal Protocol evolves to fight climate change', 2016.

[7] M. Garry, 'The Rising Threat of HFOs and TFA to Health and the Environment', ATMOsphere, 2022.

[8] Cooling Post, 'PFAS ban proposal delayed', Apr. 03, 2022. https://www.coolingpost.com/world-news/pfas-ban-proposal-delayed/

[9] Cooling Post, 'Euro green seeks total ban on F-gases', Oct. 18, 2022. https://www.coolingpost.com/world-news/euro-green-seeks-total-ban-on-f-gases/

[10] R. Ciconkov, 'Refrigerants: There is still no vision for sustainable solutions', *International Journal of Refrigeration*, vol. 86, pp. 441–448, Feb. 2018, doi: https://doi.org/10.1016/j.ijrefrig.2017.12.006.

[11] A. Hafner, C. H. Gabrielii, and K. Widell, *Refrigeration units in marine vessels*, 2019:527. Copenhagen: Nordic Council of Ministers, 2019. doi: 10.6027/TN2019-527.

[12] LR, 'Rules and Regulations for the Classification of Ships', Jul. 2022.

[13] ISO, 'ISO 817:2014+A1:2017 - Refrigerants. Designation and safety', 2017.

[14] LR, 'ShipRight Design and Construction. Risk Management. Risk Based Certification (RBC)', Sep. 2021.

[15] DNV, 'Rules for Classification - Ships - Part 4 Systems and components - Chapter 6 Piping systems', Jul. 2022.

[16] DNV, 'Rules for Classification - Ships - Part 6 Additional class notations - Chapter 7 Environmental protection and pollution control', Jul. 2022.

[17] CEN-CENELEC, 'Refrigerating systems and heat pumps. Safety and environmental requirements. Part I: Basic requirements, definitions, classification and selection criteria. EN 378-1:2016', 2016.

6 Acknowledgement

The authors gratefully acknowledge the Research Council of Norway and our industrial project partners – Teknotherm Marine AS and Ulmatec Pyro AS - for the financial support [NFR project No. 308779, CruiZE].

Abbreviations:

- AC air conditioning
- AHU air handling unit
- ATEX explosive atmospheres
- CFC chlorofluorocarbons
- COP coefficient of performance
- DX direct expansion
- FCU fan coil unit
- GHG greenhouse gases
- GWP global warming potential
- HCFC hydrochlorofluorocarbons
- HFC hydrofluorocarbons
- HFO hydrofluoroolefins
- HP high pressure
- HVAC&R heating, ventilation, air conditioning and refrigeration
- IMO International Maritime Organization
- LFL lower flammability limit
- LP low pressure
- ODP ozone depletion potential
- ODL oxygen deprivation limit
- PFA perfluoroalkyl and polyfluoroalkyl
- RCL refrigerant concentration limit
- RMC refrigerated cargo installations
- RPA refrigeration machinery for provision stores and air-conditioning.
- TFA trifluoroacetic acid