Glosten

ASC RESEARCH VESSEL REPLACEMENT PROGRAM

# GREEN SHIP ALTERNATIVES STUDY

PREPARED FOR

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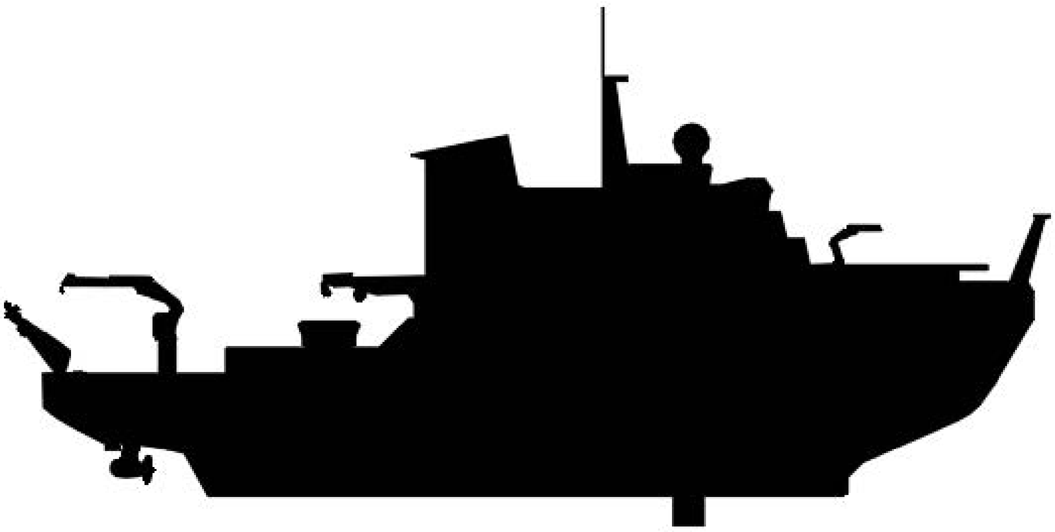


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# Revision History

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# Abbreviations

| | |
|---|---|
| ARV | Antarctic Research Vessel |
| BWMC | Ballast Water Management Convention |
| BWTS | ballast water treatment system |
| CFD | computational fluid dynamics |
| CMU | compression melt unit |
| CU | coefficient of utilization |
| DEF | diesel exhaust fluid |
| DP | dynamic positioning |
| EALs | environmentally acceptable lubricants |
| ECA | emission control area |
| EPA | U.S. Environmental Protection Agency |
| FOG | fats, oils, and grease |
| GWP | global warming potential |
| HRD | hydrotreated renewable diesel |
| HVAC | heating, ventilation, and air conditioning |
| IMO | International Maritime Organization |
| LNG | liquified natural gas |
| NOx | nitrogen oxides |
| ODP | ozone depletion potential |
| OWS | oily water separator |
| PM | permanent magnet |
| ppm | parts per million |
| PST | Polar Service Temperature |
| ROV | remotely operated vehicle |
| SCR | selective catalytic reduction |
| SOx | sulfur oxides |
| TSS | total suspended solids |
| ULSD | ultra-low sulfur diesel |
| URN | underwater radiated noise |
| UV | ultraviolet light |
| UVT | UV transmittance |
| VFDs | variable frequency drives |

# Executive Summary

This report evaluates various environmental technologies and practices that are potentially applicable to the Antarctic Research Vessel (ARV). The purpose of the evaluation is to recommend technologies that should be included in the ARV Performance Specifications. In some cases it can be clearly stated that a technology is recommended or *not* recommended. In many cases, *conditional* recommendations are made, pending design decisions not yet made. Similarly, technologies may be *conditionally* recommended pending further evaluation during the design process when tradeoffs can be better understood and evaluated. Technologies are presented in five categories, with a section devoted to each: Hull Technologies, Auxiliary Systems and Equipment, Pollution Control Systems, Outfitting, and Alternative Fuels.

Some of the technologies that are recommended in this report have already been included in the specifications. Their addition here should be considered as providing further justification and explanation for inclusion in the specifications.

Table ES-1 provides a high-level summary of the recommendations.

**Table ES-1: Summary of green ship technologies recommendations**

| Technology | Recommended? (Yes/No/Conditional) | Explanation |
|---|---|---|
| **Hull Technologies** | | |
| Hull/appendage optimization | Yes | |
| Advanced hull coatings | Yes | |
| ROVs for inspection and cleaning | Yes | |
| Underwater radiated noise reduction | Yes | |
| Air lubrication of hull | No | |
| Water lubrication in ice | No | |
| **Auxiliary Systems and Equipment** | | |
| **Electric Equipment** | | |
| Variable frequency drives | Yes | |
| Premium efficiency motors | Yes | |
| Permanent magnet motors and alternators | Conditional | Once a propulsion system is selected, permanent magnet motors should be considered as an option. |
| Energy storage batteries | Yes | |
| Harbor generator | Yes | |
| High efficiency lighting | Yes | |
| Smart lighting controls | Yes | Recommended for some spaces such as labs but may not be appropriate for all spaces. |
| **Climate Control Systems (HVAC)** | | |
| Waste hot water and steam | Yes | |

| Technology | Recommended? (Yes/No/Conditional) | Explanation |
|---|---|---|
| Air to air heat exchangers | Conditional | Conditionally recommended pending a more detailed design evaluation of available space. |
| Advanced HVAC controls | Yes | |
| Decentralized HVAC systems | Conditional | Recommended for some spaces but should be evaluated with tradeoffs during design |
| Heat pumps | Yes | |
| Environmentally friendly refrigerants | Yes | |
| Refrigerant systems management plan | Yes | |
| **Airborne Noise** | | |
| Interior and exterior noise limits | Yes | Recommend that effects of noise on wildlife be considered using the latest research at the time of the vessel design. |
| **Fire Suppression** | | |
| Clean agent – 3M Novec™ 1230 | Conditional | Conditionally recommended but further design analysis is needed to understand the design tradeoffs. Compare to water mist. |
| Water mist | Conditional | Conditionally recommended but further design analysis is needed to understand the design tradeoffs. Compare to Novec 1230. |
| **Pollution Control Systems** | | |
| **Lubricant and Hydraulic Oil** | | |
| Environmentally acceptable lubricants | Yes | |
| **Treatment and Segregation** | | |
| High efficiency oily water separators | Yes | |
| Oil cleaners | Yes | |
| Segregation of used engine oil | Conditional | Environmentally beneficial but may complicate vessel design and operations. Conditionally recommended pending owner input and further design verification. |
| **Oily Leak Prevention** | | |
| Stern tube leak control | Yes | Recommend that, where possible, water based stern tube seals be considered as they eliminate the possibility of oil leaks. |

| Technology | Recommended? (Yes/No/Conditional) | Explanation |
|---|---|---|
| Electric winches and windlasses | Yes | Recommended with considerations for cold weather and avoiding locations where immersion in seawater is possible. |
| **Wastewater Treatment and Reclamation** | | |
| Biological wastewater treatment | Conditional | Conditionally recommended pending further design validation and comparison to Electrolytic treatment. |
| Electrolytic wastewater treatment | Conditional | Conditionally recommended pending further design validation and comparison to Biological treatment. |
| **Garbage Management** | | |
| Comprehensive waste management plan | Yes | |
| **Food Waste Management** | | |
| Macerators/pulpers | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| Biological grease traps | Yes | |
| Food composter | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| Dehydration and/or vacuum sealing | Conditional | May be preferred to refrigerated stores but a recommendation depends on results of waste management plan and evaluation of design tradeoffs. |
| **Recycling** | | |
| Baler | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| Metal and glass shredder/crusher | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| **Conventional Garbage Management** | | |
| Trash compactor | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| Incinerator | Conditional | Conditionally recommended pending results of waste management plan and evaluation of design tradeoffs. |
| **Air Emissions Reduction** | | |
| Use ultra-low sulfur diesel (ULSD, <15 ppm) when available | Yes | Recommended but added cost and reduced availability are operational constraints that must be considered by the owner. |

| Technology | Recommended? (Yes/No/Conditional) | Explanation |
|---|---|---|
| Use emissions aftertreatment system in the Antarctic | Yes | |
| **Ballast Water Treatment System Technologies** | | |
| Ultraviolet light | Yes | |
| Electrochlorination | No | |
| Bulk chemical (includes chlorine dioxide) | No | |
| **Outfitting** | | |
| Extra insulation thickness | Yes | |
| Thermal insulating coating | Yes | |
| Insulated glass on exterior boundaries | Yes | |
| **Green Material Selection** | Yes | |
| **Alternative Fuels** | | |
| Liquid natural gas | No | |
| Hydrogen | No | |
| Ammonia | No | |
| **Green Diesels** | | |
| Biodiesel | No | |
| Renewable diesel | Conditional | Recommended if available. |
| Synthetic diesel | Conditional | Recommended if available. |

# Section 1 Introduction

## 1.1 Purpose

This study examined available technologies that can potentially reduce the fuel consumption and environmental impact of the ARV. These included technologies applicable to the hull, auxiliary ship systems, pollution control systems, and outfitting. Technologies related to propulsion systems and power generation are addressed in References 1 and 2.

This report describes the technologies and discusses their benefits and drawbacks for the ARV. Some technologies are recommended for inclusion in the ARV Performance Specifications. Some technologies or procedures are presented which are already required by regulations, but where specific recommendations or exceptions are added. Other technologies are presented which exceed regulations but offer economic, environmental, and/or operational benefits to the owner. The study is forward looking, considering that regulations generally become more restrictive over time.

## 1.2 Vessel Operational Environment

The ARV will operate in the Antarctic, with a minimum mean daily low temperature of -35°C (-31°F), Reference 3. For any equipment selected for the ARV, the Polar Service Temperature (PST) would be -45° C (-49ºF). The designer will need to consider the PST when specifying equipment.

The Antarctic is also an environmentally sensitive area. MARPOL 73/78 defines certain sea areas as 'special areas' in which, for technical reasons relating to their oceanographical and ecological condition and to their sea traffic, the adoption of special mandatory methods for the prevention of sea pollution is required. Under the Convention, these special areas are provided with a higher level of protection than other areas of the sea. The Antarctic has special protections under Annex I, II, and V. Use of heavy fuel has been banned in the Antarctic since 2012. The Protocol on Environmental Protection to the Antarctic Treaty (aka Madrid Protocol), also provides for comprehensive protection of the Antarctic environment and dependent and associated ecosystems (see Section 4.1 for more detail).

## 1.3 Methodology

A list of technologies was developed from four broad categories:

- **Hull Technologies:** Technologies affecting the shape, material, or coatings of the vessel hull that would benefit the environment, either directly or indirectly. This section also includes noise.
- **Auxiliary Systems and Equipment:** Technologies affecting ship systems or equipment that could improve overall efficiency (reduce fuel consumption) or benefit the environment (reduce harmful emissions to air or water).
- **Pollution Control:** Any system, technology, or process relating to the management of waste products. These could be technologies for reducing waste (recycling or reuse), reducing accidental discharges, or for processing normal waste streams in a way that reduces discharges to air or water.
- **Outfitting:** Materials installed on the vessel that could improve efficiency (reduce fuel consumption) or reduce environmental impact in some other way.

For each category, the technologies are described and potential benefits or drawbacks are presented as they relate to the mission of the ARV. Some technologies are recommended because they offer an obvious benefit, with limited drawbacks. Others are not recommended for various reasons. Finally, some technologies are recommended with conditions. In these cases, not enough is known at this stage of design, but it is recommended that the technologies be assessed further during the subsequent stages of design.

# Section 2 Hull Technologies

The ARV hull form will need to meet a complex and conflicting set of requirements. It must provide enough buoyancy to support the weight of the vessel while providing enough space for the interior arrangements and cargo. The hull must have enough stability and good seakeeping for all weather conditions that the vessel will encounter. Finally, it must be able to operate within the ice during Antarctic missions. A well-designed hull should do all of the above while having the least possible resistance (in ice and open water) for maximum speed at minimum power.

In order to minimize the propulsion losses due to the hull, one must reduce the overall hull resistance. In open water the vast majority of that resistance comes from viscous effects between the hull and the water. As speeds increase, the effects of wave making become more significant. The design flexibility will depend on many factors and must be balanced against the vessels primary mission requirements. Because viscosity effects are dominant while operating in open water, the majority of methods for reducing resistance focus on reducing skin friction.

The ARV will also operate a significant amount of time in the ice. Hull resistance in ice is primarily from ice friction on the hull, energy required to break ice, and the propeller-ice interaction. The propeller ice interaction refers to the amount of energy used in milling large pieces of ice that flow into the propellers. Modern ice breaking hull forms are typically configured to move ice broken at the bow under the hull then outboard and away from the path of inflow to the propellers.

An efficient icebreaking hull can reduce fuel consumption. For ice operations the bow form breaks ice in two primary modes: ice crushing and ice bending. A bow that minimizes ice crushing in favor of breaking ice by bending typically requires less power since ice crushing or compression requires a larger amount of energy compared to breaking ice in bending.

Other approaches and technologies that can reduce resistance in ice include reamers and use of air or water lubrication to reduce the friction of the ice on the hull. Air lubrication is discussed further in Section 2.5. Reamers effectively increase the beam of the vessel forward, as on R/V *Sikuliaq*. Reamers may also be advantageous for other design aspects, such as coring systems, because the hull aft of the reamers can have parallel midbody allowing thus a straighter deck edge. Additionally, reamers can help improve turning performance in ice.

Many aspects of icebreaking hull design have been patented by one designer or another. As such, not all options for improvement in icebreaking or open water performance will be available to all designers.

## 2.1 Hull/Appendage Optimization

Design of the ARV hull form will impact overall efficiency and fuel consumption. The vessel will be spending the majority of mission time in open water; therefore, its open water efficiency is important. Typically for open water vessels, a CFD (computational fluid dynamics) -driven hull form optimization would be used for determining the optimum hull shape that addresses a set of ranked criteria such as: lowest resistance; maximum dimensions; minimum displacement, etc. However, such an optimization analysis would also need to consider the hull form features needed for efficient icebreaking operations which may make it unsuitable for optimization with standard open water CFD analysis tools. The hull form will need to be a compromise between open water and ice performance and will require optimization through a comprehensive analysis and model testing program.

In addition to the hull form it will be important to optimize hull appendages such as transducer flats, thruster apertures; and centerboard(s) since all of the hull appendages add to overall resistance and fuel consumption. The hull will also need to be configured to minimize bubble sweepdown across the transducer flat (see ARV Bubble Sweepdown Study, Reference 4). This may not lend itself to existing analytical optimization tools but will require, at a minimum, an evaluation of hull streamlines via CFD and/or model testing.

