Antarctic Research Vessel (ARV)

Engineering Report: Green Ship Alternatives Study Report

Document No.: 5E1-052-R101

Revision: P2

Prepared by the Antarctic Support Contractor
for the
National Science Foundation Office of Polar Programs

Revision History

Revision #	Date	Section (if applicable)	Author/Editor	Change Details
P0	April 13, 2022	All	M. Gahagan	Initial draft for release.
P1	September 30, 2022	All	M. Gahagan	Added Sections: 2.3, 3.5 – 3.7, 4.2, 4.3, 5.1.5, 5.4, 6.2.2.2, 6.2.2.3, 6.5.2.4, 6.6.2.2, 8 Added Summary tables throughout. Revised existing sections to suit design development of dependent auxiliary, electrical, and propulsion systems.
P2	January 3, 2023	All	M. Gahagan	Added technology summary table to Section 1, Executive Summary. Revised Section 6.5.2.4 to recommend the MAGS system. Added Biodiesel section to Section 4.3. Added discussion of potential chiller bypass in Section 5.1.5. Added discussion of VPG throughout Section 6 Revised Section 9 tables

Prepared by:

Signature	Print Name	Date
	Michelle Gahagan	Apr 13, 2022

Signature *Print Name* *Date*
Michelle Gahagan, Assistant Department Manager, Machinery, Gibbs & Cox

Checked by:

Signature	Print Name	Date
	Kurt Sarau	Apr 13, 2022

Kurt Sarau, Senior Principal Engineer, Gibbs & Cox

Engineered/Managed by:

Signature	Print Name	Date
	Joshua Ware	Apr 13, 2022

Joshua Ware, Machinery Department Manager, Gibbs & Cox

Approved by:

Signature	Print Name	Date
	Patricia McGinn	Apr 13, 2022

Patricia McGinn, Assistant Vice President-Machinery Division, Gibbs & Cox

Table of Contents

List of Figures

List of Tables

1. Executive Summary

This report has been developed to evaluate green ship technologies that could be implemented on the Antarctic Research Vessel (ARV). The report defines various options for green technology incorporation to assist the National Science Foundation (NSF) in determining appropriate design features.

The use of green technology onboard the ARV was previously investigated during the Concept Design phase and documented in a Green Ship Alternatives Study, authored by Glosten (Reference 3). The Contract Design Green Ship Alternatives Study was reviewed to inform report format and scope. However, this report serves as a stand-alone document to reflect the specific green design considerations and decisions researched and implemented during the ARV Preliminary Design phase.

While existing environmental regulations create a baseline for incorporation of green practices on the ARV, the proposed technologies contained in this report serve to build upon this baseline to align the design of the ARV with the mission of the NSF to promote the progress of science. This approach also allows the ARV design to be forward-looking in anticipation of future regulations. A wide swatch of green technologies were researched, investigated, and analyzed. This report also provides justification for green technologies that are required to be incorporated into the ARV design as required by the ARV Performance Specifications (Reference 1).

Within this report, green technologies are presented in six categories:

1. Hull Construction,
2. Electrical Systems,
3. Propulsion Plant,
4. Auxiliary Systems and Equipment,
5. Pollution Control Systems, and
6. Outfitting.

Each category will detail systems, features, and practices that can reduce fuel consumption and environmental impact of the ARV. The following principles, outlined in the United States Coast Guard (USCG) Proceedings Magazine (Reference 2)), will serve as a guideline for establishing a green ship design:

- *Minimize energy use.*
- *Minimize use of hazardous materials and environmental contaminants.*
- *Minimize air emissions.*
- *Minimize discharges to water.*
- *Minimize waste and scrap.*
- *Maximize use of recycled and recyclable material.*
- *Maximize use of rapidly renewable and regional materials.*

In addition to these guidelines, underwater radiated noise (URN) and its environmental impact is explored and discussed. Analysis of the available technologies to carry out the above principles has resulted in the incorporation, recommendation, or elimination of green technologies as summarized in Table 1 below.

Table 1: Summary of Incorporation Status

Technology	Report Section	Status	Remarks
Hull Technologies			
Hull Form balancing Icebreaking and Open Water Performance	2.1	Incorporated	–
Hull Lubrication	2.1	Further Study	Benefits of hull lubrication will be explored once a final hull form has been converged upon.
Abrasion-Resistant, Low Friction Hull Coating	2.2.2.2	Recommended	This would be documented in the detail Design Phase in a Paint Schedule.
Hull Cleaning (both divers and ROVs)	2.3	Recommended	Hull cleaning method can be selected or modified at any time during ship's lifetime.
Electric Systems			
IEPS	3.1	Incorporated	–
Hybrid Battery	3.2	Incorporated	–
Generator Set Configuration *Father-Son*	3.3	Incorporated	–
Generator Set Configuration *Equally Sized*	3.3	Eliminated	Eliminated in favor of a father-son configuration that has lower space, weight, and fuel consumption.
VFDs	3.4	Incorporated	–
Premium Efficiency Motors	3.5	Further Study	Availability will be explored during the Detail Design phase during equipment selection.
PM and SR Motors	3.6	Further Study	Availability will be explored during the Detail Design phase during equipment selection.
LEDs	3.7.1	Incorporated	–
Lighting Controls	3.7.2	Recommended	Lighting controls will be implemented in the Detail Design Phase in the Lighting Plan and IMACS control schema.
Propulsion Plant			
Azimuthing Propulsor *Podded Electric Drive*	4.1.1	Incorporated	–
Azimuthing Propulsors *Mechanical Drive*	4.1.1	Eliminated	Eliminated in favor of electric drive propulsors which have lower mechanical losses and better reliability.

Technology	Report Section	Status	Remarks
Wind Power	4.2	Eliminated	Eliminated due to expected low output of system and compromises to ship stability, lines of sight, science operations.
Alternative Fuels *Methanol and Hydrogen* *Ammonia*	4.3	Eliminated	Eliminated due to low bunkering availability and required increases in fuel storage capacity that would be unmanageable on the ARV given its power needs and allotted space for fuel tankage.
Alternative Fuels *Biodiesel*	4.3.1	Further Study	In the future, should bunkering become available, biodiesel could be used as a drop-in fuel. Should heating of fuel tanks be required, use of biodiesel is not recommended as tank heating would be accomplished using the oil-fired heater which would lead to higher fuel consumption of oil-fired heater.
Auxiliary Systems			
Decentralized HVAC	5.1.1	Incorporated	–
Centralized HVAC	5.1.1	Further Study	At this time, decentralized is expected to be more energy efficient than a centralized system. Upon calculation of individual space cooling and heating loads in the Detail Design phase, the selection of the HVAC system architecture will be re-evaluated to determine if decentralized is the most energy efficient architecture as expected.
VFDs (HVAC)	5.1.2	Recommended	Potential application will be explored in the Detail Design Phase when all fans have been sized.
Air to Air Heat Exchangers	5.1.3	Eliminated	Eliminated due to its inefficiency in meeting the high heating demands of the ARV.
Heat Pumps	5.1.4	Eliminated	Eliminated due to lack of reliable heat source for transferring of heat via heat pump.
Advanced HVAC Control Systems	5.1.5	Recommended	These controls will be implemented in the Detail Design Phase in the HVAC System and IMACS control schema.
Environmentally Friendly Refrigerants	5.1.6	Recommended	Environmentally Friendly Refrigerants will be explored in the Detail Design Phase during equipment selection of chillers and refrigeration plants.
Waste Heat Recovery	5.2	Incorporated	–

Technology	Report Section	Status	Remarks
Low-Flow Water Consumers	5.3	Recommended	Low-flow consumers will be explored in the Detail Design Phase during equipment selection.
NOVEC 1230	5.4.1	Incorporated	–
Water Mist	5.4.2	Incorporated	–
FM-200	5.4	Eliminated	Eliminated in favor of NOVEC and water mist which have significantly lower global warming potentials.
Pollution Control Systems			
Oily Water Separator (5 ppm)	6.2.2.1	Incorporated	–
Environmentally Acceptable Lubricants	6.2.2.2	Recommended	Engine, propulsor, and handling systems vendors will be engaged in Detail Design to determine the suitable EAL selection for these applications.
Ballast Water Management System *Ultraviolet Light*	6.3.2	Incorporated	–
Ballast Water Management System *Electro-chlorination* *Chemical Injection* *Thermal (Heat)*	6.3.2	Eliminated	Eliminated in favor of UV-type BWMS for its established place in the market, its non-reliance on active substances, and its independence from ballast water salinity.
Sewage Treatment Plant *Biological Membrane*	6.4.2.1	Incorporated	–
Sewage Treatment Plant *Electrolytic*	6.4.2.1	Eliminated	Eliminated due to its reliance on water salinity that may not be met in all areas of ship operation.
Incinerator (Gasification System)	6.5.2.4	Incorporated	–
Air Emissions Reduction *Exhaust Gas Recirculation*	6.6.2.1	Incorporated	–
Air Emissions Reduction *Selective Catalytic*	6.6.2.1	Recommended	While the currently selected engines utilize Exhaust Gas return for emissions reduction, other diesel engine suitable for the ARV utilize Selective Catalytic Reduction.
Ultra Low Sulfur Fuel	6.6.2.2	Incorporated	–
Outfitting			
Increased Thermal Insulation	7.1	Further Study	Tradeoff should be further studied in Detail Design phase, when detailed space heating and cooling load calculations are performed.
Green Material Selection	7.2	Further Study	Outfitting details will be further explored in Detail Design and captured in various outfitting lists and schedule.

