A hazard-based approach to designing with modern refrigerant gases for naval ships

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Synopsis

The Montreal Protocol on substances that deplete the ozone layer and EU Regulation 517/2014 on fluorinated greenhouse gases limit the continued use of R134a and other commonly used refrigerants in domestic and industrial applications, including the marine sector. Many navies have also committed to comply with the legislation even though they are often exempted. The legislation is driving the use of alternative refrigerants that have higher flammability or toxicity characteristics than those previously used. The introduction of these alternative refrigerants potentially introduces new hazards that must be considered in systems design. This is especially pertinent in naval vessels which typically have large equipment cooling requirements compared to similar size commercial ships, furthermore the equipment is often located in densely-packed machinery spaces, and with a higher crew occupancy. Naval vessels also face additional operational risks and have a greater requirement to maintain capability in the event of an incident or accident.

Standards and guidance documents are available for designing with refrigerants of these alternative types, however these are not tailored to a naval application, and do not consider the context of the system and operational constraints, so may result in an increase in cost and weight to the ship design that is disproportional to the perceived risk. This paper reviews the current literature and standards to understand the properties of the refrigerants, the safety controls that can be employed and in what context they are used. The individual hazards associated with the different classes of refrigerant are identified and possible mitigations for each are investigated with reference to the naval context.

These findings are used to define a hazard-based approach to system design. The method is compared to current standards to demonstrate the impact on the design. It is found that the hazard based approach results in different controls being incorporated in the design than would be used following the requirements from international standards or classification society rules. The proposed approach is recommended for consideration for future naval ship designs and included in classification society rules.

Keywords: Refrigeration, refrigerants, chilled water, HVAC, Naval, Marine, Safety

Author's Biography
Mark Fox is a Senior Naval Specialist at Lloyd's Register. A chartered engineer with a wide range of experience in marine engineering design and consultancy. Current responsibilities include support to navies and shipyards on the implementation of Lloyd's rules and rule development to ensure rules are appropriate for newer technologies.

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1. Introduction

1.1. Current status of Marine Refrigeration

Almost all ships, commercial and naval, use refrigeration plants for air conditioning and cooled storage. According to the IMO greenhouse gas study in 2014 (International Maritime Organisation, 2014) the majority of systems at sea utilise R22 as the refrigerant, however this has become increasingly replaced by R134a and R404a, due to legislation changes banning the use of R22 in new applications. Now further changes to legislation are beginning to restrict the use of R134a and R404a, and future marine installations will be obliged to use alternative refrigerants with a lower global warming potential (GWP)[1]. The switch to alternative refrigerants has already occurred in many industries and several replacement substances are now in use. These substances include fluids that, unlike the currently used refrigerants, are flammable or toxic. The ISO 817standard (International Organization for Standardization), 2017) is used to classify refrigerants in terms of their flammability and toxicity. Currently there is very limited guidance available that is specific to the use of these refrigerants on-board marine vessels. This study attempts to understand if these refrigerants can be used safely for naval vessels and what the implications are for the design.

1.2. Legislation and Phase-out

Hydrofluorocarbons (HFCs) such as R134a are powerful greenhouse gases. The Kigali Amendment to the United Nations Montreal Protocol on Substances that Deplete the Ozone Layer requires the parties to the agreement to reduce the use of HFCs by 80-85% from the time of adoption in 2016 by 2040. EU Regulation 517/2014 on fluorinated greenhouse gases limits the production and continued use of R134a and other refrigerants with a high GWP in domestic and industrial applications, including the marine sector. For some applications the ban is already in place, for example in motor vehicle air conditioning systems. For new installations of marine type chillers the use of HFCs with a GWP of 2500 or greater is to be phased out from January 2020, and HFCs with a GWP of 150 or greater from January 2022. There is currently no legislation affecting HFC with a GWP below 150, however increasingly stringent environmental targets and legislation continue to be implemented, which may further limit use of these compounds in the future.

Currently the installation and continued use of chillers using R134a in ships is not prohibited, however the enforced reduction in production of the refrigerant has resulted in an increase in cost, and as other industries are obliged to change to alternative refrigerants the availability of off-the-shelf equipment using R134a and development of these systems will reduce.