The type of propulsor, e.g. azimuthing or conventional, will also impact mechanical and hydrodynamic efficiency (see ARV Propulsor Study, Reference 1). In all cases the shape of the hull in the vicinity of the propulsors is critical to efficient propeller performance and consequently lower fuel consumption. The added resistance due to the stem legs and gear hubs of azimuthing propellers should be optimized for least resistance. Similarly, for conventional shafts and rudders the shafting bearing struts as well as the rudder shape need to be designed for least resistance.

Hull form optimization is primarily done to save fuel and if done early in the design, it is possible to see reductions in resistance of up to 20%. Due to the many issues discussed here, such dramatic reductions are not likely. However, hull optimization is recommended for ARV since it is relatively inexpensive and brings many other benefits that can be realized in way of performance, underwater noise, etc.

## 2.2 Advanced Hull Coatings

The material used to coat the hull of a ship below the waterline serves several purposes. The primary purpose is to prevent corrosion of the steel hull. Another is to inhibit the growth of marine organisms on the hull to reduce friction and the transfer of invasive aquatic species.

Reducing drag on the hull is an essential strategy for improving energy efficiency and saving fuel. Surface roughness, which has a significant effect on frictional resistance for a ship's hull, can be caused by both physical imperfections and the accumulation of biological growth. Large marine organisms such as barnacles and mussels, as well as slimes and grasses, can attach themselves to the hull causing drag. Over time, such hull accumulations will significantly reduce the fuel efficiency of the vessel.

In the past underwater coatings had biocides such as tributyltin (TBT) added to inhibit growth on the hull but, due to toxic bioaccumulation, TBT has been banned. Another newer strategy is foul-release hull coatings. Modern foul-release coatings are designed to prevent organisms from getting a good hold on the hull. When the ship is not moving the organisms can attach themselves to the hull of a ship, but when the ship gets above a threshold velocity, the hydrodynamic forces strip the growth away. In this sense, the hulls are 'self-cleaning' and do not poison the organism. Foul release coatings are typically most effective on higher speed vessels though lower speed versions are being developed. However, it is not clear whether a foul release coating would be appropriate for the ARV since it would also need to be effective in ice.

The ARV which will be operating in ice every season, so will require coatings which are specifically designed to withstand the demands of icebreaking service, favoring characteristics such as hardness and toughness. For the ARV an advanced coating is recommended which is both hard and tough for use in ice, but also smooth for reducing friction in both ice and open water. An example would be Ecospeed coating, which the manufacturer claims should last the life of the ship.  However, such a coating will still require routine hull cleaning and periodic touching up.

## 2.3 ROVs for Hull Inspection and Cleaning

After application of a new coating system the performance will diminish over time.  Inevitably, some organisms will find a way to attach to imperfections or damaged areas of the coating. Coatings are usually applied on the dry-docking schedule, which is typically 60 months for most vessels and can be shorter for icebreaking vessels.  For optimal performance in ice or open water, the owner must maintain the integrity of the hull coating at periodic intervals.

Hull inspections are key to understanding the condition of the hull coating (including hull appendages and seachests).  Traditionally this has been done with divers or during a drydocking period.  New underwater ROV (remotely operated vehicle) technology has emerged that has made hull inspection much simpler and less expensive.  Some port authorities have employed this as a means of screening for invasive species or even looking for drugs.  With the falling cost and rapid technological improvement, self-inspection at port is a realistic possibility.  Robotic hull inspection drones could be deployed and operated by the ARV's crew.  These should be considered for the ARV.  However, since they are not permanently installed equipment, these would not be part of the contract specifications but rather owner furnished and operated by the crew.

A product developed by Jotun in partnership with Kongsberg called the *HullSkater* could be installed as a permanent piece of deck equipment for easy and fast deployment.  The device is designed to be launched over the side rail and 'crawl' or 'skate' along the hull on magnetic wheels.  The ROV is semi-autonomous and will inspect the hull for early signs of fouling and can clean the hull before the fouling can take hold.  Consequently, the ship's hull is continuously inspected and proactively cleaned.  Such devices are expected to become more widely refined and available by the time the ARV is launched.  Due to the many benefits, it is recommended this be considered for the ARV.  As this technology is new, its progress and costs should be evaluated as the ARV design progresses.

**Figure 1 Jotun *HullSkater* robotic inspection and cleaning ROV**

### 2.3.1 Regulatory Guidance for Biofouling

Considering the many important benefits to the environment of maintaining a clean hull, it is no surprise that biofouling has been addressed in the regulations. Maintaining a clean hull is discussed by the International Maritime Organization (IMO) in "*2016 Guidlines for the development of a ship energy efficiency management plan* (SEEMP)" (Reference 5). The IMO's "*2011 Guidelines for the Control and Management of ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species*" (Reference 6) provides specific design, installation, and operational guidance on how to minimize biofouling. The *"International Code for Ships Operating in Polar Waters (Polar Code)"* (Reference 7) provides more specific guidance for polar class vessel operating either year-round or intermittently in ice-covered waters.

## 2.4 Underwater Radiated Noise Reduction

Underwater radiated noise (URN) of the ARV is discussed at length in the *Underwater Radiated Noise Requirements Study* report (Reference 8). Within this study, recommended URN limits were developed primarily to ensure the successful operation of the various acoustic transducers at the relevant vessel operating conditions. Potential limits were developed for an 8 kt quiet condition, a full speed transit condition, and a station keeping condition. In each case, environmental stewardship was used as an additional driver at the portions of the spectrum which were below the transducer operating frequencies.

Regulatory agency URN notations designed with environmental stewardship in mind were reviewed and integrated into the ARV URN limit recommendations to provide this additional guidance. In the last decade, interest in underwater noise has increased significantly with ports within Europe and North America performing extensive studies on noise from vessel traffic and potential environmental impacts. In response to this increased interest, regulatory agencies have developed URN notations for vessels. The American Bureau of Shipping (ABS) provides multiple tiers of URN limits at 'quiet' reduced speeds and higher transit speeds with the goal of reducing impacts on marine mammals and other sea life. The DNV Silent (E) environmental notation provides quiet and transit URN limits for similar purposes.

Approaches for reducing URN, and noise overall, is different for every vessel and depend on what requirements are sought. The largest sources of URN are typically the large propulsion equipment such as propellers, gears, and engines (or generators). For large reciprocating or rotating machinery, the strategy is to minimize the pathways for transmission to the hull. Generator foundations are usually stiffened and the equipment is placed on special isolation mounts. Propeller noise is usually governed by cavitation. Propellers can be designed to minimize cavitation, usually up to a certain design speed but this is much more difficult for propellers designed for ice. Beyond the large equipment, further noise reduction is done by careful consideration of which equipment is producing noise and designing a way to minimize it, which usually is done by placing it on isolation mounts. For very quiet vessels, piping runs are isolated and special damping materials can be added to bulkheads or the hull to minimize transmission.

Design, construction, and maintenance of noise reduction technology has a very real cost to the vessel and the cost must be considered against the benefit of reduced URN. For example, propellers optimized for low noise can have lower efficiency meaning higher fuel burn. Applications of noise reduction technology must be applied with intention to meet specific criteria in order to make meaningful comparisons of the benefits. Typically for research vessels, low noise is mission-critical, and the environmental benefits to marine life are ancillary. It is recommended that reducing URN effects on mammals and other sea life be considered in the development of URN requirements for the ARV, specifically to the extent that this information is known at the time of design. This recommendation will be added to the specifications so the bid designer is made aware.

## 2.5 Air Lubrication of Hull

Air lubrication is a method that reduces hull resistance by injecting bubbles or pockets of air into the water beneath a vessel's hull, thereby reducing friction. To be tenable for any application, an air lubrication system must function in various sea states, not overly disrupt the flow going into the propeller, and save more energy than is consumed by the system that creates the bubbles.

Two primary air lubrication methods exist. Both are in the early stages of commercialization. One uses hull form to create a large air pocket in a cavity on the underside of the hull. The other uses a compressed air system to inject streams of micro-bubbles below the hull. The air pocket method is limited to flat-bottomed hull forms and requires incorporation of a concave space on the underside of the hull where the air pocket can be trapped. The micro-bubble method is also most effective for flat-bottomed hulls since an increase in hull slope or convexity will generally decrease the resistance a bubble encounters as it passes over the hull surface.

Air lubrication was researched specifically as a friction reduction method for operation in ice in the 1960s and 1970s and was installed on several Finnish and Soviet icebreakers. However, with the invention of the azimuthing propeller, interest in air lubrication for icebreakers faded because many of the same benefits could be achieved using azimuthing thrusters to create a turbulent propeller wash between the propeller and the ice, especially in double acting hulls (going stern first). Air lubrication technology is still considered viable for icebreakers that use conventional shafting.

Based on similar icebreaking vessels it is unlikely the ARV will have a large flat section of hull. Some flat section will be necessary, but it will likely contain the transducers whose design requires avoiding bubbles and air as much as possible. If a centerboard is provided, it would likely be part of the flat section, further complicating the containment of an air pocket. Air lubrication technology for open water use is one of the most exciting technologies in the industry due to its upper end potential for fuel savings. However, it is not considered viable for the ARV.

## 2.6 Water Lubrication in Ice

There can be benefits of using water lubrication in ice, largely from reducing the friction of snow on the hull. The benefits of using water lubrication in ice can be offset by the energy required to pump a significant amount of water onto the ice. There will also be increased maintenance as it is a sea water system and could have significant corrosion. While we recommend that the specifications stay open to novel means of reducing friction on ice, water lubrication is not specifically recommended.

## 2.7 Hull Technologies Summary

Table 1 presents a summary of the evaluation of hull technologies and recommendations for the ARV.

**Table 1 Summary of hull technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Hull/appendage optimization | • Reduced fuel consumption | • Added cost | Yes | The cost of optimization is minimal compared to the benefits of improved efficiency. |
| Advanced hull coatings | • Reduced fuel consumption<br>• Improved performance in ice | • Small added cost | Yes | ARV will require coating suitable for operation in ice. It is recommended that consideration for open water performance also be considered in evaluation of options. |
| ROVs for inspection and cleaning | • Reduced fuel consumption<br>• Improved performance in ice<br>• Reduced spread of invasive species | • Added cost<br>• Time and training of crew | Yes | This technology is still emerging, but the potential benefits are significant. |
| Underwater radiated noise reduction | • Reduced impact on marine mammals and sea life. | • Significant design and construction expense | Yes | |
| Air lubrication of hull | • Reduced fuel consumption | • Not applicable to ARV hull form<br>• Bubbles could interfere with sonar | No | Not compatible with ARV hull design, assuming the use of azimuthing propulsors. |
| Water lubrication in ice | • Reduced fuel consumption | • Added cost<br>• Unclear if net positive reduction in energy | No | Specification should allow for novel means of reducing friction in ice to be presented with analysis indicating benefit, but water lubrication is not recommended. |

# Section 3 Auxiliary Systems and Equipment

## 3.1 Electric Equipment

### 3.1.1 Variable Frequency Drives

Pumps and fans are typically sized for the maximum demand in a worst-case scenario (i.e., the "design day"). The day to day demands in typical operation are significantly less than the design day worst case. Variable frequency drives (VFDs) can be used to allow turndown of large fan and pump motors for operation when the full design capacity is not required. Power consumed by a pump or fan follows the affinity law:

$$P = P_0 \times \left( \frac{n}{n_0} \right)^3$$

Where:

$P$ = the power consumed by the pump or fan,

$n$ is the RPM,

subscripts ($n_0$ or $P_0$) = the power or speed *change.*

For example, a 25% reduction in the speed of a pump ($n$ is initial speed and $n_0$ is reduced speed) results in a 58% reduction in the power demand ($P_0$). The turndown of the pumps and fans can either be manual or automatic. Large pumps that run continuously are good candidates for VFDs. For example, the seawater pumps could be set up for a temperature-controlled operation in which they are turned down when the cooling demand decreases, thus preventing the use of unnecessary energy in pumping high volumes of seawater.

The use of VFDs does add some cost to the motor and control equipment and adds complication to the pump or fan controls, especially if automatic controls are used. Additional controls and sensors increase failure modes and maintenance items. The efficiency gains need to be thoughtfully balanced against the added cost and complexity.

Two additional concerns with using VFDs are electrical system harmonics and vibration/noise control. Specialized electrical cabling, controls, and motors need to be used with VFDs to ensure the motors operate properly and do not induce harmonic distortion to the ship's electrical system. Secondly, attention must be given to the noise attenuation of the equipment. Typically, structure-borne noise is mitigated through the application of resilient mounts for equipment. These mounts are tuned based on the excitation frequency of the equipment. When a VFD is installed, the excitation frequency of the equipment varies, increasing the complexity of noise mitigation.

VFDs are recommended on the ARV for equipment that typically has large motors sized for worst case peak demands but that is often operated with significantly reduced demand, and for larger pumps and fans that run for extended periods of time (e.g. seawater pumps, chilled water pumps, waste heat recovery pumps, larger air handlers and ventilation fans).

### 3.1.2 Premium Efficiency Motors

Typically, electric motors come in three different efficiency ratings: standard, EPAct-compliant, and NEMA (National Electrical Manufacturers Association) Premium. Figure 2 shows a comparison of the average efficiencies for the various types of electric motors.

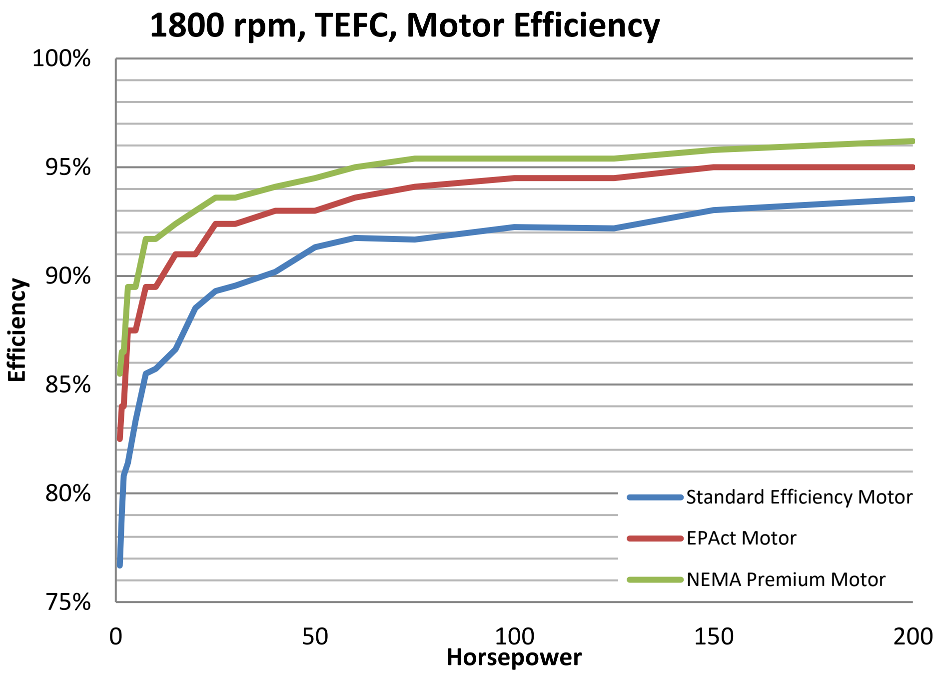


**Figure 2 Example motor efficiencies**

Since electric motor capital cost increases with increased efficiency, selection of motor type should be based on anticipated frequency of use. Premium efficiency motors are recommended for all motors where they are readily available.