These technologies allow the ARV to stay on the forefront of marine green technology. In addition, incorporation of these technologies will also allow the ARV to receive the American Bureau of Shipping (ABS) ENVIRO+ notation.

As the ARV design develops, green technologies, which serve to carry out the aforementioned green design principles, will continue to be evaluated. It is the goal of this report to ensure that the impact of ARV operation in the Antarctic is mitigated; to protect the remote and vulnerable and Antarctic environment, and to engage in environmental stewardship during the ARV's missions.

1.1. Acronyms

ABS	American Bureau of Shipping
AFS	Anti-fouling system
AIM	American Innovation and Manufacturing (Act)
ARV	Antarctic Research Vessel
ASC	Antarctic Support Contractor
BWM	Ballast Water Management
BWMS	Ballast Water Management System
CARB	California Air Resources Board
CFC	chlorofluorocarbon
CFR	Code of Federal Regulations
COMDTINST	Commandant Instruction Manual
DNC	daily nutrient content
DNV	Det Norske Veritas
EC	electro-chlorination
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
ESS	Energy Storage System
FCU	Fan Coil Unit
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HVAC	Heating, Ventilation, and Air Conditioning
IEPS	Integrated Electric Propulsion System
IHM	Inventory of Hazardous Material

IMO	International Maritime Organization
KPP	Key Performance Parameter
LTE	Guide for Vessels Operating in Low Temperature Environments
MARPOL	International Convention for the Prevention of Pollution from Ships
MBR	Membrane Bioreactor
MCFC	Molten Carbonate Fuel Cell
MEPC	Marine Environment Protection Committee
MSD	Maritime Sanitation Device
MVR	Marine Vessel Rules
NEMA	National Electrical Manufacturers Association
nm	nautical mile
NSF	National Science Foundation
ODS	ozone depleting substance
PEM	premium efficiency motor
PM	permanent magnet [motor]
PST	Polar Service Temperature
PSU	practical salinity unit
ROV	remotely operated vehicle
SCR	Selective Catalytic Reduction
SNAP	Significant New Alternatives Policy
SOFC	Solid Oxide Fuel Cell
SR	switched reluctance [motor]
SSN	sonar self-noise
TBT	tributyltin
URN	underwater radiated noise
USCG	United States Coast Guard
UV	Ultraviolet
VFD	Variable Frequency Drive
VGP	Vessel General Permit
VOC	volatile organic compound
VOHAP	volatile organic hazardous air pollutants

2. Hull Technologies

2.1. Hull Form

The ARV hull form is required to meet the icebreaking Key Performance Parameters (KPP), defined by the ability to break 4.5 feet of level continuous ice with 12 inches of snow (for an equivalent thickness of 4.83 feet) at a speed of 3 knots or greater, while also balancing the need for open water performance. While icebreaking and open water performance each benefit from a specialized hull form, an approach combining both is critical to overall efficiency of the vessel, as a ship optimized to break ice will have poor open water performance and a ship ideal for open water will break ice inefficiently. In order to begin the process of developing a hull form which will satisfy the ARV requirements, three areas of the hull, the bow, midbody, and stern, are addressed.

To achieve the ship's KPP, breaking ice at a specified thickness and speed, the bow hull angles must be optimized. Finding optimal bow angles to meet and not exceed the KPP will greatly assist in reducing hull form inefficiencies during open water transit, as bow shapes more suitable for breaking additional ice thickness will further reduce open water performance. The three angles of interest are:

- Entrance angle,
- Flare angle, and
- Stem angle.

The entrance angle is the angle between the centerline and the tangential direction of the hull's waterline. The flare angle is the angle between the vertical plane and the side shell direction at the waterline and forward perpendicular. The stem angle is the angle between the waterline and the stem. These angles will be designed within ranges that will achieve the required ice breaking performance without creating unnecessary geometry that would be detrimental to the open water performance of the vessel.

In the midbody of the vessel, the bilge radius, where the ship bottom transitions to the side shell, is the next area where the hull form may be optimized. Here, a large radius reduces residual and cavitation resistance, benefiting open water performance. However, a large radius also reduces the midbody displacement of the hull. Selection of the bilge radius to capture open water performance gains, while also considering impact to displacement will facilitate a hull form that does not have an unneeded increase in vessel principal dimensions to achieve displacement needs.

Finally, at the stern, the transition from the ship's bottom to the propulsion platform, which provides the foundation for the azimuthing propulsors, is adjusted to suit the combined needs of the ARV. This transition is similar to the bilge radius, in that designing the transition with the correct angle provides the best water flow around the hull and into the propellers. Having a smaller angle, and therefore a smoother transition, will allow better water flow into the propeller and better open water performance. However, this angle has an impact on the displacement and arrangeable interior volume of the vessel. As with the selection of the bilge radius, careful design to capture open water performance gains while also considering impact to displacement will facilitate a hull form that does not have an unneeded increase in vessel principal dimensions to achieve displacement needs.

As the design iteration of the ARV hull form has progressed, additional features to support icebreaking and the scientific mission of the vessel were incorporated into the design.

Icebreaking features including a forward ice knife and deadrise were investigated and optimized through the use of computational fluid dynamics during investigation of bubble sweepdown and streamlines aft towards propellers. The impact of these features will be verified in model testing of the ARV, and the findings will be used to inform future design iterations so the balance of icebreaking and open water hull efficiencies may be realized. An overall summary of icebreaking is located in the Icebreaking Performance Report, 5E1-050-R201 (Reference 4).

A box keel was added to the hull to allow for placement of scientific instrumentation such as the EM124 arrays. The box keel is utilized to allow the arrays to be placed in an area less affected by bubble sweepdown. While this improves the scientific performance of the ARV, the additional wetted surface area of the box keel negatively effects the fuel economy of the vessel. This impact was minimized through the use of computational fluid dynamics to iterate the box keel and minimize its size, while still allowing for electronics to be mounted and bubble sweep down to be minimized. Further investigation of the box keel is also included in the scope of model testing and its findings used to inform future design iterations so the balance of icebreaking and hull efficiencies may be realized.

An overall summary of the hull form development and design trade-offs investigated is located in Hull Form Trade-Off Study, 5E1-051-R001 (Reference 5), and Bubble Sweepdown Computational Fluid Dynamics Report, 5E1-050-R101 (Reference 6).

At this stage of design, the hull form development has included iteration of the physical vessel size, shape, and overall balance of requirements in an efficient manner. Operational details such as hull cleaning and inspection protocols that may further improve hull efficiency in the water have not yet been investigated or incorporated.

Construction of the hull form is an additional area of opportunity that may be explored as a means to minimize the environmental impacts of the ARV. Incorporation of class society guidance to ensure compliance with Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Ship Recycling Convention) is a potential means to begin incorporating features that “prevent, reduce, minimize and, to the extent practicable, eliminate accidents, injuries and other adverse effects on human health and the environment caused by ship recycling, and to enhance a vessel’s safety, protection of human health and the environment throughout a vessel’s operating life” (Reference 7).

Additional technologies such as air or water lubrication of the hull are also potential features to be investigated and may lead to further improvements in efficiency. These technologies shall be considered once a final hull form has been selected.

As the ARV hull form is designed, it will be evaluated for impacts to its icebreaking, open water, and overall mission capability. Careful selection of features will provide a hull capable of efficient icebreaking and open water performance, while balancing overall vessel size.

2.2. Hull Coatings

Per the ARV Performance Specification, Section 630, “Advanced hull coatings specifically designed for icebreaking service shall be used. It is assumed a hard coating requiring regular cleaning would be used.” The typical purpose of hull coatings is to protect the hull from corrosion and maintain a smooth hull to reduce drag while underway. Marine biofouling, or the growth and presence of organism, barnacles, seaweed, and ‘slimes’, also contributes to ship’s drag, increasing fuel consumption, noise production, and bubble generation, the latter of which has detrimental effects on sonar operation. Anti-fouling coatings are provided on top of anti-corrosive coatings to prevent biofouling of the hull.

Selection of hull coatings should consider the environmental envelope in which the ARV is to operate. Hull coatings applied to the ARV will need to withstand ice abrasion and ice adhesion.

2.2.1. Environmental Regulations

Within a decade of the mainstream application of anti-fouling paints using the organotin compound tributyltin (TBT), high concentrations of TBT were found in shellfish off the coast of France. As a result, the International Maritime Organization (IMO) adopted the *International Convention on the Control of Harmful Anti-fouling Systems on Ships* (AFS Convention), (Reference 8), which called for a global prohibition on the application of organotin compounds acting as biocides in anti-fouling systems on ships. The convention has been amended several times, resulting in the prohibition of other compounds found in anti-fouling coatings that could have an adverse effect on the aquatic environment.