Naval vessels are required to minimise cost where possible in design and equipment selection whilst delivering the performance requirements required by the customer Navy, therefore as the use of R134a becomes more restricted and as the cost increases it will become necessary to look for alternative refrigerants. Furthermore, naval administrations and governments generally now require an environmental assessment, for which it may prove difficult to justify the use of a high GWP refrigerant when more environmentally friendly options are available.

1.3. Alternative Refrigerants

No single refrigerant that complies with current and future legislation has currently emerged as the preferred option. Different applications and industries have selected alternatives that are best suited to their individual needs and circumstances. A significant current market driver is for refrigerants that can be used in existing systems with little or no modification, these are known as “drop-in” refrigerants. However, designing a new system allows more freedom in the selection. A summary of some of the refrigerants that are now more commonly used is provided at Table 1. These include a new class of compounds called hydro-fluoroolefins (HFOs), which have very short atmospheric lifetimes, and low global warming potential. Natural fluids such as carbon dioxide (CO_2) and ammonia have also become more popular due to their low environmental impact, and low cost and abundance. Some of these fluids were used before the emergence of CFCs and HCFCs and were abandoned when their performance could not compete, however modern equipment can now improve the performance of these systems.

[1]GWP: Global warming potential. A comparative measure of the impact the gas has on retention of heat in the atmosphere. CO_2 = 1.

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Table 1- Modern alternative refrigerants

Name (type)	**ISO 817 Classification**	**GWP**	**Notes**
R134a (HFC)	A1	1430	Included for comparison. To be phased out from 2022.
R32 (HFC)	A2L	675	To be phased out from 2022.
R513a (HFO/HFC blend)	A1*	631	Blend of R1234yf and R134a. To be phased out from 2022.
R152A (HFC)	A2	124	
R1234ze (HFO)	A2L	6	
R1234yf (HFO)	A2L	4	Used in all new car air-conditioning systems
R290 (Propane)	A3	3	
R744 (CO_2)	A1	1	
R717 (ammonia)	B2L	0	

*when in the system, but will decompose into constituent fluids when released into ambient air

1.4. Refrigeration on naval vessels

Naval vessels are typically equipped with water cooled chillers and a distributed chilled water system supplying both equipment cooling and ventilation cooling and a separate refrigeration plant for refrigerated provisions stowage. It is also usual for several small domestic-style fridges to be fitted within the messes and possibly for medical use. All of these refrigeration equipments contain a refrigerant working fluid. This arrangement is similar to a commercial vessel, however naval vessels may also be fitted with radars, and combat systems and electronics which require a significant and ever-increasing cooling capacity which will be compounded by the introduction of energy weapons. Naval vessels also often have a requirement for high redundancy which further increases the capacity of the systems. There are commercial ships for which refrigerated storage is part of their main function such as cold carriers and refrigerated fishing boats, these vessels are designed around a large refrigeration plant whereas for a naval vessel it is part of the necessary auxiliary machinery.

Table 2 - Refrigeration consumers on commercial and naval vessels

Commercial Vessels	**Naval Vessels**
Air Conditioning	Air Conditioning
Refrigerated Stores	Refrigerated Stores
	Radar Mast
	Combat Systems Electronics
	High Power Electrical and Propulsion Systems

2. Method and Assumptions

In order to define a hazard-based approach to designing for alternative refrigerants, a review of literature was carried out, from which the individual hazards, and the possible preventative and mitigative controls were identified. A process was defined where the appropriate controls can be selected for the hazards associated with the preferred refrigerant.

This study is concerned with the safe integration of a system using refrigerants onto a naval vessel. It does not cover the design of the refrigeration equipment itself. It is assumed that any system installed onto a vessel will be designed to a safety standard and with appropriate safety certification.

No environmental or performance assessment of different refrigerant types is made in this study. It is important to note that the environmental impact cannot be assessed independently from the performance of the system. If a change in refrigerant and plant reduces the cooling efficiency, then the environmental impact of producing more energy to meet the demand must also be considered. The environmental impact of the production of the refrigerant and ultimate disposal should also be considered.