### 3.1.3 Permanent Magnet Motors and Alternators

Permanent magnet (PM) AC alternators and motors are inherently more efficient than conventional induction machines due to elimination of rotor conductor losses, lower resistance windings, and "flatter" efficiency curves. Due to their synchronous operation, PM motors offer more precise speed control. PM motors provide higher power density due to the higher magnetic flux compared with induction machines. PM motors generally operate at a cooler temperature, resulting in longer bearing and insulation life. Similar advantages are also seen in PM alternators. Finally, PM motors are smaller and can offer significant space savings for some applications. Reducing space required for equipment could improve maintainability of the vessel and could even increase space available for science or cargo.

Large machines that see high use such as propulsion motors or alternators could be good candidates for PM. However, PM motors are more expensive and less available, and therefore they should only be considered where they offer a significant quantifiable advantage. It is recommended that PM motors be considered on the ARV for propulsion or bow thruster service if a tangible efficiency and space advantage is estimated, and if these advantages are considered reasonable tradeoffs against such factors as cost.

### 3.1.4 Energy Storage Batteries

Energy storage batteries enable many efficiency solutions as well as improved dynamic response and reduced engine operating hours (i.e., reduced maintenance). Improved dynamic response is an especially important benefit for icebreaking vessels.

Over the last half-decade, the commercial market for marine propulsion batteries has grown tremendously due to falling prices and increased awareness of the benefits of hybrid technology. There is now genuine competition in purpose-built marine batteries. There has also been progress in the regulatory space, with most if not all class societies having developed rules for integrating lithium-ion batteries (the leading battery technology) into ships.

On land, batteries are sometimes combined with renewable energy systems to allow storage of energy produced during off-peak times. There could be times, for example if the ARV were deployed on ice or underway in windy conditions, when having renewable energy onboard could potentially be used to offset some of the fuel use. Unfortunately, the power density of renewable energy makes this impractical. Producing power equivalent to 10% of *one* of the diesel generators, or 500kW (only about 3% of the installed power), would require a turbine with a 39-meter (128-ft) blade diameter and a hub height of over 40 meters (130 ft). Solar power would be equally impractical, producing around 200 watts/$m^2$. To produce 500 kW of solar power would require at least 2,500 $m^2$ of panels which would cover most, if not all, of the ARV. Furthermore, in the Antarctic, the panels would collect a fraction of the sunlight due to the high latitudes and to be marginally effective would have to be installed with very high angles of incidence to efficiently collect the sunlight. Clouds make solar panels even less efficient.

There are many types of so-called 'hybrid' systems. Usually, hybrid propulsion refers to a system that combines both mechanical and electrical elements, and very often batteries, to optimize efficiency. If batteries are combined with a diesel electric plant, such as on the ARV, they could provide many efficiency and performance benefits.

Operating in ice, and specifically breaking ice, is an extremely energy-demanding activity. Loads can be highly dynamic, meaning they can change in magnitude very rapidly. Typically, this is handled by having more generators online so that they can respond to load changes as quickly as possible. However, this has the effect of all the generators operating at a lower load on average and burning more fuel. Batteries can react instantly to load demands and can allow the diesel engines time to 'catch up'. Depending on the battery bank size and configuration it may allow operation with fewer engines. Dynamic positioning (DP) is another example of an operation with rapid load changes. Batteries have been shown to significantly increase the efficiency of DP operations on many vessels. The first hybrid icebreakers are only just coming into operation so there is still limited real world data, but it is fully anticipated that batteries will offer great efficiency and performance benefits.

A battery hybrid is recommended for the ARV due to the many benefits for both open water and ice breaking. Battery hybrid power on the ARV is discussed in the Power Systems Study report (Reference 2).

### 3.1.5 Harbor Generator

Most of the locations visited by the ARV are unlikely to have shore power that fits the vessel's requirements. The shore power load, even in cold weather will be a fraction of the smallest of the main generator's capacity. Running generators at low load is less efficient, causes higher emissions, and can increase maintenance costs. While adding a small generator does increase the capital cost, the maintenance will be less expensive than the larger generator. A dedicated harbor generator would improve the efficiency and emissions when operating at port and is therefore recommended for the ARV.

### 3.1.6 Lighting Systems

#### 3.1.6.1 High Efficiency Lighting (LEDs)

Traditionally, the interior lighting on commercial vessels has been provided by fluorescent light fixtures. Fluorescent lighting is low cost, has low energy use, and has bulbs and fixtures that are readily available. Significant advances in commercial marine quality LED lighting systems made in the past couple of decades have made them an attractive alternative that is rapidly becoming the standard on many vessels. The rate of advancement in solid state lighting (i.e., LEDs) has not only brought down the cost, increased the efficiency, and improved the life of the light; it has also greatly increased the design flexibility with many more types of fixtures available than for fluorescent lighting.

Typical LEDs offer better directional control of light compared to fluorescent lighting, which increases the coefficient of utilization (CU) value. CU is a measure of how efficiently a fixture can transfer light to a particular area. LED fixtures themselves are slightly more efficient than fluorescent, but not significantly. However, because of the increased CU values, fewer LED fixtures are required to illuminate a room and the lighting can be more effective.

One potential advantage of some LEDs is their ability to modulate color to suit the needs of the application. Numerous LED products are now available for commercial and residential use that have programmable color. This is a potential application on ships as well that could be explored. For example, a day and a night setting could be employed for certain spaces such as passageways or even the bridge to improve visibility or comfort for the occupants.

The life of an LED light operated at a temperature of 25$^{\circ}$C is around 90,000 hours. In machinery spaces, which are closer to a temperature of 45$^{\circ}$C, the life drops to around 60,000 hours. In comparison, a fluorescent lamp has a typical life of 20,000 hours in either temperature scenario. Higher temperature can also reduce the light output of an LED.

LED lights typically have a lower startup time (instant on) and, as such, could be a better match for use with more advanced (motion detection/occupancy) type controls, as well as being a better match for cold spaces where the startup time of fluorescents lags.

LED fixtures currently cost more than fluorescent, though the differential is rapidly changing. Further consideration and monitoring of this technology is recommended as the cost–benefit analysis will likely change over the next few years. However, current LED fixtures' longer lifespan under normal temperatures make them cost competitive even at today's costs.

One concern regarding fluorescent lamps that is not a problem with LEDs is the disposal of the lamp, and the effects of the mercury used in the lamp. About 4 mg of mercury is in each fluorescent lamp. Mercury is slowly absorbed in the lamp's glass, phosphor, and tube electrodes over the lamp life, so that there is very little mercury remaining at the end of the life. The lamps should be recycled, where the remaining mercury is reclaimed for reuse. Mercury is a neurotoxin, but poses no known environmental or health threat unless the lamp is broken.

LED fixtures are a viable substitute for fluorescent lights. While more expensive initially, LEDs use less power, overall, than fluorescent fixtures, resulting in less fuel burned, and less carbon dioxide ($CO_2$) released. LED lighting is recommended for ARV.

#### 3.1.6.2 Smart Lighting Controls

Smart lighting controls can minimize the use of unnecessary lighting on the ARV. Motion-sensors can be used to turn off or turn down the lighting in a space when it is not occupied. For example, if a passageway is unoccupied, the motion sensor could signal the lighting to be reduced or shut off all but a single fixture. In a large space, the lighting could be reduced to a single fixture per zone. Smart lighting can also be networked to allow for more sophisticated control and monitoring. While the cost of lighting controls needs to be considered against the potential costs of maintenance, complexity, and overall potential for savings, it is recommended for public spaces such as labs, bridge, or corridors where the benefits would be greatest.

### 3.1.7 Electrical Equipment Summary

Table 2 provides a summary of electrical equipment recommendations.

**Table 2 Summary of electrical equipment technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Variable frequency drives | • Reduced fuel consumption | • Added cost | Yes | Recommended on large, continuously operating systems such as cooling and heating. |
| Premium efficiency motors | • Reduced fuel consumption<br>• Improved performance in ice | • Small added cost | Yes | Premium efficiency motors should be specified for all motors where they are available. |
| Permanent magnet motors and alternators | • Reduced fuel consumption<br>• Reduced volume<br>• Reduced weight | • High cost | Conditional | Recommended that PM motors be considered for propulsion and bow thrusters during the design. Since the technology is emerging, it should be evaluated against conventional motors on the basis of cost and efficiency. |
| Energy storage batteries | • Reduced fuel consumption<br>• Improved performance in ice<br>• Lower noise | • Higher upfront cost<br>• Additional space for storage<br>• Periodic replacement | Yes | Batteries are discussed in more detail in the Power Systems Study. A battery hybrid is recommended for the ARV due to the many benefits for both open water and ice breaking. |
| Harbor generator | • Higher efficiency, lower emissions, lower maintenance than using larger ship's generators for providing in-port power. | • Additional capital cost | Yes | |
| High efficiency lighting (LEDs) | • Higher efficiency than fluorescent<br>• Long life<br>• No mercury<br>• Color modulation | • Higher initial cost | Yes | The ARV should specify the use of LED lighting wherever possible. |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Smart lighting controls | • Reduced fuel consumption<br>• Improved comfort | • Added complexity<br>• Added cost | Yes | Recommended for some public spaces such as labs but may not be appropriate for all spaces. |

## 3.2 Heating, Ventilation, and Air Conditioning

Heating, ventilation, and air conditioning (HVAC) is a huge source of energy usage on a ship. It will be especially large for a vessel that spends so much time in cold regions where the difference in temperature between the vessel interior and the ambient environment is large.

Because of the large deckhouse and accommodations, the ARV will have a significant HVAC system. There may be opportunities to increase the energy efficiency of the HVAC system. However, there are significant space constraints due to the limited space available and large size of energy efficient system components. This limits the practicality of some of the high efficiency HVAC system technologies.

The design of the HVAC system for the ARV will need to weigh many tradeoffs. Waste heat should be utilized as much a practical, but some amount of electric heating is unavoidable. Space, weight, and capital cost must be considered against the need to maximize efficiency and comfort. The extreme low temperatures will require careful consideration to minimize heat losses as well as taking advantage of recovered energy, where available. The extremely low external temperatures will require that the air be humidified during certain conditions as cold air holds very little moisture. Low relative humidity is to be avoided in interior spaces. Not all spaces will require the same treatment so different approaches will need to be considered for cabins versus workspaces and laboratories. Advanced HVAC control systems (Section 3.2.2) and decentralized HVAC systems (Section 3.2.3) should be considered.

Taking a wholistic approach to the design from the very beginning will maximize opportunities for improving efficiency and comfort. It is recommended that the ARV Performance Specifications require the designer to consider these factors from the very beginning. A poorly designed and conceived HVAC system will plague the occupants for many years and is very expensive to correct after installed. This section evaluates potential HVAC requirements to include in the ARV Performance Specifications.

### 3.2.1 Waste Heat Systems

#### 3.2.1.1 Hot Water or Steam

Heating a large vessel such as the ARV is typically done using either hot water or low pressure steam. Hot water and steam systems are very efficient at transferring heat and can be generated either from burning diesel directly in a boiler, or by utilizing waste heat from the onboard generators. Using boilers or waste heat is far more efficient than using electric resistance heaters. This is especially true when the source of waste heat is a diesel generator, which converts only about 40% of diesel fuel energy to electrical power. It is recommended that waste heat from diesel generators (via jacket water and/or combustion exhaust) be used as a primary source of heating for the HVAC system on the ARV, and a diesel fired boiler or hot water heater be used as a secondary or backup source of heat. For a more detailed discussion of waste heat recovery systems, see Section 3.3.

#### 3.2.1.2 Air to Air Heat Exchangers

Another method of capturing waste heat is through air-to-air heat exchangers (Figure 3). These heat exchangers use exhausted air to precondition the outdoor "makeup air" being brought in to replace it. In the cooling season, the heat exchanger would cool the makeup air, and in the heating season, it would preheat the makeup air. This would reduce the cooling and heating demands for the makeup air. Air-to-air heat exchangers can be up to 85% efficient. These systems are used effectively shoreside and on large cruise ships. The components tend to be large, typically doubling the size of the air handlers, and successful integration into the HVAC systems on the ARV in the available space will be challenging. However, as part of a wholistic approach that considers other space and energy saving measures, air-to-air heat exchangers can be an important part of the designers' arsenal and are recommended to be required for consideration during the design by the ARV Performance Specifications.

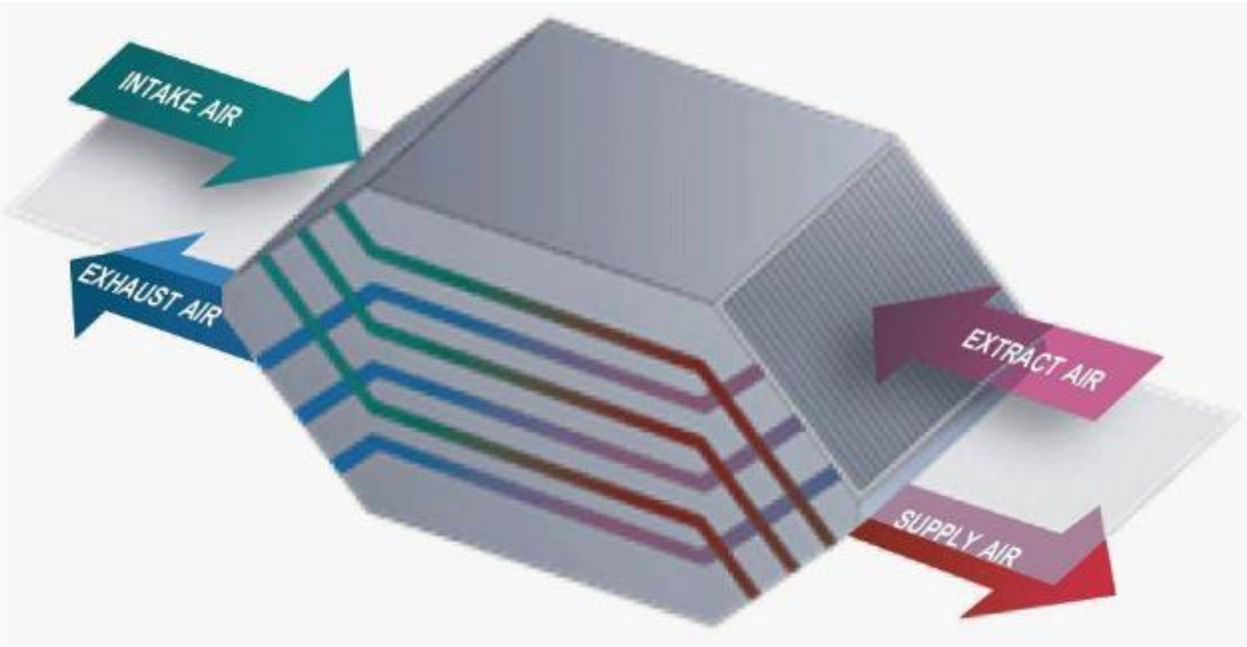


**Figure 3 Air-to-air heat exchanger (credit: Reference 9)**

### 3.2.2 Advanced HVAC Control Systems

Regardless of the type of HVAC system that is selected, modern climate controls offer greater comfort and efficiency through increased use of sensing and control technology, as well as decentralized equipment. For fluid systems, this can involve the use of three-way modulating valves to improve comfort and level of control for chilled water and hot water coils. For air systems, temperature and pressure sensors can be used to optimize the airflows through variable speed fans or variable air volume control boxes at the room terminals. Multi-stage heating coils will improve control and reduce energy consumption. Remote temperature sensing in spaces can help identify freezing issues that are of particular importance on the ARV. These systems will improve efficiency and comfort but come at a higher up front cost and are more expensive to maintain. It is recommended that these systems be at least considered during design for some spaces, such as accommodations.