2.2.2. Discussion

2.2.2.1. Anti-fouling Coatings

While traditional anti-fouling coatings use biocides to kill organisms that try to attach to the hull, increased environmental regulations on hull coatings have led to the creation of non-biocidal coating strategies. The American Bureau of Shipping (ABS) Guide for Vessels Operating in Low Temperature Environments (LTE), (Reference 9), contends that fouling is only a minor problem for ships operating in ice. It adds that “most designated anti-fouling coatings are quickly destroyed and torn from the anti-corrosion coating underneath when operating in ice”. However, in accordance with the ARV Performance Specification, the ARV “must be capable of transiting and undertaking science operations in tropical waters.” In order to receive ABS ENVIRO or ENVIRO+ notation, anti-fouling systems may not make use of organotin compounds (Reference 10). The ARV will be required to hold and maintain a valid International Anti-Fouling System Certificate in accordance with the requirements of the AFS Convention. In consideration of the use of dedicated anti-fouling coating, the system must align with the requirements of the AFS Convention.

2.2.2.2. Abrasion-Resistant, Low-Friction Hull Coatings

Traditional anti-corrosive coatings were not designed to and will not meet the severe ice abrasion and ice adhesion challenges posed for the ARV. Several special ice coatings are currently available on the market. Application of abrasion-resistant low-friction ice coatings has several advantages including:

- Decreased ice-to-hull coefficient of friction when compared to traditional anti-corrosive coatings, which leads to lower required propulsion power and fuel consumption when navigating in ice
- Increased lifetime of the hull with proper reapplication of coating to prevent corrosion
- Longer re-application intervals than traditional anti-corrosive coatings, leading to lifetime cost savings

Abrasion resistant ice coating Intershield® 163 Inerta 160 is an epoxy paint specifically designed for ships operating in temperatures down to -50°C and has become a standard product utilized on icebreakers for decades. Inerta 160 is currently used on icebreakers with higher icebreaking capability than required for the ARV. For example, the multipurpose Russian icebreaker Varandey, which is capable of breaking 5.6 ft of ice, has Inerta 160 applied to its hull. Testing of Inerta 160 has demonstrated annual fuel savings of 7-10% if the vessel is coated with Inerta 160 compared to a standard anti-corrosive system.

While Inerta 160 is one of the more commonly cited ice coatings, there are other brands available on the market that boast similar friction characteristics. This includes Ecospeed, Permax 1000, and Sigmashield 1200. A comparative cost analysis of both relative and lifecycle costs of these alternatives is currently underway, awaiting response from coatings vendors.

While Inerta 160 is a more difficult coating to apply, it is recommended due to its domestic availability, lower VOC content, and lower total weight (based on recommended dry film thickness). Additionally, Inerta 160 installation has the option to apply an anti-fouling coating though this coating would need to be reapplied after icebreaking missions.

2.3. Hull Inspection and Cleaning

The tradeoff for application of special, ice-capable coatings is that most ice-capable coatings cannot be overcoated with a traditional antifouling coating. As a result, transits to polar waters from more temperate climates will require a hull cleaning before getting underway. Hull cleaning in lieu of application of an anti-fouling coating serves the following purposes:

1. to reduce the drag created by accumulated marine bio-growth, and
2. to reduce the chance of transporting nonnative species into polar waters.
3. the weight of an anti-fouling coating can be omitted.

A hull cleaning can be performed by diver units and/or by a remotely operated vehicle (ROV). A hull cleaning is typically completed within seven to ten days of the expected sail date. If hull cleaning is used in lieu of an anti-fouling coating, it is recommended that a hull cleaning be performed prior to each mission, as suggested within seven to ten days of departure. This limits the potential of bringing nonnative species into the mission areas. If antifouling is applied, hull cleaning may still be desirable if the coating has been damaged and the mission involves especially sensitive areas.

ROVs are both easier and cheaper to employ than diver units. Additionally, ROVs can be deployed at any time, even in cold waters. However, ROVs cannot reach every inch and are less effective than diver units on intricate surfaces. It is recommended that both methods be used depending on the specific needs of each hull cleaning.

2.4. Hull Technologies Summary

Table 2: Summary of Hull Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Hull Form *Balanced for both open water and icebreaking*	- Conventional ice breaking hulls provide more open water fuel efficiency and maneuverability, as well as maintains ice breaking maneuverability.	- Slight reduction in ice breaking efficiency ahead with more ice coverage along the hull.	**Yes, Incorporated**	–
Hull Lubrication	-	-	**Further Study**	Benefits of hull lubrication will be explored once a final hull form has been converged upon.
Hull Coatings				
Abrasion-resistant, low-friction	- Decreased ice-to-hull coefficient of friction - Increased lifetime of the hull	- Reapplication required after icebreaking	**Yes**	This would be documented in the detail Design Phase in a Paint Schedule
Anti-fouling	- Reduce drag created by bio-growth - Prevent transportation of nonnative species	- Cannot be overcoated onto all abrasion-resistant, low-friction coatings - Reapplication required after icebreaking	**Conditional**	Can only be applied over Inerta 160
Hull Inspection and Cleaning	- Reduce drag created by bio-growth - Prevent transportation of nonnative species	- Requires diver units or ROVs	**Yes**	Hull cleaning method can be selected or modified at any time during ship's lifetime

3. Electrical Systems

Per the ARV Performance Specification, Section 300, "The electric plant shall be an integrated battery-hybrid, diesel-electric system. System sizing shall consider variable powering requirements depending on wide-ranging the ARV missions, including connection of systems with large motors and other electrical power requirements." The Electric Plant will be sized to meet the unique mission of the ARV. These missions will require propulsion power sized for open water transit, breaking greater than or equal to 4.5 feet of ice with 12 inches of snow (for an equivalent thickness of 4.83 feet) at 3 knots, and towing operations, among others.

Besides supporting the propulsion system, the electrical plant provides power to ensure good habitability conditions. Among these conditions is the lighting, which can be more efficient when color and intensity can be modified and controlled.

Electrical system tradeoffs including batteries and variable speed generators are further discussed in 5E1-062-R101 Electrical Propulsion Architecture Trade-off Study, Revision P0 (Reference 11).

3.1. Integrated Electric Propulsion Systems (IEPS)

Per the ARV Performance Specification, Section 300, "The electrical plant shall be as efficient as possible." The use of a diesel-electric system is the first step in ensuring plant efficiency, as diesel-electric systems are known to provide efficient operation over a variety of operating modes, consistent with the ARV operations. In the IEPS arrangement, power is generated by multiple diesel engine-driven generator sets which then provide power to the propulsion motors and ship service loads. Provision of multiple generators to serve both propulsion and ship service loads allows for the flexibility to operate only as many generators as necessary to supply the required electric loads. Diesel-electric generators can be used in different combinations to efficiently meet widely varying power demands while allowing plant redundancy. By making use of combinations of diesel engines, power loading can be balanced to ensure that the average loading of each running diesel engine is close to its optimum load point. Generator sizing is largely driven by the required propulsion power to meet the KPP icebreaking capabilities of the ARV. The icebreaking operation will require significantly more propulsion power than needed for ice-free transit.

Use of a diesel-electric propulsion system is particularly useful in icebreaking scenarios. Ice acting against the propeller causes high torque loads. In an engine-driven arrangement, diesel engines have a small speed range in which they can deliver full power. If an ice torque acting on the propeller exceeds the torque given by the engine, this will cause stalling. Electric motors, however, can maintain torque in a large speed range, making the system highly efficient in conditions of high torque loads.

3.2. Hybrid Battery Storage

The ARV Performance Specification, Section 310.1, requires the use of a battery Energy Storage System (ESS) integrated into the power system. Batteries will be a valuable technology to be used in lieu of, or alongside, diesel generator sets. A lower demand on the generators has a direct impact on fuel consumption. The batteries will primarily be used to share the peak power demand during different operating scenarios, serve as a power reserve, and increase ship reliability. When the power demand on the electric plant falls below a generator's point of peak efficiency, this gap may be bridged by using the generator's excess power to charge the batteries. This allows the generators to run most efficiently while building the battery power reserve.

Lithium-Ion batteries are the first choice. They have successfully been incorporated into a myriad of vessels for the last two decades. On the other hand, the battery bank size must be carefully calculated. Increasing system size requires additional weight and space for storage. It also requires upsizing of support systems such as firefighting and HVAC. An alternative is to add the batteries as needed for each mission. This can be facilitated by utilizing battery banks that are fitted in a 20 feet containers which include all the necessary auxiliaries to maintain the batteries working properly. Bounding of battery system sizing is further discussed in 5E1-313-P001 Battery Sizing for Lithium-Ion Batteries, Revision P0 (Reference 12).