The likelihood of an accident arising (the risk) is dependent on the detail of the design and ship operations, for this study it is assumed that the implementation of controls reduces the risk of an accident occurring, however no further assessment of probabilities is undertaken. This study considers accidents to be events leading to the injury

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or death of an individual. Hazards are defined as a physical situation or state of a system that may lead to an accident. A method for defining the probability of an event occurring can be found in IEC 61025.

3. Review of Standards and Classification Society rules

A review of standards has been carried out to understand the available guidance for designing with different classes of refrigerant, the safety controls that are recommended and in what context they are used. A summary of the scope and content of some key standards is provided in the following paragraphs.

3.1. International Standards

There are a range of international standards available regarding the use of refrigerants and designing refrigeration systems. Many of these have been updated to provide some guidance for flammable refrigerants. The international standards are not specific to marine systems and require some interpretation to apply. The scope and content of some of the key standards are described in the following paragraphs. There are a large number of standards producing organisations based in different countries and targeted at different specific industries and groups. The list reviewed here is not exhaustive however it represents a sample of commonly referenced and applied standards.

3.1.1. ISO 817:2014+A1:2017, Refrigerants – Designation and safety classification

The ISO 817 standard provides a system for assigning designations to refrigerants (e.g. R-22, R134a, R744 etc.) and also a system for classifying refrigerants based on flammability and toxicity. This provides a common understanding of the risks associated with a particular gas in the context of a defined set of terms. The definition matrix is shown in Figure 1.

Class	**Toxicity**	**A**	**B**
Flammability	Definition	Occupational exposure limit of 400 ppm or greater	Occupational exposure limit of less than 400 ppm
3	Higher flammability	A3	B3
2	Flammable	A2	B2
2L	Lower flammability	A2L	B2L
1	No flame propagation	A1	B1

Figure 1 - ISO 817 Refrigerant Classification Matrix

The implication of each classification and associated hazards are discussed at section 4.

3.1.2. EN 378-1:2016, Refrigerating systems and heat pumps — Safety and environmental requirements & ISO 5149-1:2014+A1:2015, Refrigerating systems and heat pumps – Safety and environmental requirements.

These standards cover approximately the same scope as implemented by the different standards organisations. The standards are applicable to refrigerating systems, stationary or mobile, of all sizes except to vehicle air conditioning systems, and provides guidance both on the design of the system and the location and controls that should be employed for a safe installation.

The standard defines maximum limits for the system charge of refrigerant that are based on the volume of the space where the installation is located and the occupancy of that space. This would only allow relatively small installations in occupied spaces. The standard states that machinery rooms for groups A2L, A2, A3, B2L, B2 and B3 refrigerants are to be assessed and classified as hazardous zones in accordance with EN 60079-10-1. Standard controls that are required for unoccupied refrigeration machinery spaces include:

- Refrigerant detector to be fitted with alarm and set to initiate emergency ventilation
- Segregated ventilation with calculated minimum airflow;
- For rooms containing flammable refrigerant, electrical equipment is to comply with the hazardous zone assessment.

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3.1.3. EN 60335-2-24:2010+A2:2019, Household and similar electrical appliances - Safety

(derived from IEC 60335-2-24:2010)

This standard contains requirements for the safe design of domestic and commercial refrigeration appliances and components, but do not cover safeguards or integration design. It is assumed that the equipment covered in this study has been designed and manufactured to be safe, this would generally mean complying with this standard or an equivalent.

3.1.4. ISO 20854:2019, Thermal containers – Safety standard for refrigerating systems using flammable refrigerants – Requirements for design and operation

This standard is restricted to the design and operation of refrigerating systems integrated with, or mounted on, ISO thermal containers. for use on board ships, in terminals, on road, on rails and on land, and covers the design and operation of the container refrigeration system. The standard requires the refrigeration system manufacturer to carry out an operational mode risk assessment in accordance with IEC 61025 to ensure the risk associated with the system is tolerable, and includes further guidance on risk reduction and safety measures.