### 3.2.3 Decentralized HVAC Systems

Traditional HVAC systems provide climate control to each heating zone through "terminal reheat". For each zone, air is distributed to the spaces from a central air handling unit. To provide temperature control for each space, the air is delivered well below the temperature that the space would typically be heated to and then 'reheated' by electric heaters based on the demand of the thermostat. Some of the air is continually exhausted from each space to maintain air quality. The makeup air must be heated from the ambient temperature up to the delivery temperature, which requires additional energy. Most of the air is recirculated back to the air handling unit and may even be cooled by chilled water to remove moisture. Though inefficient, this system has the advantage of being simple while also providing control over a range of temperatures to suit the preferences of the occupants.

A more efficient approach is to decentralize and distribute the heating and cooling equipment. Each cabin or space would have one or more ceiling or wall mounted units which heat or cool the air in the space. A separate system exhausts a small quantity of air from each space and a central air handler provides an equal amount of conditioned makeup air at a neutral temperature. This method avoids extensive amounts of ductwork and provides more complete climate control to each space. Less energy is lost in distribution and there is no need to centrally cool or heat air for the entire zone. This method may also be more sanitary since no air is recirculated from space to space. Furthermore, it is possible to use air-to-air heat exchangers to recover the heat from the exhaust air to help warm the incoming makeup air.

The individual units can be provided with hot and/or cold water for the heating source. Newer systems provide heating and cooling by circulating refrigerants, which may have advantages in weight and size. A hot water heating system distributed to all the small cabin units throughout the vessel would likely require too large a piping system to be practical. However, the hot water can still be used to heat the makeup air going out to the cabins or for heating air to larger spaces.

On the ARV, as on other vessels, there is no one-size-fits-all approach to HVAC. For some spaces, such as laboratories and common spaces, the decentralized approach may be necessary due to the complexity of the HVAC system requirements. Accommodations may or may not see an overall benefit for decentralized HVAC. Arguably, the superior control of decentralized systems would improve the comfort of personnel on long voyages, but the overall advantages and disadvantages should be evaluated during the design to determine what makes the most sense. It is recommended that the ARV Performance Specifications require the consideration of decentralized systems during the design process.

### 3.2.4 Heat Pumps

A heat pump is a device similar to a refrigerator or air conditioning unit, but which can be used for both heating and cooling. A refrigerator or freezer keeps a space cold by using a refrigeration cycle to 'pump' heat out and eject it to another location. A heat pump uses exactly the same principle but is reversible so can operate in either direction. The heat source can be water, air or even the ground. On a ship, a heat pump could use seawater or a freshwater loop as the heat source/sink. Heat pumps today are capable of using very low temperature 'heat' sources. On the ARV the coldest the seawater will ever be is 28° F and there will be many other sources of low-quality heat that could be used. On some icebreakers, waste heat is recirculated to the seachest or seabay to minimize icing and blockage. On R/V *Sikuliaq*, the seabay is temperature regulated to 60ºF when operating in colder waters. There are many potential sources of heat which can be used by a heat pump on the ARV and it is recommended that heat pumps be considered by the designers. While heat pumps are a potentially efficient way to make use of low temperature waste heat, if higher quality waste heat sources can be used directly for heating cabins they may be more efficient than heat pumps.

### 3.2.5 Environmentally Friendly Refrigerants

Refrigerants will be required on ARV for refrigerating and freezing provisions, science uses, and air conditioning. They can be released into the atmosphere accidentally and through normal, inevitable leakage from machinery. Once in the atmosphere refrigerants have the potential to damage both the ozone layer and contribute to climate change through global warming. These potentials are quantified as ODP (ozone depletion potential) and GWP (global warming potential). Most refrigerants today have minimal or zero impact on the ozone layer, thanks to regulations. However, the GWP of many common refrigerants are thousands of times more potent than $CO_2$ (GWP = 1). MARPOL Annex VI prohibits ozone-depleting substances after January 1st, 2020, with the exception of hydrochlorofluorocarbons, which are common refrigerants, but is silent on GWP. Lower GWP refrigerants are available, but not necessarily easy to obtain. The future availability of low GWP refrigerants when the ARV is constructed is unknown. However, it is recommended that low GWP refrigerants be specified for the ARV to the extent they are available.

### 3.2.6 Refrigerant Systems Management Plan

Various notation guides from class societies, such as the ABS *Environmental Protection Notation for Vessels* (Reference 10), provide very good design and operational guidance that can minimize the release of refrigerants. Guidance includes setting upper limits on GWP, leak monitoring in refrigeration machinery spaces, and refrigerant system management plans for crew. Such approaches provide pragmatic and tangible means of minimizing the potential release of refrigerants and are recommended for ARV.

### 3.2.7 HVAC Summary

A summary of HVAC recommendations is presented in Table 3.

**Table 3 Summary of HVAC systems technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Waste hot water and steam | • Reduced fuel consumption | • Few drawbacks if hot water or steam is already utilized for interior heating | Yes | |
| Air-to-air heat exchangers | • Improved efficiency | • Large space requirement | Conditional | Conditionally recommended based on a more detailed design evaluation of available space. |
| Advanced HVAC Control Systems | • Improved efficiency and comfort | • Higher capital cost<br>• Higher maintenance cost | Conditional | It is recommended for at least some of the spaces on the ARV. Without a more design analysis it isn't known if it's appropriate for every zone. |
| Decentralized HVAC | • Improved control and comfort<br>• Improved efficiency (less fuel).<br>• More space efficient | • More complex<br>• Increased maintenance | Conditional | It is recommended for at least some of the spaces on the ARV. Without a more design analysis it isn't known if it’s appropriate for every zone. |
| Heat pumps | • Reduced fuel consumption<br>• Current technology may cold waters<br>• Many sources of 'low quality' heat are available for use on the ARV | • Few marine installations<br>• Uncertain if marinized equipment is available | Yes | Due to potential energy savings, it is recommended that heat pumps be considered during the design. |
| Environmentally friendly refrigerants | • Reduced GWP | • Limited availability<br>• Few options for low GWP refrigerants | Yes | It is recommended that low GWP refrigerants be specified to the extent they are available. |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Refrigerant systems management plan | • Reduced release of refrigerants to the atmosphere | • Added hardware (sensors)<br>• Added management | Yes | A plan to manage the refrigerants in use on the ARV is recommended regardless of which refrigerants are in use. |

## 3.3 Waste Heat Recovery Systems

### 3.3.1 Waste Heat Recovery

Typically, diesel engines are about 40% efficient. This means 60% of an engine's output (or 1.5x the output brake horsepower) is rejected as heat to the engine exhaust, engine jacket (cooling) water, and ambient air. Most of this waste heat from diesel engines can be recovered and used for a variety of services including potable water making (evaporators), domestic hot water heating, cabin heating, fuel and ballast tank heating, seachest deicing, and deck deicing (see Reference 12 for the ARV report on deck deicing options including waste heat).

A waste heat recovery system for the ARV could consist of jacket water to hot water heat exchangers for each main diesel engine. These heat exchangers would transfer the heat from the engine jacket water to a secondary waste heat system used to supply the various heating demands. The use of waste heat for these services would reduce the electrical power or diesel fired heater demands that would otherwise be required.

The downside to a waste heat recovery system is that it requires additional piping, pumps, heat exchangers, and system controls. This increases the weight, complexity, cost, and maintenance of the vessel's auxiliary systems. However, the increased capital cost is quickly offset by reduced demand on the diesel generators. Some amount of waste heat recovery is found on almost all vessels operating in cold regions. For the ARV, which will operate in the Antarctic, a waste heat recovery system is highly recommended. The primary question for the ARV is how the system will be designed and what services will utilize waste heat. A properly designed waste heat recovery system will significantly reduce fuel usage for heating, reducing operating costs and emissions while improving range and endurance.

Consideration must be given during the design for possible limitations to use of waste heat for engines that use advanced emissions control technologies such as selective catalytic reduction (SCR). To operate properly, the combustion exhaust temperature must be high enough to allow the catalytic reactions to work efficiently. At the very least this will mean that the SCR unit will be placed upstream of the exhaust heat recovery device. It is recommended that the designer give due consideration to any temperature or operations limitations for each manufacturer's offering as they may be tradeoffs.

## 3.4 Fire Suppression Systems

Several options exist for fixed fire suppression for machinery spaces, including water mist, $CO_2$, inert gas (e.g., Inergen, i3), and chemical agents (e.g., FM-200™, 3M Novec 1230™). All of these systems have advantages and disadvantages. It is realistic to expect that several types of fire suppression agents could be used on the ARV rather than a one-size-fits-all.

### 3.4.1 Clean Agents

In 2001, the National Fire Protection Association (NFPA) developed standards for clean agent fire extinguishing systems to guide technology development to replace the ozone depleting product Halon 1301. These clean agent systems are required to have zero ODP. Table 4 shows the two most common marine clean agent fire suppression systems in the marine industry. Although all clean agent systems are considered environmentally responsible by the U.S. Environmental Protection Agency (EPA), some claim a lower environmental impact than others. 3M, the manufacturer of the Novec system, claims that their system produces significantly lower

"$CO_2$ equivalent" emissions, as defined by the Intergovernmental Panel on Climate Change (Reference 11), than the FM-200 systems.

**Table 4 Common clean agent fire suppression systems**

| System | Operation | Ozone Depletion Potential (ODP) | Global Warming Potential (GWP)[1] | Atmospheric Lifetime (ODP) (years) |
|---|---|---|---|---|
| FM-200 | • Stored as a liquid, vaporizes on discharge<br>• Absorbs heat to extinguish | 0 | 3350 | 38.9 |
| Novec 1230 | • Stored as a liquid, vaporizes on discharge<br>• Displaces oxygen to extinguish | 0 | < 1 | 0.19 |

1. GWP of $CO_2$ is 1.

One additional and important benefit of using clean agent fire suppression is that the extinguishing agents produce a breathable mixture in the protected space when released. The other common alternative is a carbon dioxide system which produces a non-breathable mixture and poses a serious asphyxiation hazard to vessel crew who may be in the space when the system is activated or if $CO_2$ is accidentally released.

Carbon dioxide is the least expensive, has no ozone depletion potential, and has a GWP value of 1. However, because $CO_2$ at the concentration required for fire suppression is lethal, it is not recommended when safe options with similar or better environmental impact are available.

Alternative chemical agent and inert gas systems are safe to use in manned spaces and have varying cost, size, and environmental impacts. Inert gas systems use various blends of inert atmospheric gases to reduce the oxygen level of the space below that required for combustion of most materials but keep it high enough that it is breathable. These gasses have no greenhouse gas content or ozone depleting potential. However, inert gas systems require more space than the chemical agent systems.

Of all the clean agents available, Novec 1230 is recommended for the ARV due to being nonlethal, widely available, and having minimal environmental footprint. Novec requires more space than $CO_2$, and roughly the same space as FM-200. It is slightly higher cost than FM-200 and higher still than $CO_2$.

### 3.4.2 Water Mist

Water mist (e.g., HI-FOG by Marioff) systems generate a very fine fog which removes heat through evaporation and also prevents radiative heat transfer. They are safe to breath after release (non-lethal) and are safe for equipment according to the manufacturers. Installation requires a high-pressure pump skid, piping, controls, and a freshwater storage tank. Regulations require 20 minutes of supply volume to be in the tank, and after that, seawater can be pumped in if still needed. Unlike all the other systems discussed, which are passive, the water mist pumps require power,. Water mist is the most environmentally friendly technology since no chemicals are used at all. The storage tank should be sized and located during the design. It is possible to use the potable water tank, but the volume required for the fire suppression must be held in reserve, which would reduce the usable potable water capacity. Water mist can be used for small or large spaces and multiple spaces can be served by a single pump skid. If lithium-ion batteries are included in the ARV, water mist is emerging as a preferred solution for protecting battery spaces. However, depending on the number, size, and distribution of the spaces being served, water mist may or may not be the best choice for every space.

### 3.4.3 Fire Suppression Systems Summary

Table 5 provides a summary of fire suppression technology recommendations. Both Novec 1230 and water mist are recommended. Each has advantages over the other and merits consideration in certain circumstances. For example, it may be that a single water mist system can be employed to provide fire suppression for the generator room and motor room, but that the emergency generator room and paint lockers would be better served with local Novec 1230 systems. Both technologies are more environmentally friendly than other alternatives and the designer will have to determine what makes the most sense in the context of the overall design tradeoffs. It is likely that the ARV will ultimately be equipped with both water mist and Novec, but in different locations.

## 3.5 Airborne Noise

The effects of ambient noise pollution on people have been studied at length and the science has been incorporated into existing ship design standards such as ABS (Hab+ and Hab++). These standards set interior and exterior noise limits for spaces on the vessel. The intention of lowering noise levels is to reduce hearing loss, reduce stress, and improve productivity. The ARV will travel into pristine areas and the machinery onboard will produce noise which could also have an impact on wildlife such as birds or other animals that could come in proximity to the vessel. It is recommended that the effects of noise on wildlife be considered by the designer using the latest research at the time of the vessel design.