Another power source could be available by fuel cell technology with the advantage of reduction in fuel consumption and lower impact (both local and global) on environment. Additional benefits include insignificant noise and vibration levels, as well as lower maintenance requirements compared to traditional combustion engines. Different fuel cell types are available and can be characterized by the materials used in the membrane. Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) technologies are high-temperature fuel cells that are flexible as regard to the choice of fuel: methanol, ethanol, natural gas, biogas, and hydrogen are most commonly used. MCFC is the more mature of these two technologies, while SOFC is considered to have the greatest potential in terms of efficiency and power density. An electric stack efficiency of 50-55% has been obtained from both MCFC and SOFC installations, and when internal consumption is included, this is lowered to 45-50%. High operating temperatures lead to high exhaust temperatures (400-800°C) that, together with a large volume flux of exhaust, yield a significant potential for heat recovery. The fuel to electric efficiency can be increased to 55-60% for MCFC plants and to above 60% for SOFC plants when heat recovery is included.

MCFC units generally have one fuel cell stack of 200 to 500kW, while an SOFC unit is built from several smaller stacks of 1-20kW each. The SOFC units can be built to be significantly more compact than MCFC units, but the complete power packs remain large in volume compared with diesel generators. High temperature fuel cells must operate at stable temperatures, and therefore have low tolerance to rapid load changes. In general, these fuel cell types can only be justified in applications where power and heat demands are high and stable.

Fuel cells have been successfully installed in marine environments and could be a solution in the future not for propulsion but to feed auxiliary systems like lighting, heating and air conditioning, instrumentation, emergency systems and other systems as needed. Nevertheless, the use of this technology for the ARV is not recommended at this time because the technology is relatively new and has not been proven in the harsh environments in which the ARV will be operating.

3.3. Generator Set Configuration

Per the ARV Performance Specification, Section 310, "Electrical power for propulsion and ship service shall be provided by at least four (4) main diesel generators sets." The generators shall be sized to meet the required icebreaking capability and ship service load demands. One basic diesel-electric operational challenge is closely matching actual electrical generation to varying electrical demands of ship systems while running any operating diesel engine at its level of peak performance. With wide variations in electrical loads, it is likely that at least one generator set will always be operating under part load. However, this is still a more efficient propulsion system arrangement than dedicated propulsion diesel engines for each propulsor.

Assuming that at least four diesel generators are used onboard the ARV, they may be sized and arranged as equally sized generators or as a father-son arrangement with a set of larger generators and a set of smaller generators. In both arrangements, the generator sets would be sized to suit the required propulsion motor load for icebreaking as well as the required ship service loads. Each arrangement has its own set of advantages. Provision of a father-son arrangement allows for more running modes and the ability to better optimize generator set operation. One anticipated challenge of the father-son arrangement would be meeting the requirement of the ARV Performance Specification, Section 310, that the generators be sized such that the required cruise speed and icebreaking performance can be achieved with any one generator offline.

The decision between equally sized generators and a father-son arrangement is partially dependent on available machinery space footprint and results of the Speed Power Analysis and Electric Plant Load Analysis to determine the required installed power. Nevertheless, the father-son arrangement is more efficient during certain operations, when the load level aligns with the genset most efficient load mode.

The current ARV power train utilizes Wabtec V250 generators in a father-son configuration of four 16V250 generators (rated at 4053 ekW each) and two 12V250 generators (rated at 3040 ekW each), for a combined power generation of 22.3 MW. To provide at least the same power while utilizing equally sized generators, six 16V250 or eight 12V350 generators would be required. In this case, using equally sized generators would lead to increased power train space and weight. Additionally, when analyzing the overall fuel consumption for the Thwaites Design Reference Mission, using equally sized generators would result in higher fuel consumption as indicated in Table 3 below:

Table 3: Fuel Consumption by Generator Set Configuration

Configuration	Installed Power (ekW)	Fuel Consumption for 91-Day Mission (LT)	Δ
Father-Son *Four 16V250* *Two 12V250*	22292	2026	-
Equally Sized *Six 16V250*	24318	2048	+22 LT
Equally Sized *Eight 12V250*	24320	2068	+42 LT

3.4. Variable Frequency Drives (VFDs)

Per the ARV Performance Specification, Section 300, “The electrical plant should be as efficient as practical. As such Variable Frequency Drives (VFD) with closed-loop control shall be considered for systems that have varying demand, such as pumps, fans, and chillers.”

A variable frequency drive is a system for controlling the rotational speed of an alternating current electric motor by controlling the frequency of the electrical power supplied to the motor. A VFD is a specific type of adjustable-speed drive.

One of the advantages of VFDs is that it lowers the starting motor current, that can be six times the rated current, and increases the torque to 150% of its rated torque while drawing less than

50% of the rated current in the low-speed range, though this low speed cannot be maintained for long because of the potential to overheat the motor.

The energy savings gained from the use of VFDs are most clearly realized when coupled with equipment that have widely spaced power demands. For example, Machinery Spaces will require high amounts of ventilation supply air in the cooling season to cool the Machinery Spaces to their design temperatures. In the heating season, with statistical outdoor air dipping to as low as -49°F, ventilation air will not be required to cool the space. Rather, only a small amount of ventilation supply air will be required to maintain air quality and exchange within the space. In this case, adding VFD control to the ventilation supply fan will allow the fan to be run at a much lower speed, providing the minimal amount of required supply air. This example is further detailed in Section 5.1.2 below.

As HVAC and auxiliary systems are designed for the ARV, operational conditions of the associated motor-controlled equipment will be evaluated to determine if VFD control would provide a meaningful amount of energy savings. The energy-savings benefits of VFD use must be weighed against VFD cost, potential VFD cooling requirement, space and weight, and addition of equipment required to mitigate harmonics generated by VFDs.

3.5. Premium Efficiency Motors

A premium efficiency motor (PEM) is a motor that complies with the National Electrical Manufacturers Association (NEMA) PEM standard adopted in August of 2001. Premium motors need to meet or exceed a set of minimum full-load efficiency levels. Premium efficiency motor standards apply to three-phase low-voltage induction motors of NEMA design A and B that are rated from 1 HP to 500 HP. PEM are designed for service at 600 volts or less, run at speeds of 3600, 1800, and 1200 RPM, and are provided with open drip-proof, explosion-proof, and totally enclosed fan-cooled enclosures.

These design features and better materials reduce motor losses, making PEMs more efficient than standard motors even at low motor loads. The disadvantage of PEMs is that the motors are larger and heavier than regular motors. PEMs are wired to work with variable frequency drives, so no especial requirements have to be specified.

An electric system is efficient when it operates with as little losses as possible; another way to save energy is to shut off idling motors to eliminate no-load losses. This action greatly improves the overall system power factor, improving the electrical system distribution efficiency; shedding slow speed motors is other solution because it avoids restarts that can cause overheating and increase motor failure.

3.6. Other Motor Technologies

Permanent magnet (PM) motors use powerful ceramic or rare earth neodymium iron boron magnets attached to the surface of the rotor to establish a permanent magnetic field. It replaces the rotor cage of the induction motor, reducing the secondary circuit rotor resistance losses. The PM motors are design for variable speed operation, improving power factor and efficiency in low operational speeds where regular motors power factor increases and efficiency decreases. PM motors are smaller than induction motors of the same hp rating and are available in reduced frame sizes. The advantages are excellent torque-speed curve and dynamic response, higher efficiency at partial loads, longer lifetime, high speed capability and high torque-to-volume ratio (high power density); the disadvantages are high cost due to the rare earth magnets and need for a controller. Another advantage is that PM motors are light weight compared to the conventional PEMs. They are suitable for adjustable speed pumps, fans and compressors, and crane and hoist systems.

New technologies for the so called “super premium” efficiency motors are still being developed, but one technology that is already in the market for motors up to 37 kW (50 HP) rating, is the copper rotor motor. Copper rotor motors substitute copper for aluminum in the “squirrel cage” structure of the motor rotor to increase motor efficiency by reducing copper losses in the rotor. That can account for 25% of total motor losses. Resistance and therefore heat losses are also reduced.

Another motor technology is switched reluctance (SR) motors. SR motors have a rotor that does not have magnets, rotor bars or windings. The rotor is a piece of shaped iron, and this design exploits the fact that forces from the magnetic field can be many times greater than those in current carrying conductors.

Like the PM motor, an SR drive system requires both a motor and an electronic power converter or controller to control torque and speed. SR motors are used in air conditioning compressors, laboratory centrifuges, and pumps used in reverse osmosis systems. The advantages of SR motors are ability to produce up to twice as much power as a conventional induction motor when compared on a size basis, simple design, rugged, lower manufacturing cost, ability to maintain high torque and flat system efficiency over a broad speed range, high starting torques and motor speeds, ability to withstand high temperatures with extremely high short-term overload capability, ability to be run forward or backward as a motor or generator, cool rotor. They are available in NEMA and IEC frames, and the SR motors with drives are available in the 30 HP to 335 HP size range with base speeds from 200 to 10,000 RPM or more depending on the application.

The disadvantages are ripple torque, high vibration levels, and acoustical noise as the motors require a conventional controller.