3.2. Classification Society Rules

Almost all commercial ships are designed and built to the rules of a classification society, intended to ensure that the ship is safe to sail and carry out its defined functions. Increasingly naval ships are also designed either with full or partial compliance to classification society rules and in some cases are maintained in-class. Classification society rules are developed over time using the experience gained from classing a large number of ships. In addition, classification societies conduct research and development to ensure that the content of the rules reflects the latest technology. Classification society rules also invoke statutory requirements such as SOLAS or ANEP77, and cannot be considered in isolation. Safety requirements for refrigerants from two of the largest classification societies are summarised below.

3.2.1. Lloyd's Register Rules and Regulations for the Classification of Naval Ships, January 2020

Lloyd's Register rules require refrigerant gas detectors to be fitted in compartments containing refrigeration plants for chilled water and air conditioning. Notations are used to describe the scope of the vessels systems that are within the scope of the classification. Under the PRM notation there is a requirement for plants using flammable or toxic refrigerant to be located outside the main machinery space in a separate gastight compartment with minimum ventilation of 30 air changes per hour.

There are further requirements under the ENV notation; this states that natural refrigerants or HFOs should be used, where possible but does not prohibit the continued use of HFCs. For systems using more than 3kg of flammable refrigerants (class 2L or above) additional requirements include a segregated non-sparking mechanical ventilation system with a minimum capacity of 30 air changes per hour, and leak and oxygen detection equipment. Further instructions are provided detailing maximum leakage rates and records to be maintained, a risk assessment to be carried out, and spaces to be indicated on a hazardous area plan.

3.2.2. DNV GL Rules for Classification Naval Vessels December 2015

DNV GL Rules for naval vessels state that safety refrigerants of group 1 or class L according to DIN 8960 shall be used. There are requirements for storage of bottles of refrigerant. The rules state that refrigerating machinery is to be installed in spaces separated by bulkheads from other service spaces unless approved by the naval administration. Further requirements include separation from accommodation spaces, leak detection, and a segregated ventilation system with a minimum capacity of 30 air changes per hour.

4. Refrigerant hazards

4.1. Hazard sources and descriptions

ISO 5149 lists the following potential sources of hazards associated with refrigerating systems:

1. the direct effect of extreme temperature;
2. excessive pressure;
3. the direct effect of the liquid phase;
4. the moving parts of the machinery, and;
5. the escape of refrigerants.

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As previously stated, this study is not concerned with the safe design of the machinery which is related to the sources 1 to 4 as listed. It is therefore source number 5, the escape of refrigerants that is of interest. The potential hazards originating from the escape of refrigerants defined in the standard are shown in Table 3. Eliminating the escape of refrigerant or leak from the equipment negates this source of hazards. Refrigerating machinery has generally always been designed to minimise leaks due to safety and environmental concerns and also to prevent the constant renewal of the gas and obvious inconvenience and expense, however historical evidence shows that it is very difficult to completely eliminate leaks in large systems, and the assessment is carried out based on the assumption that leaks can occur.

Table 3 - Direct hazards arising from the escape of refrigerant

Hazard	**Description**
Fire	Fire and flame propagation due to ignited leaking refrigerant resulting in a fire injury
Explosion	Explosion caused by an accumulation of leaked refrigerant leading to a flammable concentration and ignition in a confined space resulting in explosion injury
Toxicity/Caustic effects	Toxic concentration of refrigerant gas in the atmosphere resulting in poison or chemical injury
Freezing	Low temperature leaking refrigerant resulting in cold burns/frostbite;
Asphyxiation	Displacement of normal atmosphere caused by leak of refrigerant resulting in asphyxiation

The standard also lists possible environmental issues and panic as having potential indirect effects leading to harm. Environmental issues are reduced through the use of the newer refrigerants, and the effect of panic is not easily quantified. These indirect effects are not considered further in this study.

Fire and explosion both have the potential for secondary hazards to emerge caused by damage to the ships structure or systems, smoke inhalation, or development of dangerous combustion products. This study focuses on controls for the primary hazards only.