**Table 5 Summary of fire suppression system technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Clean agent – Novec 1230 | • Low ozone-depleting potential<br>• Non-lethal<br>• Can be used in small and large spaces | • More expensive than other agents<br>• Higher volume than $CO_2$ | Conditional | Recommended for the ARV over $CO_2$ or FM-200. It should be evaluated side-by-side with water mist for specific applications. |
| Water mist | • Most environmentally friendly - no chemicals<br>• One skid/tank can serve multiple space by adding piping and nozzles<br>• Very easy to replenish – by filling tank with fresh water. | • May be more expensive than clean agents depending on the size of the system<br>• More complicated to install and maintain<br>• Requires tank space for fresh water | Conditional | Recommended pending more detailed design with consideration for space and arrangements. A single skid can serve multiple spaces, which may have advantages for space savings, but it should be evaluated side-by-side with Novec 1230 for specific applications. |

# Section 4 Pollution Control Systems

## 4.1 Regulations for Marine Polution

Prevention of pollution from ships is regulated by MARPOL 73/78, Annexes I through VI (Reference 13). The Annexes relevant to this section are:

- Annex I: Regulations for the Prevention of Pollution by Oil.
- Annex IV: Regulations for the Prevention of Pollution by Sewage from Ships.
- Annex V: Regulations for the Prevention of Pollution by Garbage from Ships.
- Annex VI: Regulations for the Prevention of Air Pollution from Ships.

Annexes I and II are mandatory to all signatory nations. Currently the United States is signatory to Annexes I, II, III, V, and VI.

Since the early 1990s, the Antarctic area (south of 60 degrees south latitude) was designated one of several "Special Areas" requiring higher levels of environmental protection under certain MARPOL Annexes (Reference 14). Coast Guard regulations (33 CFR §151.A, Reference 15) implement MARPOL Annexes I, II, and V, and the 1991 Protocol on Environmental Protection to the Antarctic Treaty (), also known as the 'Madrid Protocol.'.

The Madrid Protocol has six Annexes. Annexes III (*Waste Disposal and Waste Management*; Reference 16) and IV (*Prevention of Marine Pollution*; Reference 17) are most relevant to the ARV pollution control measures and practices.

## 4.2 Lubricant and Hydraulic Oil

The EPA estimates that machinery and operational discharges and leaks contribute to 61% of the lubricant pollutants in port waterways (Reference 18). Numerous state and international rules have been developed to curtail such discharges. The principal regulation governing the discharge of oil is MARPOL 73/78, Annex I, which limits oil discharge to concentrations of 15 parts per million (ppm) or less. The technologies described below are methods of treating oily water to meet this discharge requirement and prevent the illegal or accidental discharge of oil or oily mixtures into the sea.

### 4.2.1 Environmentally Acceptable Lubricants

In 2013, the EPA updated its Vessel General Permit to include requirements for environmentally acceptable lubricants (EALs). These lubricants must be used for any exposed system installed *below the waterline* and are *suggested* for systems installed on deck as well. EALs are defined by their biodegradability, low toxicity to the marine environment, and low likelihood of bioaccumulation in marine organisms. The Vessel General Permit requires EALs to have, at minimum, the compositions outlined in Figure 4.

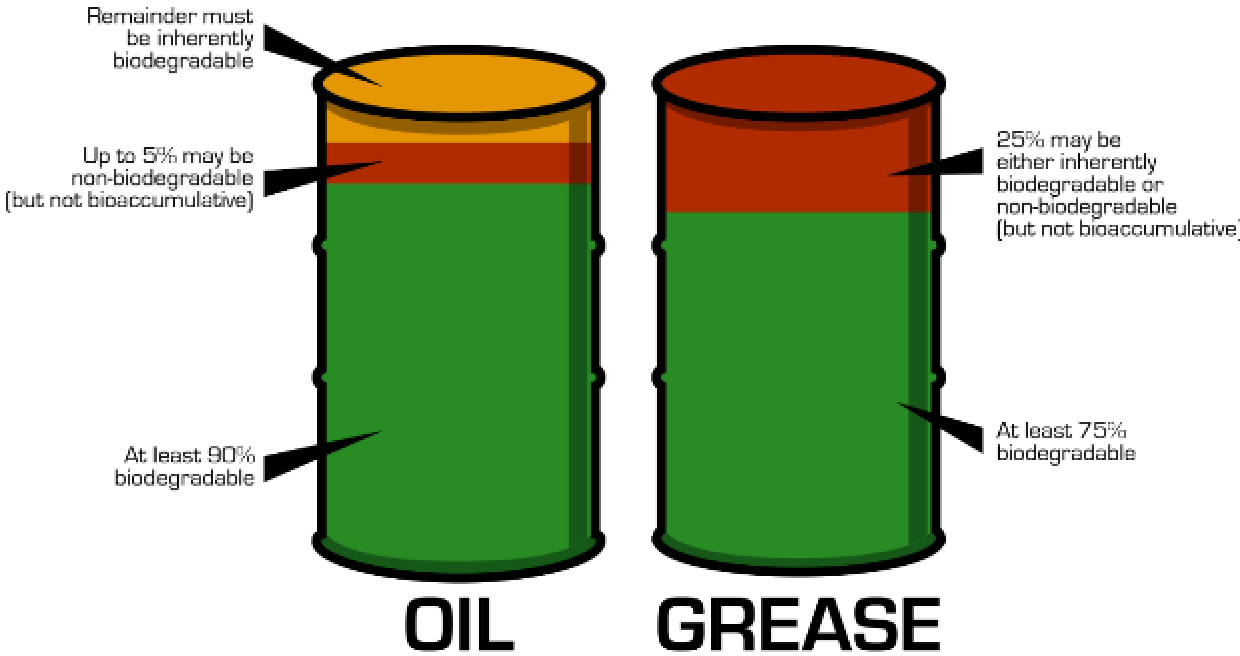


**Figure 4 EAL allowable oil and grease breakdown (Image source: Reference 19)**

Although EALs are currently only required or vessels operating in the United States, the use of EALs in all practical applications onboard the vessel reduces the potential for harmful oil pollution. EALs are discussed in detail in Reference 18. It is recommended that EALs be used wherever practical on the ARV.

### 4.2.2 Treatment and Segregation

#### 4.2.2.1 High Efficiency Oily Water Separator (≤5 parts per million)

When the ARV is operating within the Antarctic region, *any* discharge of oil or oily mixture is prohibited by Annex IV of the Antarctic Treaty. Therefore, all sludge or other oily residues shall be retained onboard for disposal at reception facilities or as otherwise permitted under Annex I or MARPOL 73/78.

MARPOL Annex I limits oil discharge to a concentration of 15 ppm or less. However, oil discharges of less than 5 ppm are currently required for vessels operating in Canadian inland water, including the Great Lakes. It is reasonable to expect that 5 ppm discharge limits may be expanded to additional areas as environmental laws become increasingly restrictive. There are numerous oily water separators (OWSs) available that meet the MARPOL requirements. There are also several OWSs on the market that can exceed the current requirements and produce effluent with less than 5 ppm. To achieve the lower discharge oil content, 5 ppm certified OWSs generally require additional separation equipment, which adds somewhat to the size and cost of the unit. However, as regulations are getting tighter over time, a higher efficiency OWS is recommended for ARV.

#### 4.2.2.2 Oil Cleaners

Extending the life of a vessel's oil supply helps to reduce environmentally costly oil disposal. Centrifugal oil cleaners integrated into a vessel's lube oil system can remove contaminants from “dirty oil” and extend its usable life, reducing oily waste. To the extent oil life can be prolonged (and oil waste reduced) this would have obvious cascading benefits for the ARV, such as reduced clean oil storage, reduced waste oil storage, and potentially reduced operating costs. These benefits must be weighed against the added equipment cost, space, and weight.

#### 4.2.2.3 Segregation of Used Engine Oil

Marine vessels produce a significant amount of oily waste from various equipment onboard. In many cases, all oily waste products including used engine oil are routed to single sludge tank where they are comingled with numerous other contaminates. If used engine oil is instead kept in a separate waste oil tank, it is possible for the oil to be recycled by an oil recycling facility. For a vessel like the ARV, the tradeoffs of added complexity in design, construction and operations must be weighed against the benefits.

### 4.2.3 Oil Leak Prevention

Lubrication oil leakage from machinery is a frequent, unmonitored, and uncontrolled source of pollution. Leaking oil-filled stern tubes, hydraulic deck machinery, and deck runoff are primary sources of this type of pollution.

#### 4.2.3.1 Stern Tube Leak Control

Lip seals on conventional oil-filled stern tubes are subject to wear and damage over time, which can result in oil leakage directly to the surrounding marine environment. Table 6 outlines alternative types of stern tube lubrication that can reduce the impact or occurrence of stern tube oil leaks. It is recommended that, where possible, water based stern tube seals be considered as they eliminate the possibility of oil leaks.

**Table 6 Alternative stern tube lubrication**

| Method | Description |
|---|---|
| Seawater lubricated stern tubes | The stern tube bearing has an open connection to the sea, where water is continuously run through the bearing to provide sufficient lubrication. |
| Positive pressure lip seal | This type of seal utilizes positive air pressure applied toward the seal to prevent leakage. Can also be used in conjunction with specially bio-degradable lubricants to provide lubrication to the stern tube. |
| Closed loop freshwater stern tube lubrication | This lubrication method is a closed loop system that utilizes a fixed volume of fresh water. Although designed not to leak, the system will not discharge oils or oily water mixtures to the sea in the event of a seal failure, since the stern tube is lubricated with fresh water instead of oil |

#### 4.2.3.2 Electric Winches and Windlasses

On larger vessels, deck machinery such as tow winches, windlasses and other mooring equipment, and davits are often hydraulically actuated. Any failure or degradation of the hydraulic equipment, including hydraulic hoses and fittings, seals, gaskets, or other components can result in hydraulic oil leaks. Replacing hydraulic deck machinery with electric machinery virtually eliminates the risk of oil pollution from these sources. Whether this equipment on the ARV is electric or hydraulic, it must also be designed for the low temperature environment with consideration for freezing, icing, condensation, and even fluid viscosity. The overall complexity and robustness of the ice rated equipment should be compared for both electric and hydraulic.

Hydraulic oil becomes highly viscous when operating in cold weather and must be heated in order to remain operable which requires excess energy. Electric machines also require heating to protect against condensation and other cold weather effects but to a lesser extent than hydraulics. Another consideration for electric deck machinery is sea water intrusion. Any equipment mounted on the aft deck will be subject to green water immersion in rough seas. It is not recommended to have electric machinery located where electric parts may be exposed to immersion in sea water. In general, electric deck winches and windlasses are recommended for ARV but with due consideration for their location.

### 4.2.4 Lubricant and Hydraulic Oil Summary

Table 7 provides a summary of recommendations regarding lubricant oil pollution control technologies.

**Table 7 Summary of lubricant and hydraulic oil pollution control technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Use environmentally acceptable lubricants (EALs) wherever practical | • Reduces harm to the environment<br>• Already required by VGP for below water systems | • Few drawbacks. | Yes | EALs are widely available and required for any system operating below the water line, such as stern tubes. |
| Treatment and Segregation Technologies | | | | |
| High efficiency oily water separators (≤ 5 ppm) | • Better for marine environment | • Higher initial cost<br>• More complicated machinery. | Yes | OWSs meeting 5 ppm or lower are available. This is recommended for the ARV since regulations tend to get tighter over time. |
| Oil cleaners | • Reduces overall lube oil usage<br>• Reduces need to store lube oil onboard<br>• Increases time between oil changes | • Added cost for equipment<br>• Added space needed for equipment<br>• Equipment maintenance | Yes | Oil cleaners are recommended for ARV due to the many potential benefits of reducing oil usage. |
| Segregation of used oil | • Oil can be recycled at a shore-based facility | • Separate oil tank needed for used engine oil | Conditional | Environmentally beneficial but requires separate used oil tank. Recommended if tank can be accommodated in the design |
| Oil Leak Prevention Technologies | | | | |
| Stern tube leak control | • Reduces or eliminates leakage from stern tube into water | • More complex<br>• Higher initial cost<br>• More maintenance | Yes | It is recommended that, where possible, water based stern tube seals be considered as they eliminate the possibility of oil leaks. |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Electric winches and windlasses | • Reduces sources of oil pollution<br>• More efficient than hydraulics in cold weather | • May be more complicated<br>• May be more expensive<br>• Less robust in locations subject to immersion in sea water | Yes | There are many potential benefits of electric over hydraulic winches and windlasses other than reducing oil pollution. However, the effects of cold weather and immersion in seawater should be considered and compared during design. |

## 4.3 Wastewater Treatment and Reclamation

When operating in the Antarctic area, vessels certified to carry more than 10 people are prohibited from discharging sewage[1] within 12 nautical miles of land or ice shelves. Beyond this distance the discharge must be moderated at a controlled rate while the vessel is moving at least four knots (References 15 and 16).

Generally, the current regulation governing the discharge of sewage at sea is Annex IV of MARPOL. While the United States is not a party to Annex IV, a vessel operating on international voyages is subject to foreign port state action if it does not comply with Annex IV. Since the ARV will engage in foreign voyages, its marine sanitation device (MSD) must comply with the requirements of Annex IV at the minimum. This requires that the MSD be certified to IMO MEPC 159(55) (Reference 20) and MEPC 227(64) (Reference 21) for nutrient removal. There are a number of different MSD technologies available with many tradeoffs.

### 4.3.1 Biological Wastewater Treatment

Biological wastewater systems utilize microorganisms to break down the organic components of black and gray water. This can be accomplished either aerobically (with oxygen) or anaerobically (without oxygen). Typically, aerobic biological wastewater systems are considered less impactful to the environment since they do not produce methane as a byproduct. In most off-the-shelf systems, an aerobic or anerobic waste system is combined with a filtration system to treat human waste.

Disadvantages of biological wastewater treatment systems include the necessity of restocking microorganism solutions for treatment and potentially significant sludge production that must be stored onboard until it can be transferred ashore for disposal (some manufacturers claim to have eliminated sludge production). Biological systems can also be upset by inadvertent additions of disinfectants that kill the active bacteria. While biological systems are able to process gray water, the gray water effluent (including galley wastewater) can add additional burden on the system. If gray water is collected and treated along with the sewage (black water), the system will need to be sized appropriately. The manufacturer of the biological water treatment system should be consulted as to whether gray and black water should be separated.

Ultrafiltration systems are utilized in some biological sewage treatment systems by passing the final waste stream through a membrane filter to improve the quality of the effluent. Low molecular weight substances, like water, can permeate the membrane, while other organic contaminants and bacteria in solution cannot. Membrane bioreactors use ultrafiltration but also generate significant amounts of sludge, which needs to be managed through collection and disposal.

Small and medium sized biological systems are now available on the market. The ARV designer will need to consider the space limitations of equipment, collection tanks, and sludge storage and conveyance (if required) in whatever system is chosen. Some examples of biological wastewater treatment systems are listed in Table 8.

[1] Sewage is defined in 33 CFR § 151.79 as drainage and wastes from: (1) toilets, urinals, WC scuppers; (2) medical premises via wash basins and scuppers; (3) live animal spaces; and (4) other wastes when mixed with these listed drainages.