3.7. Lighting Systems

Lighting typically accounts for 10% or 20% of total power generation when using existing non-efficient lighting systems. Energy efficient lighting provides the same quality and illumination levels as regular lighting systems. Traditional incandescent lamps and high discharge lamps consume large amounts of electric power, but most of it is consumed as heat instead of light; for example, 90% of the power required produces heat in an incandescent lamp. Another disadvantage is their short life span which increases their cost due to maintenance.

Lighting power consumption can be reduced by selecting high efficiency fixtures and lighting control.

3.7.1. Light Emitting Diodes (LEDs)

LEDs are solid semiconductor devices; they produce little heat and higher quality lighting than any other lamp. They use 85% less energy and can last 8 to 20 times longer compared to traditional incandescent lamps.

LEDs are made up of semiconductor materials to form PN junctions; whenever current flows across these junctions, it releases energy in the form of light. The wavelength and hence the color of the light depends on the composition of the junction materials; therefore, LEDs can generate different colors. LED lamps are available in different shapes, styles, and sizes according to their application and can be dimmed and change colors.

3.7.2. Lighting Controls

The efficiency of the lighting system also incorporates proper lighting control that allows the operation of lamps whenever they are needed. These sensors detect the presence of people, motion or occupancy and based on the sensor output it turns the lights on or off. Types of these controls include automatic timers, infrared sensors, passive infrared (PIR) sensor and ultrasonic sensors and dimmers.

Photo sensors monitor daylight conditions and accordingly send signals to the main controller to turn the lights off at dawn and on ay dusk.

Lighting control can be as versatile as needed; it is an essential part of an efficient lighting system.

3.8. Electric Systems Summary

Table 4: Summary of Electrical Systems Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
IEPS	- Dynamic response - Built-in redundancy - Enhanced maneuverability - 360° steering - Less maintenance	- Complex systems integration	**Yes, Incorporated**	–
Hybrid Battery Storage	- Reduced fuel consumption - Added flexibility in power generation system	- Large footprint and weight for batteries and battery support systems	**Yes, Incorporated**	See Battery White Paper (Reference 12)
Generator Set Configuration				
Equally Sized	- Smaller quantity of engines and use of identical engines simplifies engine maintenance operations	- Inefficient loading of generators	**No**	–
Father-Son	- More flexibility in power loading - Gains in efficiency - Ability to use son generator as harbor generator	If provision of father-son configuration drives up generator quantity: - Longer maintenance operations - Greater machinery space footprint used	**Yes, Incorporated**	–
VFDs	- Better control of speed and torque - Reduction in power draw when operating at lower frequencies	- Heavy and bulky - Creates harmonics - Expensive	**Conditional, Incorporated**	Should only be used for applications with highly variable loading Required for PEM, PM, and SR motors
Premium Efficiency Motors	- Better efficiency than induction motors, especially when lightly loaded	- Heavier than regular induction motors	**Further Study**	Best suited for small motors with a normally light load Availability will be explored during the Detail Design phase during equipment selection

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Other Motor Technologies				
PM and SR Motors	- More efficient than PEMs - Lighter and smaller	- Expensive - Smaller market availability	**Further Study**	Best suited for motors above 50 HP that require high torque Availability will be explored during the Detail Design phase during equipment selection
Lighting Systems				
Light Emitting Diodes (LEDs)	- 85% more efficient - Smaller - More flexibility on color, dimming	- Requires a more complex control system	**Yes, Incorporated**	–
Lighting Controls	- Reduction of lighting power draw	- Additional required sensors and logic written into control system	**Yes**	Lighting controls will be implemented in the Detail Design Phase in the Lighting Plan and IMACS control schema

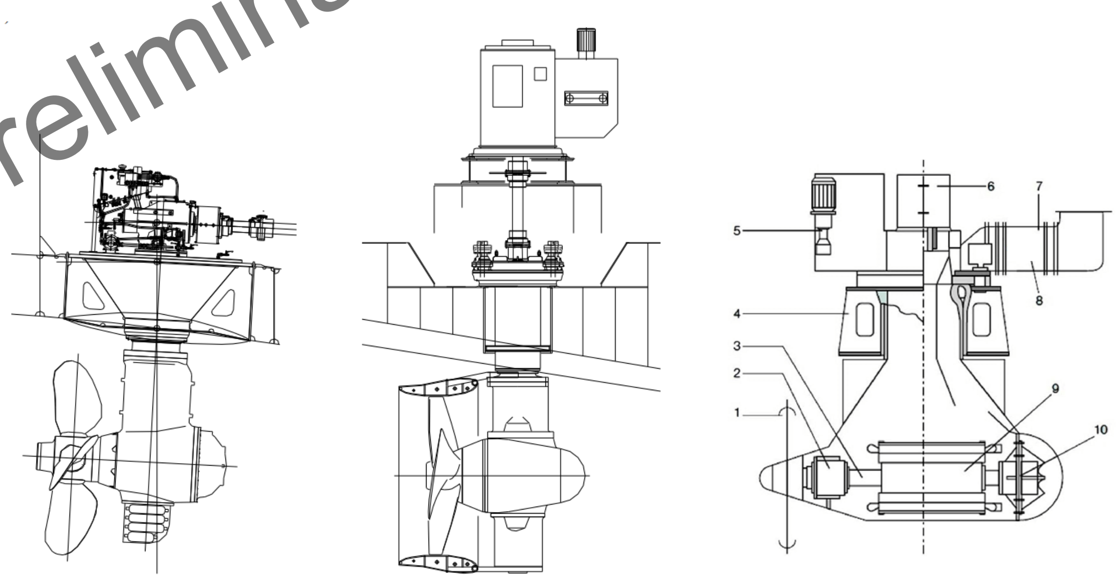
4. Propulsion Plant

4.1. Propulsor Selection

Per the ARV Performance Specification, Section 235.1, “The vessel shall be equipped with twin azimuthing propulsors.” Azimuthing propulsors have become the industry standard for icebreaking. The key design feature of azimuthing propulsors that contributes to their high operational capability is the directional freedom of the propulsors. As the units can be rotated about the vertical axis, full propulsion thrust can be vectored in any direction. This provides a significant increase in maneuverability when compared to a typical shaft line and rudder arrangement. Increased maneuverability in ice allows for quicker operations in ice. By combining steering and propulsion into one unit, azimuthing propulsors do not suffer the hydrodynamic losses seen when using a conventional shafted propeller and a rudder. The icebreaking mode has been identified as the mode of operation with the highest power consumption and thusly, highest fuel consumption. This indicates that propulsor efficiency in icebreaking should be a high priority of the propulsion system, while still optimizing non-icebreaking operations.

Azimuthing propulsion units are divided into two categories based on power transmission: azimuthing podded electric drives and azimuthing mechanical drives. Azimuthing podded electric drives are self-contained propulsion units consisting of an electric motor housed within the submerged portion of the unit. Azimuthing mechanical drives consist of a motor located within the ship that is connected to the propeller by a series of shafts and a gearbox system. Azimuthing mechanical drives are available in Z and L configurations. The compartmental nature of the azimuthing propulsors allows for reclamation of space typically occupied by long shaft lines and shaft alleys in a shafted-propeller arrangement. The three discussed propulsors are depicted in Figure 1 below.

Figure 1: Azimuthing Propulsor Configurations



From left to right: Z-Drive, L-Drive, and Podded configurations

4.1.1. Discussion

While mechanical drive azimuthing propulsors and podded electric drive azimuthing propulsors conform to the same principle of propulsion, podded propulsors boast better maneuverability in ice, higher power, and lower mechanical losses. Data provided by ABB lists a mechanical loss of only 0.5% for ABB Azipod® podded propulsors, while Wartsila estimates 4 to 5% mechanical losses for Z-drives and 2 to 3% losses for L-drives.

4.1.2. Underwater Radiated Noise (URN)

All azimuthing propulsors exhibit increased underwater radiated noise when compared to a conventional shafted propulsion system. This is primarily due to the location of noise generating equipment directly in the water, rather than within the hull of the vessel. While conventional shafted systems keep all equipment except the propeller out of the water, Z- or L-drives and Azipods locate gearboxes or the entire propulsion motor within the water, respectively.

Both Z- and L-drive propulsors require that a lower gearbox is located below the hull which is a significant source of noise and vibration within the water. Noise from the lower gearbox will be most prominent at gear-mesh frequencies which are determined by the propulsor rotation rate and number of teeth on each gear. Typically, these tones occur at frequencies between 250 Hz and 1,000 Hz but are unique to the ultimate gearing design of the propulsor.

Azipods typically have no gearing within the water, but instead relocate the propulsion motor from within the hull (on a conventional shafted or mechanical azimuthing propulsor system) to inside the pod, within the water. The Azipod therefore radiates noise directly into the water at frequencies which are related to the physical size and rotation rate of the motors along with details of the electrical signal from drive cabinets including at the switching frequencies.