4.2. Flammability and toxicity limits

Refrigerants defined as flammable will only ignite provided a minimum concentration is present. This is defined as the lower flammability limit (LFL). It is possible to calculate the maximum mass of refrigerant in a given volume to remain below the flammability limit. Similarly, there is a minimum concentration for acute toxic effects to be realised; defined as the toxicity limit. It is important to note that refrigerant escaping from a plant or storage cylinder will not instantly mix with the surrounding atmosphere and a higher concentration will exist close to the leak source.

For very small masses the concentration of leaking refrigerant will rapidly dissipate to below the level where the effect will be realised, or in the case of ignition, the maximum total energy generated by combustion of the refrigerant is such that the effects would be very localised. This limiting mass of refrigerant is defined in ISO 5149 as the practical limit and values are provided for different refrigerants. The standard also contains a method that defines a maximum allowed charge for a set volume to keep the concentration of refrigerant in the atmosphere within safe limits. This is based on a combination of the mass to keep within the LFL and toxicity limit with a safety margin applied, and defined limits based on a combination of flammability and toxicity tests and historically established charge limits. Different limits are defined based on whether the space is normally occupied and whether persons who have access are authorised and aware of any safety precautions. The limits are specific to the properties of the individual refrigerants however step changes are also applied based on the flammability and toxicity class.

The lower flammability class 2L was introduced into the ISO 817 classification standard after the original definitions of classes 1, 2 and 3. Class 2L refrigerants are flammable, but have slower flame propagation. It is important to note that the 2L definition is for the behaviour of the gas at 23°C, and the flammability characteristics are dependent on temperature and it is therefore important to consider the behaviour of the refrigerant at the maximum design temperature of the compartment. The same hazards exist for all flammable refrigerants; however, the risk of an accident may be less for class 2L refrigerants.

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4.3. Other specific physical properties

It is important to note that different refrigerants within a class also have different physical properties, and the controls put in place must therefore be tailored, for example the specific gravity of the gas governs whether the mixture arising from a leak will be more concentrated at the deck or deckhead of the compartment and the ventilation should be located appropriately. Heavy refrigerants could also flow into open drains and bilges. The behaviour of the refrigerant when in contact with other materials and fluids should be considered. For example, adding water to liquid R717(ammonia) causes a rapid expansion of ammonia gas (EN 378:2016) with has the potential to increase the hazards associated with a leak, and water may not therefore be preferred for firefighting in compartments containing ammonia systems.

4.4. Hazards applied to refrigerant class

The identified hazards can be applied to the ISO 817 classification system as shown in Table 4

Table 4 - Identified hazards applied to refrigerant class

Class	**Toxicity**	**A**	**B**
Flammability	Definition	Occupational exposure limit of 400 ppm or greater	Occupational exposure limit of less than 400 ppm
3	Higher flammability	Flammability Explosivity Freezing Asphyxiation	Flammability Explosivity Toxicity Freezing Asphyxiation
2	Flammable	Flammability Explosivity Freezing Asphyxiation	Flammability Explosivity Toxicity Freezing Asphyxiation
2L	Lower flammability	Flammability Explosivity Freezing Asphyxiation	Flammability Explosivity Toxicity Freezing Asphyxiation
1	No flame propagation	Freezing Asphyxiation	Toxicity Freezing Asphyxiation

5. Preventative and mitigative controls

A number of controls can be implemented to prevent an incident from occurring. The following steps, as defined in ISO 20854, can be used when applying controls to a hazard:

1. Eliminate hazards or reduce risks as much as reasonably practicable;
2. apply appropriate protection measures against hazards which cannot be eliminated;
3. inform users about residual hazards and indicate whether specific measures should be taken to reduce the associated risks, where relevant.

The safety case owner must assess which controls provide the required level of safety to agree with their safety policy, however if the risk is to be minimised to be as low as reasonably practicable (ALARP) then all controls that increase safety should be implemented unless they are completely prohibitive in cost or prevent the vessel from achieving its function.