**Table 8 Biological wastewater treatment systems meeting current regulations.**

| System Name | Technology | Application |
|---|---|---|
| Evac EcoOcean | Moving Bed Bioreactor Biological Treatment Plant | Cruise ships, large passenger capacity vessels |
| Evac MBR | Membrane Bioreactor Biological Treatment Plant | Medium sized vessel/crew complement |
| Evac EcoTreat | Submerged Fixed Film Bacteria Biological Treatment Plant | Small vessels/small crew |

Biological wastewater systems are considered an environmentally attractive technology and are conditionally recommended for consideration on the ARV. The designer will need to evaluate the various design tradeoffs during the design.

### 4.3.2 Electrolytic Wastewater Treatment

Electrolytic wastewater systems decontaminate waste by passing electrical current through the waste solution from cathode to anode. This causes the waste solution to separate into basic components, allowing the waste to be separated from water. The systems are fairly compact but do require several tanks for treatment. The complexity is low compared to some systems which should reduce maintenance and since no chemicals are normally used the operating cost is typically low. Electrolytic wastewater systems are considered an environmentally attractive technology and are conditionally recommended for consideration on the ARV. The designer will need to evaluate the various design tradeoffs during the design.

### 4.3.3 Wastewater Treatment and Reclamation Summary

Table 9 presents a summary of recommendations for wastewater treatment and reclamation technologies.

**Table 9 Summary of wastewater treatment and reclamation technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Biological wastewater treatment | • No harmful chemicals to buy or discharge<br>• Long life | • Higher initial cost<br>• More complex systems<br>• Most systems generate sludge<br>• Can sometimes require several tanks<br>• May require segregation of gray and black water | Conditional | Biological wastewater systems are recommended for their clean effluent and lack of chemicals but consideration for sludge storage and gray/black water segregation should be accounted for in the design if required by the manufacturer. |
| Electrolytic wastewater treatment | • Does not use chemicals<br>• Fairly low maintenance<br>• Can treat black and gray water | • Requires several tanks<br>• Added cost | Conditional | The system meets all regulations and avoids the use of chemicals but it is unclear how the size compares to biological systems. |

## 4.4 Garbage Management

IMO MARPOL Annex V, *Prevention of Pollution by Garbage from Ships*, regulates the discharge of garbage from ships. The Annex applies to all ships and requires a garbage management plan for ships over 100 gross tonnage and carrying 15 persons or more. Per Annex V Regulation 1, "Garbage means all kinds of victual, domestic and operational waste excluding fresh fish and parts thereof, generated during the normal operation of the ship and liable to be disposed of continuously or periodically…." IMO's 2012 *Guidelines for the Development of Garbage Management Plans* (Reference 22) provides more detailed guidance.

The Antarctic is designated as a 'special area' within MARPOL. Within a special area the disposal into the sea of all plastics, incinerator ash, paper, rags, glass, metal, crockery, dunnage, and packing materials is prohibited. The food waste must be comminuted and disposed as far as practical from land, but not less than 12 nautical miles from the nearest land.

Annex III of the Madrid Protocol (Reference 16) requires the ship to develop an annually reviewed waste management plan (Article 8) which classifies waste types. The plan and reports required per Article 8 are to be submitted to the committee that oversees the Antarctic Treaty.

### 4.4.1 Comprehensive Waste Management Plan

A primary challenge for the ARV will be managing the volume of garbage over the long duration voyages since limited space is available. Per MARPOL, the garbage management plan "…shall provide written procedures for collecting, storing, processing, and disposing of garbage, including the use of the equipment on board. It shall also designate the person in charge of carrying out the plan."

Annex III of the Madrid Protocol (Waste Disposal and Waste Management) requires development of a waste management plan (See Section 4 above). In addition to cataloging and tracking all waste, Article 2 requires that some types of waste be removed and disposed outside of the Antarctic Treaty area, including some types of food waste such as 'introduced avian products'. The waste management plan developed during the design process will need to consider these factors.

In addition to the plan required by regulations, a plan should be established during design that would allow the management of waste to be optimized. To this end, the collection, conveyance, processing, storage, and/or disposal of waste streams should be considered during the design of the ARV. This will ensure that the impact to the vessel and the crew is minimized and that there is adequate space available for processing and storage. It may also be desirable to consider policies that minimize the types of waste generating material that can be brought on board in the first place since any waste coming on must be retained for eventual disposal on shore (unless it is to be incinerated). A waste management plan is required by MARPOL Annex V and detailed in MEPC.220(63). However, the guidance does not specify that the plan is started during the design process of the ship. It is recommended that a waste management plan is developed during the design of the ARV and that the plan is used to inform what equipment be specified.

### 4.4.2 Food Waste Management

#### 4.4.2.1 Macerators / Pulpers

Macerators and pulpers are compressive equipment used to significantly reduce the volume of food waste, resulting in increased food waste storage capacity for operation in remote areas or long-duration voyages. Typically, macerator and pulper systems will grind up food waste and introduce water into the system as a lubricant. Once the food waste is ground, a dewatering system squeezes out the excess water so the food waste can be compacted into smaller volumes. The food waste can then be stored in refrigerated storage lockers until it can be disposed of or composted onboard the vessel. The use of macerators is conditionally recommended based on the outcome of the comprehensive waste management plan.

**Figure 5 Example of a commercial scale pulper for processing shipboard food, cardboard, and paper.**

#### 4.4.2.2 Biological Grease Traps

Before gray water from the galley can be treated, animal fats, oils, and grease (FOG) must be removed, as they reduce the operational life of many wastewater treatment systems. Grease separators/interceptors are used for this purpose and generally operate by separating FOG either mechanically or electrically. Coalescing separators and gravity interceptors are the most common types of grease separators. With these separators the collected FOG must be periodically cleaned out for disposal ashore.

Biological grease traps are a slow but effective technology for managing galley grease. They utilize biological activators to break down and degrade FOG into fluids. By breaking down these fats, biological grease traps significantly reduce solid waste by-products. Biological grease traps are recommended for the ARV.

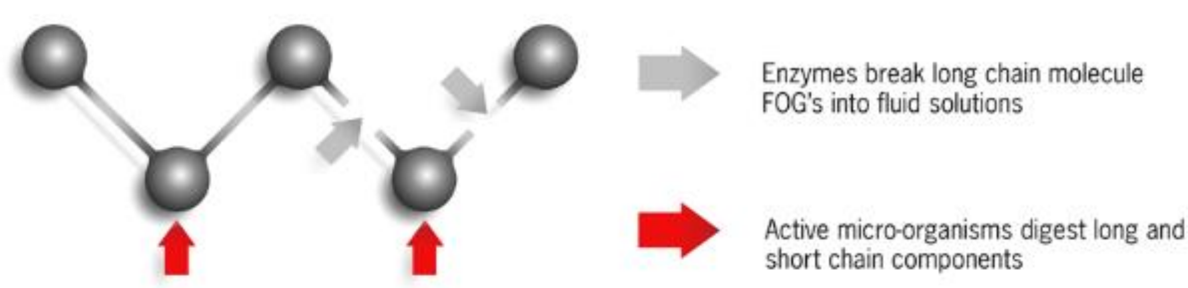


**Figure 6 ACO Marine's biological grease trap activator process (Image source: Reference 23)**

#### 4.4.2.3 Composter

Composting food waste is not common onboard marine vessels, but it is becoming increasingly popular in land-based commercial kitchens, supermarkets, and entertainment venues. As a result, large-scale commercial food composting equipment is readily available for potential installation. One company in particular, ORCA technology, has developed a novel food composter for use on cruise ships. These composters can process between 15 and 100 pounds of food waste per hour. According to the manufacturer the waste is converted into gray water. The use of composters is conditionally recommended based on the outcome of the comprehensive waste management plan.

#### 4.4.2.4 Dehydration and/or Vacuum Sealing

Food waste dehydrators can be used in combination with vacuum sealing technology to reduce food waste volume, leading to lower disposal costs and increased storage capacity. Dehydrating and vacu-sealing food waste allows it to be stored for extended periods of time in *non-refrigerated* storage areas without producing odors. This reduces the equipment and power requirements for large, refrigerated food waste stores. The use of vacuum sealing is conditionally recommended based on the outcome of the comprehensive waste management plan.

### 4.4.3 Recycling

#### 4.4.3.1 Balers

Balers are designed to reduce the volume of recyclable materials through compression. The result is a dense, uniformly shaped “bale” of recyclables that can be offloaded for recycling ashore. Like other technologies introduced in the previous section, balers help to increase waste storage capacity for operation in remote areas or long-duration voyages. The use of balers is conditionally recommended based on the outcome of the comprehensive waste management plan.

#### 4.4.3.2 Metal and Glass Shredders/Crushers

Marine shredders and crushers efficiently reduce the volume of metal, glass, and other solids onboard a vessel. The reduction in volume makes it easier for recyclables to be stored and transported off the vessel to be recycled in port, or to be sent to elsewhere for recycling when the receiving port is unable to process. As seen in Figure 7, these units can be sizeable, so the waste volume reduction benefit does come at the cost of a higher machinery space footprint. The use of metal and glass shredders/crushers is conditionally recommended based on the outcome of the comprehensive waste management plan.

**Figure 7 Commercial-scale metal/glass shredder**

### 4.4.4 Conventional Garbage Management

#### 4.4.4.1 Trash Compactors

Similar to the recycling solutions discussed in the previous section, compacters reduce the volume of non-food, nonrecyclable waste onboard, improving the ease and flexibility of disposal and effectively increasing the time a vessel can remain at sea without calling ports with reception facilities. There are many commercial compacter options available that are tailored for marine applications, including some options that can bag and palletize the waste for ease of disposal.

The unit shown in Figure 8 is a compression melt unit (CMU) that processes shipboard plastic into disks. A vertically mounted ram in the CMU compresses the plastic upwards against the chamber door. The ram, door, and chamber are heated to the process temperature. The combination of heat and pressure result in the formation of a thin disk. Processing plastics into such disks results in an estimated 30:1 reduction in plastics volume. Once again, this volume reduction does involve a tradeoff given the unit's size footprint. The use of trash compactors is conditionally recommended based on the outcome of the comprehensive waste management plan.

**Figure 8 Two large CMUs installed onboard a U.S. Military Sealift Command vessel**

#### 4.4.4.2 Incinerators

One of the conventional means of managing waste on ships is to incinerate it. Incinerators must meet the requirements of IMO Resolution MEPC 244(66) (Reference 24), which covers the design, manufacture, performance, operation, and testing of marine incinerators. There are a range of marine-grade incinerators available that can dispose of paper, plastic, and other wastes in compliance with emissions requirements, effectively decreasing the volume of these waste items onboard by up to 90%. Marine incinerators are designed for safe onboard operation with automated input, combustion, and disposal sequences. The incinerator unit selected must be sized for the anticipated waste stream. While incinerators are effective at reducing waste volume, they consume diesel fuel and produce ash in addition to their combustion stream going up the exhaust stack. If available space for trash or waste processing becomes a significant issue, then an incinerator could be necessary. However, if it can be managed onboard, there are more environmentally friendly means of managing the waste stream.

There are newer incinerator technologies such as the Plasma Arc Waste Destruction System (PAWDS). This system operates on an entirely different principle from conventional incinerators and can be used for any combustible waste, including sludge. First the waste is shredded and milled until it forms a powder. Then it is moved to the thermal section where a plasma torch combusts it directly. No refractory material is required, and no diesel fuel is burned for heating. After passing through a scrubber, the final product is clean gas with no visible plume plus ash. Currently the system has been installed on several naval vessels and the manufacturer claims it can be scaled up or down. While it has primarily been targeted for military vessels it is possible it will be developed for commercial use in the future. It is difficult to assess how the size would compare to a conventional incinerator without a commercial product, but the technology promises a clean, all-electric incineration solution.

The use of incinerators is conditionally recommended based on the outcome of the comprehensive waste management plan. Prior to development of the builder specification, the latest regulatory requirements should be consulted regarding incinerators as well as consulting with both NSF and ASC.

### 4.4.5 Garbage Management Summary

Table 10 provides a summary of recommendations regarding garbage management.

**Table 10 Summary of garbage management technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Comprehensive waste management plan | • Can minimize overall waste generated<br>• Can minimize specific types of waste<br>• Balances overall needs vs. practical limitations | • Takes time and expertise<br>• Not always done at design stage so will cost more | Yes | A garbage management plan is required by MARPOL Annex V and detailed in MEPC.220(63). However, the guidance does not specify that the plan is started during the design process of the ship. Recommend specifying a waste management plan be completed during contract design. |
| Food Waste Management Technologies | | | | |
| Macerators/pulpers | • Reduce volume for storage<br>• Compressed food waste can be composted, or dehydrated, or refrigerated<br>• Discharge of food in the Antarctic already requires comminuting before discharging overboard | • Equipment takes space<br>• Added crew time to process waste<br>• Storage takes space on ship | Conditional | Recommendation will depend on results of waste management plan and evaluation of design tradeoffs. |
| Biological grease traps | • Can reduce amount of waste oil and solid waste by-products<br>• Grease traps are already required for galleys | • May be more expensive | Yes | |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
| --- | --- | --- | --- | --- |
| Composter | • Digests food waste to gray water | • Consumes fresh water and power<br>• Not common on marine vessels | Conditional | |
| Dehydration/vacuum sealing | • Reduces weight and volume of food waste<br>• Storage doesn't require refrigeration | • Generates additional plastic waste<br>• Bulk storage must be removed from shore | Conditional | Dehydration/vacuum sealing might be preferred to refrigerated storage but a recommendation will depend on results of garbage management plan and evaluation of design tradeoffs. |
| Recycling Technologies | | | | |
| Baler | • Reduces volume of recyclable materials | • Added equipment needed<br>• Bales must be stored | Conditional | Recommendation will depend on results of garbage management plan and evaluation of design tradeoffs. |
| Metal and glass shredder/crusher | • Reduces volume of recyclable materials | • Equipment takes space<br>• Added crew time to process waste<br>• Storage takes space on ship | Conditional | Recommendation will depend on results of garbage management plan and evaluation of design tradeoffs. |
| Conventional Garbage Management | | | | |
| Trash compactor | • Reduces volume of solid waste<br>• Special machines are available for plastic-only compaction | • Not compatible with on shore recycling.<br>• Material is ultimately bound for a landfill. | Conditional | Recommendation will depend on results of garbage management plan and evaluation of design tradeoffs. |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Incinerator | • Effectively reduces large amounts of shipboard solid waste to ash<br>• Has a small footprint<br>• Can also work for sludge | • Not considered the most environmentally friendly solution<br>• Conventional systems use diesel fuel | Conditional | Recommendation will depend on results of garbage management plan and evaluation of design tradeoffs. |

## 4.5 Air Emissions Reduction

Air emissions from ships are regulated internationally by MARPOL Annex VI, and domestically by the EPA. As a US-flagged vessel the engines must comply with EPA. The engines on the ARV will be over 30 liters per cylinder based on their power and speed, which makes them EPA 'Category 3' marine diesel engines. The final ruling on emissions for engines of this size was released on April 30, 2010. The strategy to reduce emissions for Category 3 engines involved a multi-level approach: on-engine emissions reduction technology (exhaust aftertreatment); designation of an emission control area (ECA) for nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter for US waters; and sulfur limits on fuel. The emissions requirements for EPA Category 3 engines were intentionally aligned with IMO limits (IMO Tier III) since most vessels utilizing engines in this size range travel on international voyages. Per the IMO Tier III requirements, use of exhaust aftertreatment is only required within an ECA. At this time, the Antarctic is not an ECA and there are no known plans to designate it as one.