For both types of azimuthing propulsor, the prominent tones are expected to occur below the lowest operating frequency for the selected sonar transducers which is typically between 2 kHz and 3.5 kHz for the sub-bottom profiler. While higher order harmonics for these machinery tones may enter this range, it is expected that the levels will be substantially reduced based on measured data for previously installations of each type.

All types of propulsors (including conventional shafted systems) will exhibit elevated underwater radiated noise at vessel speeds where the propeller is cavitating. At high vessel speeds, the propeller is expected to cavitate to some degree for each design and broadly, neither of the azimuthing propulsor types are inherently better than the other in this regard. Cavitation inception speed will be impacted by many factors including blade design, inflow conditions due to hull design, and hydrodynamic influence of the propulsor itself within this inflow.

This is discussed in additional detail within the Glosten Concept Design phase report, *Underwater Radiated Noise Requirements Study* (Reference 13). The study also discusses the selection of the underwater radiated noise requirements for the ARV, which included expected propulsion system, required maximum URN for proper sonar transducer operation at moderate vessel speeds, and use of the ABS UWN (T) notation as a baseline for a cruising speed URN transit limit. The purpose of the transit condition limit is to provide a reasonable limit for environmental purposes which is achievable given the chosen propulsion systems and goals of the vessel. The selected transit limit is generally similar to other limits which are designed for reducing impacts on marine mammals and other sea life such as the DNV Silent (E) notation.

A prediction of vessel noise against these criteria including impacts from the chosen azimuthing propulsors are provided within the Underwater Radiated Noise (URN) and Sonar Self-Noise (SSN) Report, 5E1-073-R201. Per the report, URN levels are only predicted to exceed the analysis criteria with the baseline vessel outfitting at frequencies controlled by the ABB Azipod frequency converter supply, which occur at 600 and 1500 Hz. ABB is able to reduce these tones significantly through modification to the frequency converter supply. Further work will be done in conjunction with ABB to ensure that sufficient reduction in these tones is achieved. There are currently no predicted URN excesses due to propeller cavitation.

4.2. Wind Power

The ARV will operate in areas with strong prevailing winds. This wind energy as a source of green energy is worthy of consideration for use on the ARV.

A market survey was conducted and three principal modes of utilizing wind energy on the vessel were identified. Below, these three modes of harnessing wind power will be described and the risks and opportunities of each system described.

4.2.1. Active Power Generation

The wind turbine is ubiquitous on land in high wind. Provision of an active power generation system onboard the ARV would produce some useable energy that could be added to the ARV's power plant. The electrical energy generated by such a wind turbine could with minimal modification tap into the ARV power plant and supplement the batteries and the generators for use in propulsion or ship loads. Wind turbines typically have a substantial operational envelope and are elevated on a pedestal with the generator at the center of rotation. In order to supplement a single genset, a turbine would need to be on the order of 90 m diameter with a supporting pedestal the order of 120 m. Placement of such a spar and system onboard the ARV is problematic in multiple ways. The added windage, added weight, and potential interference with science operations are all factors disqualifying such a horizontal axis wind turbine. Additionally, both vertical and horizontal axis wind turbines have motion limitations of less than 15 degrees of roll or pitch, preventing their installation on the ARV.

4.2.2. Staysail

Sails on masts have driven ships on the sea for millennia, given the abundance of wind energy in the ARV's operation area, it could possibly generate many tons of thrust with a sail plan when the wind is from the right direction. Permanently installed sailboat type masts present a risk to operations and renders the prospect unsuitable. However, one common type of sail utilizes a "mast of opportunity" and may be suitable for ARV with certain restrictions. Such a staysail is generally hoisted on a mast and tacked on deck. The existing cranes and existing threaded inserts on deck could allow nearly limitless configurations of staysails on the ARV. Such triangular sails are commonly attached to a mast of some sort and to the ship deck and supported by a taut wire between the two secure points. The third point of attachment could be nearly anywhere on main deck that did not interfere with operations.

Some of the disadvantages of such a staysail configuration for sail power are wind shadow, equipment usage, and safety. These will be large sails, but the house of the ARV is larger still. If the wind is from an importune angle relative to the course of the ship the staysail will not be very effective. The need to rig the sail to the deck cranes will render that crane unavailable for other operations. Finally, the staysail rigging will be under wind load, which may be unstable in the vicinity of the house. The potential for loading and unloading of the sail in proximity to ship's crew is seen as a potential safety concern. A staysail may be able to prove a point that the ARV can be sailed, but it will not serve as even a slightly reliable source of propulsion.

4.2.3. Kite

Most promising among the sailplans studied is kite power. Observing the launch of a kite surfer into the air illustrates the power that a kite can generate. Kite systems are currently in development that utilize larger versions of the aforementioned kites and promise to generate enough thrust to drive the ARV at 5 knots. Such a kite configuration places the line of fire to a single point on the ship, which could be made safe. In this way, the kite and it's rigging are far from the deck of the ship when loaded. This kite control system may be able be attached to the ship using foredeck ISO sockets, so it could be brought only on missions where useful. The kite system could keep the permanent changes to the ship to a minimum and could be removed if unneeded. However, launch and recovery of the system could become an issue, particularly if the kite should land in the water and control lines be shorn by the propulsors.

Kites currently on the market are geared towards ships making long ocean passages through the trade winds, utilizing routing software to guide the ship master to along the course most advantageous to the kite sailplan. The ARV will have a course dictated by concerns other than optimum sail angle and the ARV will not get the same utility as the ocean going liners.

Another utilization of kites is in small scale kite powered generators, where the sawing motion of the kites is turned into electrical power. It remains to be seen if this technology is in any way able to provide sufficient energy to propel or heat the ARV. There are likely other kite based systems not reviewed as it is a rapidly maturing market. It is clear that using such kites for propulsive power is a developing field, and creation of new capabilities are likely within the service life of the ARV. This topic could merit further study in the future kite-type products develop.

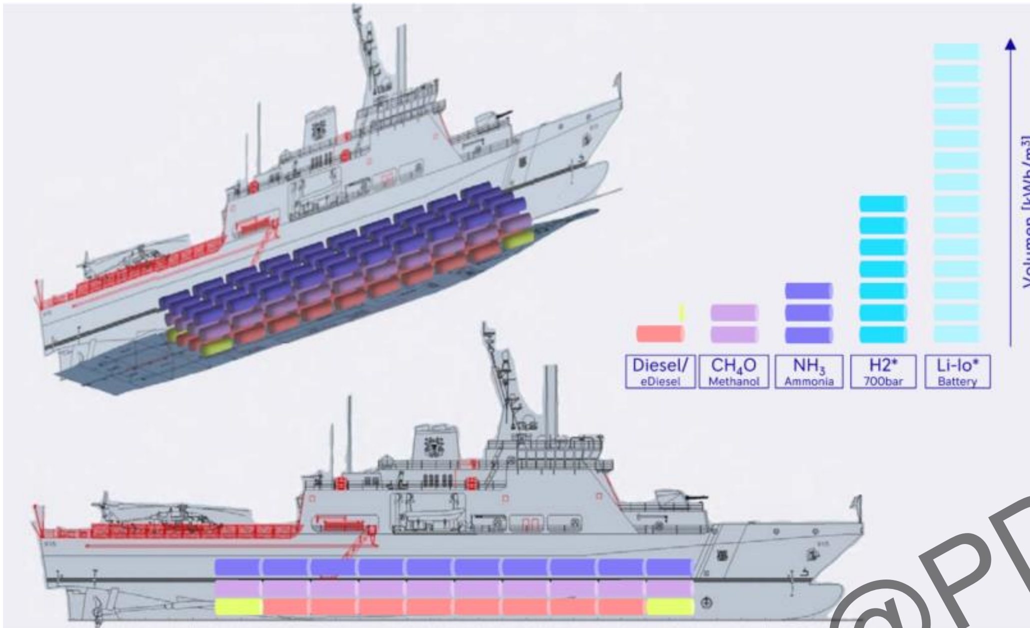
4.2.4. Discussion

Wind energy is abundant in the operational area of the ARV, and methods of harnessing wind energy continue to mature. All manner of sailing or wind generation hardware may be attached to the ARV, but none without compromise to the science mission. With the current state of sail technology, its incorporation into the ARV design is not recommended.

4.3. Alternative Fuels

Per the ARV Performance Specification, Section 070.2, the established mission range of the ARV is to be 90 days. The vessel will need to store the required endurance fuel capacity to meet this requirement. When looking for alternative fuels, key considerations include logistics (fuel availability / fuel change flexibility), fire safety, and combat compatibility. A study was completed to investigate the fuel storage needed for an offshore patrol vessel with an 18 MW (~4,000t) main engine the results can be visualized below in Figure 2.

Figure 2: Equivalent Fuel Storage Needs



In order to achieve the same degree of fuel endurance, the required increases in fuel storage for alternative fuels are listed below in Table 5. Each alternative fuel has its own drawbacks that will need to be improved before they are truly considered. The ARV is not recommended to utilize alternative fuels in its mission, as the drawbacks of the volume and weight requirements are insurmountable to meet the required mission range.