Naval vessels may have additional defined threats and emergency scenarios that could require additional controls to prevent the hazards from arising, such as shock protection or protection from weapons damage. These threat scenarios are dependent on the vessel and the concept of operations as defined by the naval administration, and no attempt to define potential controls is made here, however protecting the integrity of the system and preventing leaks from occurring is clearly the preferred option. If this cannot be achieved, then consideration of increasing the resilience of the controls and safeguards should also be considered in the context of the whole ship damage scenario.

Basic minimum controls such as warning labels, personal protective equipment, and training are assumed to be implemented as required by statutory and normal process. The possible controls that have been identified through the literature review are explained in the following paragraphs (6.1 to 6.10). Section 6 describes how these can be applied to protect against the relevant hazard.

5.1. Limited mass of refrigerant

The hazards associated with an escape of refrigerant are dependent on a minimum concentration being present in a given volume. Limits can therefore be applied based on the volume of the space containing the refrigeration system, however suitable safety factors and additional controls may be required to protect against local high concentrations.

5.2. Segregation of refrigeration machinery space

Locating the machinery in a separate compartment which is not normally manned with a suitable physical barrier removes the person from the vicinity, therefore in the event of a refrigerant leak the risk of injury is reduced. The barrier should be gastight to eliminate the possibility of the refrigerant leaking into an adjacent space.

5.3. Leak detection with alarm

Leak detection enables many of the other controls, by alerting the operator and allowing them to act. It is also possible for controls such as initiating ventilation to be automated. The leak detection system must therefore be very reliable to prevent a single point of failure from allowing an accident to occur. The leak detection system should be tested regularly, and consideration given to multiple independent leak detection systems, with suitable software integrity to match a safety critical function.

5.4. Minimum ventilation

Maintaining a minimum level of ventilation in the compartment will help to ensure that leaks of refrigerant do not cause local high concentrations without being detected. Consideration must be given to the location of the vent outlet, which will depend on the type of refrigerant carried.

5.5. Emergency ventilation

If a leak is detected, then the compartment can be quickly vented to atmosphere to remove the potential hazard. This can be automatically initiated by the leak detection system or initiated from a continuously manned watch station to ensure there is no delay in response.

5.6. Removal of ignition sources

A source of ignition is required to provide the energy required to initiate combustion of a refrigerant. Removing ignition sources by using intrinsically safe or non-sparking equipment will prevent a fire from occurring.

5.7. Firefighting systems

In the event of ignition of the refrigerant, firefighting systems can be used to avoid escalation by extinguishing the fire and preventing the fire from spreading and causing further damage to the ship.

5.8. Removal of flammable materials

In the event of ignition of the refrigerant, the absence of any flammable material in the vicinity will ensure that there is no further fuel for the fire and limit the spread.

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5.9. *Fire boundary*

Surrounding the refrigeration system with a fire boundary will serve to control the spread of fire in the event of ignition of the refrigerant. In addition, the boundary will protect the refrigeration system from fires originating outside of the compartment.

5.10. *Strengthening of compartment*

In the event of ignition of refrigerant causing an explosion a structurally strengthened compartment will prevent a risk of injury to persons located outside the compartment and structural damage to the ship that could cause follow-on accidents or loss of functionality.

5.11. *Relevant Controls applied to hazards*

Some of the controls are effective for all of the identified hazards associated with an escape of refrigerant, and some are particular to specific hazards. The identified controls can be associated with the applicable hazards as shown in Table 5.

Table 5 - Controls associated with hazards

Controls	**Flammability**	**Explosivity**	**Toxicity**	**Freezing**	**Asphyxiation**
Limited mass of refrigerant	Yes	Yes	Yes	Yes	Yes
Segregation of refrigeration machinery space	Yes	Yes	Yes	Yes	Yes
Leak detection with alarm	Yes	Yes	Yes	Yes	Yes
Minimum ventilation	Yes	Yes	Yes	Yes	Yes
Automatic emergency ventilation	Yes	Yes			
Remove ignition sources	Yes	Yes			
Removal of flammable materials	Yes				
Firefighting	Yes				
Fire boundary	Yes				
Strengthened compartment		Yes			