### 4.5.1 Ultra Low Sulfur Fuel

Since January 1st 2020, the worldwide sulfur limit on fuel outside an ECA is 0.5% (5,000 ppm). Inside an ECA the limit is 0.1% sulfur (1,000 ppm). Use of lower sulfur fuel can significantly reduce emissions even further, specifically SOx and black carbon (soot) from main engine/generator exhaust. Lower sulfur fuel is also better for the aftertreatment systems which use catalyst material that are susceptible to sulfur poisoning. There are a variety of diesel fuels available for marine diesel engines with different fuel specifications and sulfur content. Light distillate diesel fuels include the cleaner-burning ultra-low sulfur diesel (ULSD) which has a sulfur content below 15 ppm. The primary disadvantages of ULSD are its higher price point relative to marine gasoil (MGO)/DMA[2] fuel and lack of worldwide availability. Additionally, use of ULSD has less lubricity and its use should be approved by the selected engine manufacturer to ensure it does not adversely affect the engine. It is recommended to use ULSD whenever available.

### 4.5.2 Emissions Aftertreatment in the Antarctic

While operating inside the ECA of the USA, the ARV will be required to meet reduced emissions requirements. To comply with the lower $NO_x$ levels required inside the ECA the engines will require an SCR device in the exhaust system. These systems are supplied and certified with the engines by the manufacturer, and when operating, will chemically reduce most of the $NO_x$ to inert nitrogen gas ($N_2$). The systems inject an aqueous mixture of urea, known as diesel exhaust fluid (DEF), into the exhaust gas stream before it passes over a catalyst which facilitates the reactions. When the unit is operating the DEF is consumed and must be replenished. DEF is becoming more widely available, especially inside an ECA. A consumption rate of approximately 5-10% of fuel rate can be assumed.

It is not required to use the SCR when outside of the ECA, though an operator may consider doing so to protect the air in sensitive areas. As the Antarctic is a very sensitive environment, it would be beneficial to operate the aftertreatment system while south of 60 degrees latitude. However, this will come with the extra expense of the DEF as well as onboard storage, which will need to be accommodated in the ARV design. Storage of DEF is an important consideration

[2] DMA is a marine distillate fuel classification per ISO 8217 (Reference 25).

for the ARV, as every extra gallon of DEF that is carried is potentially displacing a gallon of fuel.

DEF storage requires corrosion resistant tanks, typically stainless steel, and therefore must be considered during the design process. A conservative assumption would be an additional 10% of the diesel storage volume be added for DEF storage. The freezing temperature of DEF is typically around 12 ºF (-11 ºC). Freezing should not be an issue because the tanks will be installed below the waterline and not against the skin of the vessel, and heating the DEF tanks is possible using waste heat. It is recommended to use aftertreatment within the Antarctic which will require accommodating the additional DEF storage tanks in the design specifications. Having the tanks will not obligate the use of aftertreatment but does provide the owner with the flexibility of using it in the future.

### 4.5.3 Air Emissions Reduction Summary

Table 11 presents a summary of recommendations for air emissions reduction technologies.

**Table 11 Summary of air emissions reduction technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Use ULSD when available | • Reduces sulfur and PM emissions<br>• Better for the SCR (aftertreatment system) | • Higher cost than MGO/DMA fuel<br>• Reduced lubricity<br>• Less available globally | Yes | ULSD (<15 ppm) is recommended for use when available and especially inside the Antarctic in combination with the aftertreatment system. |
| Emissions aftertreatment systems in the Antarctic | • Reduces NOx and PM in sensitive environments | • Requires carrying additional DEF<br>• Added cost | Yes | |

## 4.6 Ballast Water Treatment System Technologies

Since the 1990s, the IMO and national maritime administrations have been working to find a means of preventing the transference of aquatic invasive species and other non-native organisms from one port region to another. Aquatic invasive species are most frequently transported inadvertently in ships' ballast water, which may be taken up into a vessel's ballast tanks at one port of call and discharged at another port of call in a different ecological zone. The IMO Ballast Water Management Convention (BWMC), an international agreement that provides a regulatory framework for managing and enforcing ballast water operations, entered in to force in September 2017. Vessels that operate under the flag of a state that is party to the BWMC (or operates in the waters thereof) must comply with its regulations. Methods practical to this application to meet ballast water management regulations are described.

Proven ballast water treatment system (BWTS) technologies used to remove or inactivate organisms in ballast water are described in Table 12. Each approach is generally implemented in-line during ballast uptake and/or discharge and used in conjunction with a filtration system that removes larger organisms prior to treatment. Manufacturers utilizing each of these technologies have been approved to achieve vessel compliance with the international BWMC, and systems are increasingly being approved according to more strenuous requirements laid out by the United States Coast Guard (USCG).

**Table 12 BWTS technologies**

| Technology | Description |
|---|---|
| Ultraviolet light (UV) | Utilizes ultraviolet light to neutralize organisms in ballast water. |
| Electrochlorination | DC current produces hypochlorite (bleach), which generates free radicals that neutralize organisms. |
| Bulk chemical | Hypochlorite is manufactured offsite and delivered to the vessel to be stored and mixed with ballast water to neutralize organisms. |
| Chlorine dioxide ($ClO_2$) | Chemicals are combined to create a solution of chlorine dioxide, which is injected into ballast water to neutralize organisms. |

These systems each have benefits and drawbacks based on the water quality characteristics at expected ballast loading locations. Four key water quality characteristics contribute to the effectiveness of each of the systems: UV transmittance (UVT), salinity, total suspended solids (TSS), and oxidant demand. For example, in-line EC systems are dependent on ambient salinity to produce a biocidal oxidant; when salinity is too low either a brining system or a sea water storage system is required. For UV systems, UVT must be medium to high; otherwise, systems are limited in their operation by their type approval certificate, including reduced throughput capacity. When UVT values are too low, the BWTS will fall out of compliance with the ballast regulations. For most systems, high TSS levels can overwhelm the filters and degrade system performance.

Water quality characteristics are less critical to in-tank treatment methods, which rely on the period between ballast uptake and discharge to achieve ballast discharge compliance.

A potential alternative to treating seawater for ballast is to generate fresh water to be used as ballast. Glosten designed a system that utilized waste heat to generate fresh water at a rate that generally matched the fuel burn, which allowed fresh water to be used as ballast. The advantage of such a system is that a BWTS is not required, and fresh water as ballast will reduce corrosion in ballast tanks and associated piping. However, USCG currently only accepts use of water sourced from a public water supply (33 CFR 151.2025; Reference 26) for ballast as an acceptable ballast water management (BWM) method. But USCG has not explicitly approved potable water production onboard to satisfy the BWM requirements. Given this and the other demands for waste heat on an icebreaker, this is not currently a practical approach.

Table 13 presents a summary of recommendations for ballast water treatment technologies.

**Table 13 Summary of ballast water treatment technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Ultraviolet | • Compact and simple<br>• No chemicals needed for purchase or storage<br>• Most environmentally friendly to the ocean (no chemical discharge) | • Higher power<br>• Can have issues in highly turbid waters and some fresh water scenarios<br>• Replacement bulbs are expensive | Yes | USCG and IMO Type approved UV system are available in the size range required for the ARV and as it is the most environmentally friendly and simplest for the size, it is recommended for ARV. |
| Electrochlorination | • Low power<br>• Chemicals are generated onboard<br>• More reliable efficacy across water types (fresh, turbid, brackish, etc.)<br>• Easily scalable for larger vessel sizes | • Chlorine based so less environmentally friendly<br>• More complicated to install and maintain<br>• Greater footprint onboard<br>• Only works in (or with) seawater<br>• May have complications operating in very cold waters | No | Electrochlorination could work fine for ARV but have limited installations on research vessels. However, when compared to UV, is not as attractive from an operational and environmental perspective. |
| Bulk chemical (includes chlorine dioxide) | • Very low power (only pumps needed for injection)<br>• Most reliable efficacy across water types (fresh, turbid, brackish, etc.)<br>• Most mechanically simple of all system types | • Requires purchase and storage of large amounts of bulk chemicals<br>• Has potential arrangement challenges<br>• Limitations to scaling to larger vessels | No | |

# Section 5 Outfitting

Operating in the Antarctic will require the ARV to be designed for extremely low ambient temperatures. Even if interior heating is done with waste heat it will still be essential to minimize the loss of heat during cold weather through adequate thermal insulation on the exterior boundaries. Heat losses from transmission through boundaries depend on the following formula:

$H_t = A*U*\Delta T$ = Heat loss through bulkheads, windows, doors, etc.

Where:

A = Area of the surface

U = overall heat transmission coefficient

$\Delta T$ = Temperature difference across the boundary

Of the three variables (area, temperature difference, and heat transmission coefficient), only the heat transmission coefficient can be realistically controlled. The temperature difference from inside to outside during the most extreme weather can exceed 100° Fahrenheit. The value for U will depend directly on the effectiveness, and the thickness of the insulation on the boundary bulkhead.

## 5.1 Extra Insulation Thickness

Additional insulation on exterior surfaces of air conditioned or heated spaces is recommended to reduce heating and cooling loads. The tradeoff of additional insulation is added weight and cost. It is suggested in Reference 27 to use a minimum of 3" of insulation with a 1.5" beam wrap, but for a Polar Class vessel additional insulation may be required. The beam wrap is the insulation that is wrapped around a stiffener or a beam that may stand out past the bulkhead insulation. For example, if the bulkhead insulation is installed at a thickness of 3" and the bulkhead stiffeners or beam is 5" deep, with a flange, the steel surface will form a 'short circuit' for heat transmission unless it is also wrapped in insulating material.

## 5.2 Thermal Insulating Coating

Bulkhead insulation is typically bonded to the bulkhead by adhesives or pressure to prevent air pockets between the insulation and the bulkhead. If there is not a good initial bond, or if the bond fails over time and an air gap develops, condensation will occur behind the insulation during very cold weather. The condensation has several negative consequences. Firstly, it is absorbed into the fibrous material which quickly reduces the effectiveness of the insulation and can also lead to further degradation and loss of bonding. Secondly, the trapped moisture can lead to corrosion under insulation (CUI) which can be a major issue, especially for piping systems, but also for bulkheads on ships.

Insulating coatings are a type of paint that generally contains a filling of microscopic ceramic spheres that provide an effective insulating boundary in a very thin layer. The coatings were initially developed to address condensation below the waterline on ships. Where the shell of the vessel contacts the water, it can cause excessive condensation if the interior environment is ventilated and above the seawater temperature. In humid environments and cool sea conditions a substantial amount of moisture can be generated and collect in the bilge. This can lead to corrosion and leaks. A spray-on coating that can reduce the surface temperature difference and is bonded to the steel resolves this.

It was soon realized that these insulating coatings could be used in many places on a ship, including behind conventional insulation to prevent CUI. Additionally, when insulation is installed it must be terminated several inches from the deck,windows, and doors. This can lead to exposed areas that can cause condensation as well as lose heat, especially in cold regions. Insulating coatings can be applied to these boundaries and greatly improve the overall efficiency of the boundary as well as the comfort of the space and longevity of the materials.

For the ARV, it is recommended that insulating coatings be used wherever practical, including behind insulation. Insulating coatings can theoretically reduce the thickness of fiber insulation needed, or at least improve the overall effectiveness of the insulation.

## 5.3 Insulated Glass on Exterior Boundaries

Glass is a poor insulator and the main source of heat loss on an exterior bulkhead with windows. Similar to residential and commercial construction, double paned, insulated windows and portholes are available for ships. These windows are sometimes filled with an inert gas such as argon to further reduce heat loss. Also, coatings can be applied that are low E (low emissivity) and can reflect heat back in or out of the vessel to further reduce radiative heat transfer. Since the ARV will operate in extremely cold weather, these windows are recommended wherever practical.

## 5.4 Insulation Summary

Table 14 presents a summary of the evaluation of insulation technologies and recommendations for the ARV.

**Table 14 Summary of insulation technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Extra insulation thickness | • Reduces heat losses on exterior boundaries<br>• Reduced HVAC loads<br>• Improves comfort | • Added weight<br>• Added cost | Yes | Consideration for insulation thickness is typically done during the vessel contract design. Due to the extreme cold operating environment of the ARV, requiring added insulation is recommended. |
| Thermal insulating coatings | • Improves effectiveness of conventional insulation<br>• Eliminates CUI<br>• Prevents condensation and corrosion in bilges exposed to the exterior water | • Added weight<br>• Added initial cost | Yes | Thermal insulation coatings are recommended wherever practical on exterior boundaries. |
| Insulated glass on exterior boundaries | • Reduces heat and radiation losses out windows<br>• Improves comfort of spaces | • Added initial cost<br>• Can sometimes fog up if the seal is compromised | Yes | Insulated windows are recommended for the ARV wherever practical. |

# Section 6 Green Material Selection

Material selection is a critically important aspect of sustainable vessel design. Through all stages of a vessel's service life, from construction to eventual disposal, there are numerous opportunities to reduce environmental footprint through judicious material selection. This might include: incorporation of sustainable materials for construction, outfitting, and furnishing; minimizing the use of hazardous or poisonous materials; and proper containment and disposal of hazardous materials used in construction processes. Green materials can also be materials that are less energy intensive to produce or dispose of, meaning a lower carbon footprint over the lifecycle of the material.

Careful attention should be given to material selection throughout the design and construction process. Selections should reflect consideration of the total life cycle of the products and the vessel itself, including end-of-life disposal. Consideration should be given to the use of sustainably sourced and environmentally friendly materials in the outfitting of the vessel. In particular, the use of low-VOC coatings, adhesives, and floor coverings is recommended where a suitable product is available.

**Table 15 Summary of green material selection**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Green material selection | • Less toxic<br>• Lower carbon footprint<br>• More recyclable | • More effort during design and construction to source materials<br>• Potentially higher initial cost | Yes | Consideration for greener materials is recommended to the extent practical. |

# Section 7 Alternative Fuels

Even if a vessel's propulsion and auxiliary systems are very efficient, the design of a green vessel should consider fuel type. EPA has established national ambient air quality standards for six of the most common air pollutants – carbon monoxide, lead, ground-level ozone, particulate matter, nitrogen dioxide, and sulfur dioxide – known as "criteria" air pollutants. The fuel used to generate power will directly affect the environmental footprint of the vessel, both in terms of $CO_2$ and criteria pollutants. The economy and the shipping industry are currently overwhelmingly powered by fossil fuels. Diesel, in its various forms, is the standard fuel powering ships today and is a major contributor to air pollution and climate change.