Table 5: Comparison of Alternative Fuel Types

Alternative Fuel Type	Planned Mission Time	Volume Factor	Requirement
Diesel Fuel	90 days	1x	–
eDiesel	90 days	1.1x	–
Methanol	90 days	2x	
Ammonia	90 days	3x	Cannot be located below waterline. Weight of ship would shift and lose stability.
H2	90 days	7x	
Lithium-Ion Batteries	90 days	17x	

4.3.1. Biodiesel

Of the alternative fuels listed above, biodiesel, or biofuel, referred to as eDiesel in Figure 2 and Table 5 above, can be considered to be one of the most technically ready options as it is a drop-in fuel that would not require extensive modifications to ship infrastructure. Biodiesel can be blended with Ultra-Low Sulfur Diesel (ULSD) to further reduce engine emissions. For example, on-road diesel is typically a 5% biodiesel, 95% ULSD blend. One complication with blending biodiesel is that biodiesel has a higher cloud point than ULSD, causing the blend to gel at higher temperatures than pure ULSD. At this time, bunkering availability in Punta Arenas has not been identified. With time, as ULSD-biodiesel blends becomes more commercially available for the marine sector, it is recommended that their chemical properties be examined to determine their impact on engine fuel consumption and if additional tank heating installations will be required should biodiesel be used.

4.3.2. Methanol and Hydrogen

Methanol is currently utilized on ships with both 2-stroke diesel-cycle engines and 4 stroke otto-cycle engines. Methanol is a liquid alternative that can be stored in an ordinary tank with some changes due to the low flashpoint. The use of methanol in fuel cells is heavily under development.

The current most prevalent system for converting hydrogen's chemical energy into electricity are fuel cells. Which includes the drawbacks of current fuel cell research; high investment prices, large volume, and weight challenges. Hydrogen itself is a volatile gas and special considerations must be paid to storing it on any ship.

4.3.3. Ammonia

Use of ammonia for internal combustion engines and fuel cells is being explored as an alternative fuel. Ammonia has the opportunity to develop into a zero-carbon fuel and provides early hope for complete elimination of carbon from the worldwide fleet with byproducts of nitrogen and water. The drawbacks of ammonia come with storing it. When stored in a cold environment, tanks must be constructed for temperature and/or pressure control due to ammonia continuously generating boil-off gas, which can increase the pressure in a sealed tank. While the benefits of ammonia are promising, the requirement for three times a given amount of diesel fuel is impractical for the ARV.

4.4. Propulsion Plant Summary

Table 6: Summary of Propulsion Plant Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Azimuthing Propulsors				
Mechanical Drive	- Carries all inherent benefits to azimuthing propulsor technology (directional freedom, high maneuverability) - Familiarity of use (used on Sikuliaq, Thompson, and Haakon) - URN: Electric motor located within hull (rather than underwater), reduces underwater noise from motor	- Higher mechanical losses - Additional space required in the fore-aft direction for shafting arrangement - URN: Significant tones at gear-mesh frequencies	**No**	–
Podded Electric Drive	- Proven PC3 capability - Higher power output for similar size propulsor - Lower mechanical losses - Better reliability - URN: no gears, no mesh tones	- Low market availability for ice-capable podded propulsors; expensive - URN: additional noise from motor located in the water, including electrical switching frequencies	**Yes, Incorporated**	–
Wind Power				
Active Power Generation	- Able to provide energy suitable for ships service power - Energy production regardless of relative wind angle - Mature technology	- Permanent installation - Interference with science operations - Significant cost to center of gravity and windage, compromising stability	**No**	–

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Staysail	- Mature technology - May be deployed only when useful and may otherwise be stowed	- Effectiveness highly dependent on wind direction - Effectiveness diminished by house structure - Would place lines of load in proximity to crew working areas - Dependent on wind speed and angle	**No**	A staysail rig is very low cost and could indeed propel the ARV in some circumstances. As a proof of concept this could be tenable, but it is unlikely a staysail arrangement will ever be configured that would provide reliable propulsion to the ARV without compromising science mission.
Kite	- Single line of load may be restricted from crew working in proximity - Potential to generate electricity or provide thrust to ship - May be deployed only when useful and may otherwise be stowed - Potential to generate substantial thrust	- Developing technology - Risk of malfunction and loss of kite - Dependent on wind speed and angle	**No**	–
Alternative Fuels				
Biodiesel	- More environmentally friendly than pure diesel fuel	- Comparably less bunkering availability - Chemical properties could require heating fuel tank	**Further Study**	In the future, should bunkering become available, biodiesel could be used as a drop-in fuel. Should heating of fuel tanks be required, use of biodiesel is not recommended as tank heating would be accomplished using the oil-fired heater which would lead to higher fuel consumption of oil-fired heater.
Methanol and Hydrogen	- More environmentally friendly than pure diesel fuel	- Comparably less bunkering availability - Increases required fuel storage to an unsustainable point	**No**	–

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Ammonia	- More environmentally friendly than pure diesel fuel	- Comparably less bunkering availability - Increases required fuel storage to an unsustainable point	**No**	–

5. Auxiliary Systems and Equipment

5.1. Heating, Ventilation, and Air Conditioning (HVAC) Systems

Per the ARV Performance Specification, Section 512.1, "The design of the HVAC system on the ARV shall maximize both energy efficiency and comfort while maintaining reasonable reliability standards." Cooling of air onboard the ARV will be provided by the Chilled Water System using air conditioning plants. Heating of air will be provided by a combination of electrical heating and hydronic heating provided by a combination of the oil-fired water heater and economizers. Air conditioning plants and oil-fired water heaters are known drivers of space and weight onboard vessels that utilize hydronic heating systems. As such, decreasing their required capacity leads to a lighter ship and, in turn, lowers overall fuel consumption. In the case of the oil-fired heater, a decrease in system capacity has a direct and immediate impact on fuel consumption. Similarly, lower electric demand from consumers of electric heating places a lower load on ship service generators and results in a decrease in fuel consumption and exhaust emissions.

With a Polar Service Temperature (PST) of -49°F, the hydronic heating and electric heating demands onboard the ARV will be significantly higher than those of typical ships in non-low-temperature environments. Lowering heating demands is a priority of the HVAC design. This may be accomplished through careful system arrangement and implementation of HVAC technologies aimed at increasing system efficiency as detailed below.

5.1.1. Centralized and Decentralized HVAC Systems

Per Reference the ARV Performance Specification, Section 512.1, "Decentralized HVAC systems which condition air locally, separate from outside supply air and exhaust systems shall be evaluated as a means of improving efficiency and reducing space in overheads for ducting, etc."

Areas onboard the ARV with compartments that share similar HVAC design temperatures, such as berthing areas, may be treated as an HVAC 'zone'. Within this zone, these compartments may make use of a centralized or decentralized system. A typical centralized system would consist of a built-up system, consisting of a filter, cooling coil, fan, and re-heater, oftentimes packaged as an Air Handling Unit (AHU), that distributes air, taken from the weather, which has been treated to a certain degree by the AHU, to the compartments. Supply terminals to the spaces are then provided with reheaters to heat the air to the desired temperature of the space. Replenishment air from the weather is provided to the AHU to ensure proper air quality of the air circulated by the AHU. A separate exhaust system is used to exhaust air from the washrooms directly to the weather. In this arrangement, air must be naturally exhausted from the space to the Passage, with a return terminal to the AHU in the Passage to balance the supply and return of the AHU.

Conversely, a decentralized system may be used for these spaces. In this arrangement, replenishment air from the weather is provided directly to the spaces by a central ventilation supply fan. Fan coil units (FCUs) within the space treat and circulate the air in the space. A separate exhaust system is used to exhaust air from the washrooms directly to the weather. Examples are provided in Figure 3 and Figure 4 below depicting these arrangements.