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6. Designing for different refrigerants

6.1. Design process

The potential hazards associated with the different refrigerants have been defined and possible safeguards identified. It is now possible to link the required safeguards to the hazards associated with the particular refrigerant. Applying safeguards is generally associated with additional cost or impact on the ship design; the naval administration and ship designer must decide if the controls required to use a given refrigerant safely are acceptable when incorporated with the whole vessel design. A diagram illustrating this process is included at Figure 2:

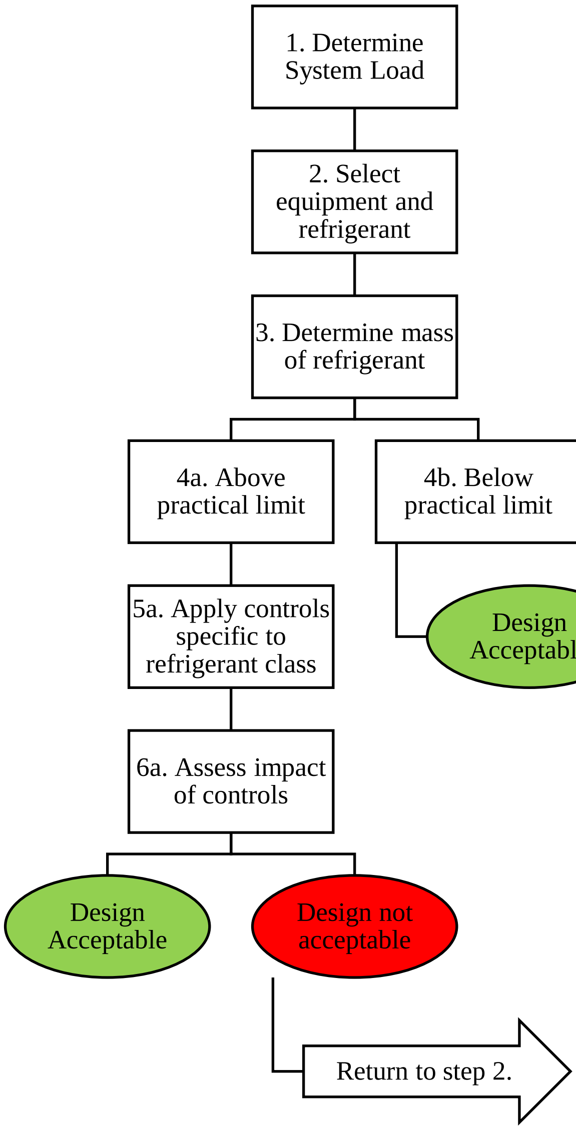

Figure 2 - Safe Refrigeration Design Process

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6.2. Comparison of design methods

Considering an example vessel requiring a refrigerant charge above the practical limit, the differences in the design features required through application of the proposed method, international standards and classification society rules for different refrigerant types can be identified as shown in Table 6.

Table 6 - Comparison of controls for different design methods

Refrigerant Category	**Controls implemented**		
	Proposed Method	**ISO 5149 International Standard**	**Class Society Rules (depending on notations)**
A3/A2	• Limited mass of refrigerant • Segregation of ref. mach. space • leak detection with alarm • Minimum ventilation • Automatic emergency ventilation • Removal of ignition sources • Removal of flammable materials • Firefighting • Fire boundary • Strengthened compartment	Occupied space • : Charge limited to lessor of 20% x LFL x Room volume or 10kg. Unoccupied space • No charge limit • Segregated minimum ventilation • Non-sparking equipment	• Leak detection • Segregation of refrigeration machinery space • Minimum ventilation requirement **SOLAS/ANEP77** • Removal of ignition sources • Removal of flammable materials • Fire detection • Firefighting • Fire boundary
A2L	• Limited mass of refrigerant • Segregation of ref. mach. space • leak detection with alarm • Minimum ventilation • Automatic emergency ventilation • Removal of ignition sources • Removal of flammable materials • Firefighting • Fire boundary • Strengthened compartment	Occupied space • Charge limited to 20% x LFL x Room volume or 195 x LFL Unoccupied space • No charge limit • Segregated minimum ventilation	• Leak detection • Segregation of refrigeration machinery space • Minimum ventilation requirement **SOLAS/ANEP77** • Removal of ignition sources • Removal of flammable materials • Fire detection • Firefighting • Fire boundary
A1	• Limited mass of refrigerant • Segregation of ref. mach. space • leak detection with alarm • Minimum ventilation	• No requirements	• Leak detection