The marine industry is in the very early stages of transitioning to cleaner fuels. A number of pilot projects and very early commercial stage projects are underway around the world using various new fuel types. Some or all these fuels can be made from petroleum based sources, or alternatively can be synthesized using renewable energy. Biofuels are another, cleaner option. Biofuels, including biodiesel, have been used in some marine applications but typically require some modifications to the engine and are usually blended up to some limit. Use of biodiesel should only be done with consultation from the engine manufacturer.

Electrofuels, or e-fuels, are an emerging class of carbon-neutral synthetic fuels that can be a 'drop-in' replacement for liquid or gas fuels. E-fuels are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. They are produced by combining, via electrolysis, hydrogen made using renewable electricity with $CO_2$ captured from the ambient air or concentrated sources such as industrial flue gases. The promise of these fuels lies not only in the fact that they are carbon-neutral, but also in that they can directly replace (drop-in) fossil fuels using existing infrastructure. Therefore, consuming them would not necessarily require new technology. E-fuels are not yet widely commercially available and will cost more initially. Until e-fuels are commercially competitive with fossil fuels, and produced in similar quantities, their impact will be small. The design of the ARV should consider fuels which are not only available today, but which could potentially be replaced with carbon neutral e-fuels in the future.

Below is a discussion of several fuels which are potential alternatives for the marine industry. Each has advantages and disadvantages for the ARV, but none are widely commercially available today.

## 7.1 LNG

Liquified natural gas, or LNG, is the most compact way of storing natural gas. LNG is the primary means of exporting or importing natural gas from overseas but in the last decade has been promoted as a cleaner fuel alternative to diesel because it has lower particulate emissions, no sulfur, and lower greenhouse gas emissions (although inadvertent methane releases and combustion 'slip' have added controversy to this assertion). Storing LNG as a fuel requires pressurized, highly insulated tanks made from cryogenic alloys, typically stainless steels, and extremely low temperatures (-160° C/-260° F).

Regulations for gaseous fuels are driven by the IGF Code (Reference 28), which has been the basis for rules developed by classification societies and other regulators. LNG tanks may not be stored closer than 1/5 of the total beam width from the edge of a vessel, which greatly restricts where the tanks can be located. Furthermore, installing LNG tanks below the main deck requires the tanks be housed in a space that is adequately ventilated and provides space for inspection.

For a given unit of energy, LNG fuel is about 1.7 times greater in volume than diesel, but since it must be stored in insulated cylindrical tanks, it is significantly less volumetrically efficient than diesel. Also, the tanks must allow room for thermal expansion of the fluid, which only allows utilizing about 75% of the internal volume. A rough estimate is that four 20' x 100' cylindrical LNG tanks would be required to meet the endurance range for the ARV. These tanks would therefore be a significant design driver, requiring significant compromises in other areas of vessel design. Furthermore, LNG is not widely available today and it is unlikely it would be available in the volumes and locations required for the ARV. Based on this, LNG would be an impractical fuel choice for the ARV.

## 7.2 Hydrogen

Hydrogen is another alternative fuel that is currently receiving attention in parts of the maritime community. 'Green' hydrogen is made from zero carbon energy sources, such as solar, wind, or nuclear power and is considered a promising fuel of the future based on how clean it is. When combusted, water is the primary biproduct, along with some small amounts of NOx. When a fuel cell is used, only water is produced. Hydrogen can be stored as a compressed gas or a cryogenic liquid. Liquid hydrogen, $LH_2$, is the densest way to store it but unfortunately it is even less volumetrically efficient than LNG. $LH_2$ is also not widely available in the volumes needed, and green $LH_2$ is even more rare, and expensive. For these reasons, hydrogen is not considered as a feasible fuel for the ARV.

## 7.3 Ammonia

Ammonia, $NH_3$, is another chemical 'carrier' of hydrogen, but it does not contain a carbon atom, so combusting it or otherwise stripping and using the hydrogen as a fuel has the advantage of being zero emissions and zero carbon. 'Green' ammonia is made by adding a nitrogen atom to green hydrogen (made from electrolysis using carbon-free power). Synthesizing green ammonia takes additional energy steps, first to separate the nitrogen, and then to combine the hydrogen and nitrogen ($NH_3$ synthesis). The nitrogen separation and the ammonia synthesis must also be done using green energy to be considered carbon-neutral. However, ammonia has some advantages over both LNG and hydrogen.

Ammonia can be stored at atmospheric pressure at around -30ºF, which is cold but not *cryogenic* like LNG and $LH_2$. Ammonia is corrosive and very poisonous, therefore it still must be stored in independent stainless steel tanks rather than hull tanks. As a gaseous fuel, it must still follow the IGF code and therefore cannot be stored near the edge of a vessel. It has a similar, though slightly better, volumetric energy density to $LH_2$ but has only a bit more than half of the energy per volume as LNG. To meet the endurance requirement of the ARV, the volume of fuel needed would be about twice that of LNG (and many times that of diesel), but it could possibly be stored more efficiently in large stainless steel tanks below deck. However, storing an adequate volume of ammonia to meet the ARV's endurance requirements would require a larger vessel, with significant other compromises. Ammonia as a fuel is a very new concept today and it is uncertain whether it will be widely available in the areas the ARV will operate. As technology and fueling infrastructure advances, ammonia may become a viable marine fuel, but at this time it is not considered practical to use ammonia as a fuel for the ARV.

## 7.4 Green Diesels

### 7.4.1 Biodiesel

The term "biodiesel" most commonly refers to pure or blended fuels produced from plant- or animal-based feedstock. Common feedstock sources include soybean oil, canola oil, inedible animal fat, and recycled cooking oil. Biodiesel is produced from feedstock through a process called trans-esterification, which is used to create fatty acid methyl esters. Coproducts such as glycerin are then removed, and the product is purified to meet ASTM D6751 (Reference 29). Fuel meeting this standard is referred to as B100. ASTM D975 (Reference 30) allows blending ULSD with up to 5% B100 without additional control or marking. B100 is also commonly blended with ULSD in concentrations from 6 to 20% (B6 – B20).

Although biodiesel has been widely adopted for road vehicles, marine usage is much more limited. ISO 8217 (Reference 25) is used as a fuel specification for most worldwide ship fuel and restricts fatty acid methyl esters to 7%. Biodiesel blends differ from ULSD in several ways that that are relevant to shipboard use. These include material compatibility, higher water absorption, greater susceptibility to biological growth, higher cloudpoint, and solvent-like properties when first introduced into a fuel system.

Biodiesel has a lower carbon footprint and produces lower criteria pollutants than standard petroleum diesel, but due to operational issues cannot typically be used in high blends, which limits the benefits.

### 7.4.2 Renewable Diesel

Hydrotreated renewable diesel (HRD) refers to fuel that is chemically similar to fossil-fuel diesel but is produced from renewable feedstocks. Whereas traditional biodiesel is a mono-alkyl ester produced from lipids, renewable diesel utilizes different chemical processes to add hydrogen to and eliminate oxygen from the feedstock (hydrodeoxygenation), resulting in similar chemical compounds to those produced when diesel fuel is produced from normal petroleum-based feedstock. In some cases, HRD is processed using the same refinery equipment and processes as ULSD. Renewable diesel is required to meet the same ASTM D975 standards as petroleum-based diesel. Both biodiesel and renewable diesel can be produced from lipids such as vegetable oils and animal fats. The hydrodeoxygenation process used for renewable diesel can more economically handle animal fats than biodiesel production processes, which require an additional pre-conditioning step when using animal feedstock rather than vegetable oils. Renewable diesel can additionally utilize cellulose from crop residue and woody biomass, which cannot be used for regular biodiesel production.

Since renewable diesel is chemically similar to regular diesel, it is advertised as a substitute that requires no special considerations. It is often called "drop-in diesel" for this reason. It can be transported, stored, and consumed using all of the same equipment normally used with ULSD. Renewable diesel is commercially available in some areas but comes at a higher premium than traditional diesel.

Although chemically more similar to petroleum diesel, renewable diesel has many of the same benefits as biodiesel. It is more expensive than biodiesel, but it may be readily substituted for ULSD with no risk of operational issues. Using renewable diesel results in lower $CO_2$ equivalent emissions, and preliminary results suggest lower criteria pollutant emissions as well. Renewable diesel is an attractive option for the ARV, but its availability and cost are a barrier. Although renewable diesel could be obtained today in the United States, its availability in the operating area for the ARV is not certain.

### 7.4.3 Synthetic Diesel

Diesel manufactured using green energy as an electrofuel is sometimes referred to as synthetic diesel. Synthetic diesel is theoretically carbon neutral if it is made with green hydrogen and all renewable energy. Synthetic diesel meets ASTM D975 and therefore, similar to renewable diesel, is a drop-in fuel. It contains no sulfur and produces less particulates when combusted. One advantage over renewable diesel is that it does not require any biological feedstocks for its production. Synthetic diesel should be considered a future-fuel as it is not widely available today. If scaled up it could very easily be integrated into the existing worldwide infrastructure for bunker fuel distribution. Synthetic diesel would be an attractive option for the ARV in the future and would not require any modification of the ship.

## 7.5 Alternative Fuels Summary

Table 16 presents a summary of the evaluation of insulation technologies and recommendations for the ARV. Based on availability and cost, it is recommended that the ARV use standard ULSD. If other diesel alternatives such as renewable diesel or synthetic diesel ever become available at scale, that would be an easy drop-in solution that would significantly reduce the $CO_2$ emissions of the ARV in the future.

**Table 16 Summary of alternative fuels technologies and recommendations**

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| LNG | • Lower particulate emissions than diesel<br>• No sulfur emissions<br>• Lower greenhouse gas emissions | • Cryogenic storage requirements<br>• IGF code storage tank placement requirements<br>• Large volume needed to meet ARV endurance range would drive vessel design<br>• Limited availability | No | |
| Hydrogen | • Zero carbon<br>• Very clean-burning | • Cryogenic storage requirements<br>• Large volume needed to meet ARV endurance range<br>• Expensive<br>• Limited availability | No | |
| Ammonia | • Zero emissions and zero carbon<br>• Can be stored at atmospheric pressure at around -30ºF<br>• Could be stored in tanks below deck | • Must be stored in independent stainless steel tanks<br>• IGF code storage tank placement requirements<br>• Impractically large volume needed to meet ARV endurance range<br>• Limited availability | No | |
| Biodiesel | • Lower carbon footprint and lower criteria pollutants than petroleum diesel | • Operational issues if used in high blends | No | |
| Renewable diesel | • Meets ASTM D975 ("drop-in" diesel)<br>• Lower $CO_2$ equivalent emissions<br>• Lower criteria pollutant emissions | • Uncertain availability in ARV operating area | Conditional | If available at scale, would be a very easy way to significantly reduce the $CO_2$ emissions |

| Technology | Benefits | Drawbacks | Recommended for ARV? | Comments |
|---|---|---|---|---|
| Synthetic diesel | • Carbon-neutral if made with green hydrogen and all renewable energy.<br>• Meets ASTM D975 ("drop-in" diesel)<br>• Ready substitute for ULSD, no risk of operational issues<br>• Contains no sulfur<br>• Lower combustion particulates than petroleum diesel | • More expensive than biodiesel or petroleum diesel<br>• Currently limited availability | Conditional | If available at scale, would be a very easy way to significantly reduce the $CO_2$ emissions |

# Section 8 Specification Changes

## 8.1 Recommended Changes

Table 17 summarizes the green ship technologies recommended for inclusion in the ARV Performance Specifications.

**Table 17 Recommended technologies**

| Technology | Specifications Section |
|---|---|
| **Hull Technologies** | |
| Hull optimization | 070.3 |
| Hull coatings | 631 |
| ROVs for hull inspection and cleaning | 593 |
| Underwater radiated noise reduction | 073 |
| **Auxiliary Systems and Equipment** | |
| **Electric Equipment** | |
| Variable frequency drives | 314 |
| Premium efficiency motors | 302 |
| Energy storage batteries | 201 |
| Harbor generator | 311, 315 |
| High efficiency lighting | 330 |
| Smart lighting controls | 330 |
| **HVAC Systems** | |
| Waste hot water and steam | 311, 411, 536 |
| Advanced HVAC controls | 512 |
| Heat pumps | 512 |
| Environmentally friendly refrigerants | 516 |
| Refrigerant systems management plan | 516 |
| **Airborne Noise** | |
| Interior and exterior noise limits | 073 |
| **Pollution Control Systems** | |
| **Lubricant and Hydraulic Oil** | |
| Environmentally acceptable lubricants | 542, 556 |
| High efficiency OWS | 593 |
| Oil cleaners | 542 |
| Stern tube leak control | 593 |
| Electric winches and windlasses | 570, 580 |
| **Garbage Management** | |
| Comprehensive waste management plan | 593 |
| Biological grease traps | 593 |

| Technology | Specifications Section |
|---|---|
| **Air Emissions Reduction** | |
| Use ULSD ( <15 ppm ) when available | 201.1, 311, 312, 541.2 |
| Use emissions aftertreatment system in the Antarctic | 593 |
| **Ballast Water Treatment** | |
| Ultraviolet technology | 529 |
| **Outfitting** | |
| Extra insulation thickness | 632.1 |
| Thermal insulating coating | 632.2 |
| Insulated glass on exterior boundaries | 632 |
| **Green material selection** | 701 |

## 8.2 Conditionally Recommended Technologies

Table 18 lists technologies where we recommend further consideration is required. Language can be added to clarify the intent and what actions the designer should take.

**Table 18 Conditionally recommended technologies**

| Technology | Specifications Section |
|---|---|
| **Electric equipment** | |
| Permanent magnet motors and alternators | 301, 335 |
| **Auxiliary Systems and Equipment** | |
| Decentralized HVAC Systems | 512 |
| Air to air heat exchangers | 512 |
| Fire suppression: Novec 1230 and water mist | 555 |
| Segregation of used engine oil | 593 |
| **Pollution Control Systems** | |
| Wastewater treatment: biological and electrolytic systems | 593 |
| **Garbage Management** | |
| Food waste: macerators/pulpers | 593 |
| Food waste: composter | 593 |
| Food waste: dehydration and/or vacuum sealing | 593 |
| Recycling: baler | 593 |
| Recycling: metal and glass shredder/crusher | 593 |
| Garbage: trash compactor | 593 |
| Garbage: incinerator | 593 |
| **Alternative Fuels** | |
| Renewable diesel | 201.1, 311, 312, 541.1, 541.2 |
| Synthetic diesel | 201.1, 311. 312, 541.1, 541.2 |