Refrigerant Category	Controls implemented		
	Proposed Method	**ISO 5149 International Standard**	**Class Society Rules (depending on notations)**
B2L	• Limited mass of refrigerant • Segregation of ref. mach. space • leak detection with alarm • Minimum ventilation • Automatic emergency ventilation • Removal of ignition sources • Removal of flammable materials • Firefighting • Fire boundary • Strengthened compartment	Occupied space • Charge limited to lesser of 20% x LFL x Room volume or 10kg. Unoccupied space • No charge limit • Segregated minimum ventilation	• Leak detection • Segregation of refrigeration machinery space **SOLAS/ANEP77** • Removal of ignition sources • Removal of flammable materials • Fire detection • Firefighting • Fire boundary

7. Conclusions

The different potential hazards associated with the escape of refrigerant in the naval marine environment have been considered. Specific control measures have been associated to the potential hazards. The review of existing standards and rules found that there is limited guidance specific to marine refrigeration installations, and there are currently different requirements depending on the standard followed

It can be seen that different types of refrigerant require different controls, although some controls are applicable to all refrigerants. Limiting the mass of refrigerant within a given space was identified as one way to limit the potential impact of a leak, however the specific mixing behaviour and leak rate would need to be known to wholly mitigate the hazard simply through managing the charge size. In addition, the charge size is defined by the cooling demand and compartment volume is limited by the dimensions of the vessel therefore this control may not be possible to apply for a given design. Physically segregating persons from the refrigeration machinery by locating in a separate gas tight compartment is also an effective way of reducing the risk of an accident, however it can be expected that the compartment will need to be accessed at times for maintenance. It is possible that without limiting the charge size or segregating the refrigeration machinery a combination of the other identified controls may satisfy the safety requirements for a given situation, but this is dependent on the risk acceptance threshold of the safety case owner.

All possible controls should be applied to a system unless a risk assessment can demonstrate that the risk introduced by a given design can be considered to be ALARP with none or only some of the controls. It is recommended that the process described in this study or a similar hazard assessment is carried out for any installations using new or alternative refrigerants.

A useful further piece of work would be to apply the described process to a real or representative ship design with a defined load and compare the impact on the final design for different refrigerants in order to quantify the cost or operational implications. The proposed process could also potentially be further developed through inclusion of a quantitative risk assessment; this could be used to refine the controls required based on probabilities and an acceptable injury rate.

8. References

DNV GL. (2015). *RULES FOR CLASSIFICATION - Naval vessels.* DNV GL AS.

International Maritime Organisation. (2014). *Third IMO Greenhouse Gas Study*. London: International Maritime Organisation.

International Organisation for Standardization. (2014). *ISO 5149-1:2014 Refrigerating systems and heat pumps — Safety and environmental requirements.* International Organisation for Standardization.

International Organization for Standardization). (2017). *ISO 817:2014/AMD 1:2017 Refrigerants — Designation and safety classification.* International Organization for Standardization).

Lloyd's Register. (2020). *Rules and Regulations for the Classification of Naval Ships, January 2020.* Lloyd's Register Group Services Limited.

The British Standards Institution. (2016). *BS EN 378-1:2016 Refrigerating systems and heat pumps — Safety and environmental requirements.* BSI Standards Limited.

The British Standards Institution. (2019). *BS EN 60335-2-24:2010+A2:2019 Household and similar electrical appliances - Safety*. BSI Standards Limited.

The British Standards Institution. (2019). *BS ISO 20854:2019 Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation.* BSI Standards Limited.