Figure 3: Centralized HVAC System

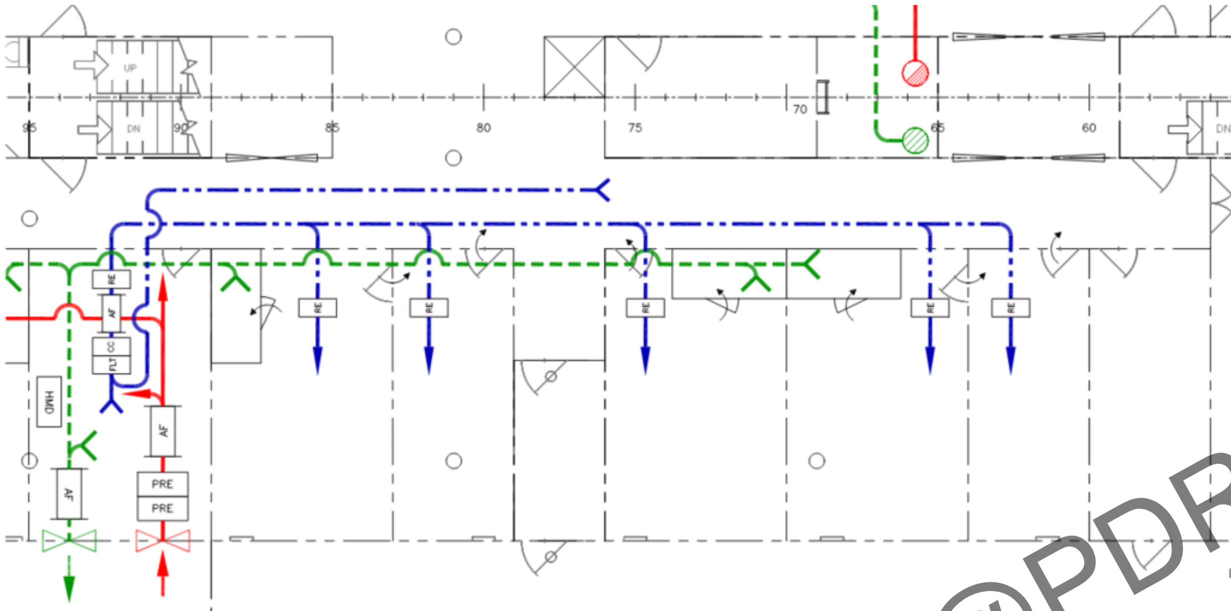
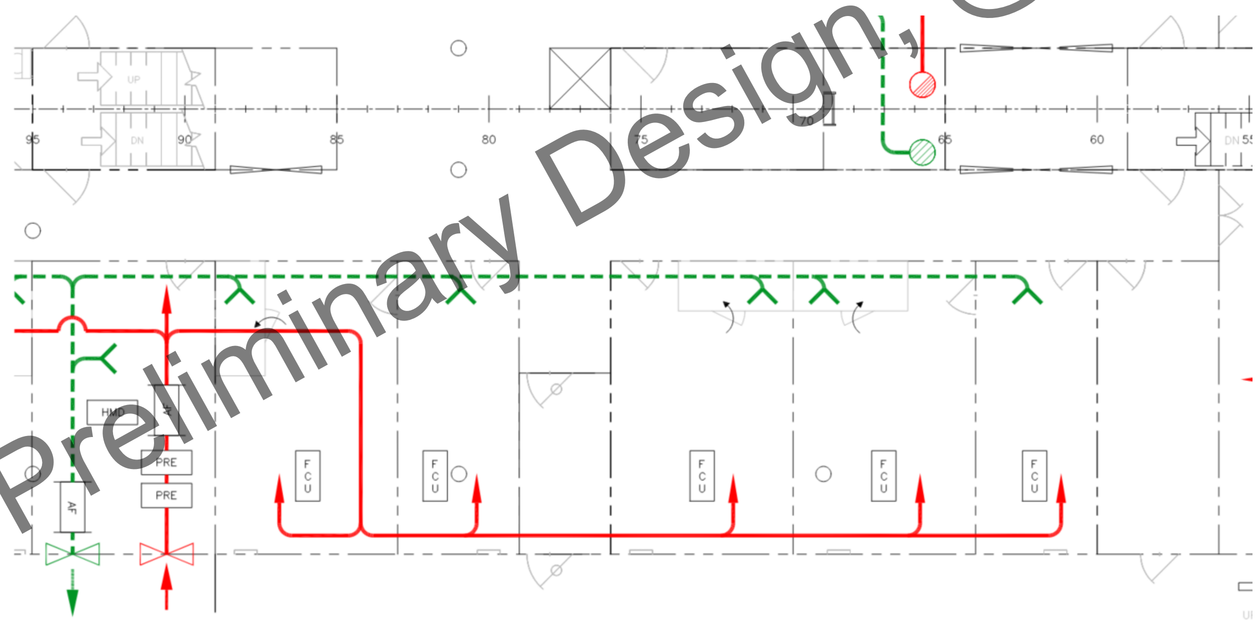


Figure 4: Decentralized HVAC System



Both configurations will allow for individual space heat control. The decentralized system will allow for individual space cooling control. Coupled with a variable primary flow Chilled Water System, the decentralized system allows for cooling to be carried out based on individual space cooling loads at any given time rather than providing a blanket amount of maximum cooling to all accommodation spaces as is done in a centralized system.

A drawback to the centralized configuration is that it requires more distributive duct work as supply, exhaust, and return ductwork all have to be provided, adding weight and cluttering the overhead. This is leveled against the architecture of a decentralized system, which requires a high number of individual fan coil units, which will produce some noise and require individual maintenance. Noise, however, may also be a concern for the centralized system as the natural exhaust from the space to the Passage will require an undercut door or bulkhead opening with wiremesh to facilitate the natural flow of air. This creates a pathway for Passage noise to disrupt the staterooms.

An additional drawback to the centralized system of particular importance at this time is that recirculation of air between habitability spaces creates a significantly higher potential for the transmission of airborne pathogens.

For these reasons, a decentralized HVAC system is recommended for accommodation space areas onboard the ARV at this time. Upon calculation of individual space cooling and heating loads in the Detail Design phase, the selection of the HVAC system architecture will be re-evaluated to determine which solution is more energy efficient.

5.1.2. Variable Frequency Drives (VFDs)

Per the ARV Performance Specification, Section 512.1, "temperature and pressure sensors on air systems to optimize airflow through variable speed fans or variable air volume terminals" shall be evaluated for use on the ARV.

VFDs are commonly used in commercial HVAC systems. VFDs control the speed of 3-phase motors. There are many benefits to be realized with the use of VFDs, including:

1. Conservation of power by reducing the fan speed when full fan capacity is not needed,
2. Reduction in operation cost, and
3. Reduction in the heating load by lowering the fan's speed and reducing the amount of cold air entering being introduced in the heating season.

While these benefits can be achieved with the provision of two-speed fans, which typically operate at full and half speed or full speed and 2/3 speed, VFD-controlled fans allow significantly higher power savings. As fan motor power has an exponential relationship with fan speed, a two-speed fan operating at 50% speed consumes only one-eighth (1/8) of the power it requires at full speed. VFDs can further reduce the motor speed to a level as low as 20 to 25% of the full speed. A fan driven by a VFD and operating at one-fourth (1/4) speed consumes less than 2% of its power at full speed.

For example, consider the lower level of a Main Machinery Space with design temperatures of 120°F in the cooling season and 40°F in the heating season with a supply fan sized at 23000 CFM. The supply fan has been sized to maintain the space at 120°F in the cooling season with 100°F supply air from the weather. In the heating season, when cooling demand is no longer applicable, the fan may be run at low speed. This scenario is analyzed to determine the required preheating demand in the heating season with the fan running at full-speed, half-speed, and 30% rated speed. Single speed fans are not typically used for Machinery Spaces but have been analyzed to illustrate the benefits of using VFDs for spaces requiring large quantities of ventilation air. The analysis was performed based on a weather air temperature of -49°F and space equipment load of -300000 BTU/H. Results are detailed in Table 7.

Table 7: HVAC VFD Analysis

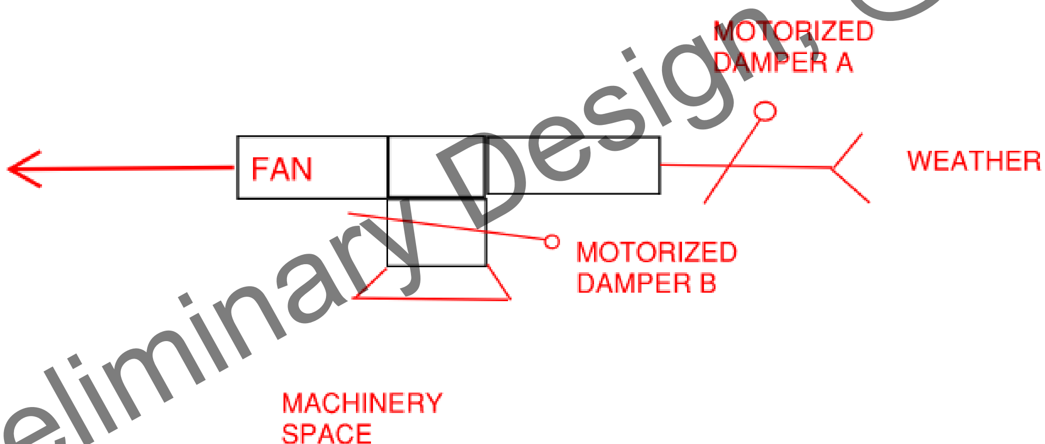
Fan Type	Air Quantity (CFM)	Preheating Demand (kW)
Single-speed	23000	662
Two-speed	11500	290
VFD-controlled (25%)	5750	100

In this scenario, use of VFD results in an 85% reduction in preheating demand when compared to full-speed operation and a 66% decrease when compared to a two-speed fan.

Pressure and temperature sensors may be provided in spaces served by VFD-controlled supply and exhaust fans to provide input to the Machinery Control System to control the fans. This control schema will allow the fans to automatically maintain space temperatures and balance space pressure.

Additionally, VFDs may be used in a ventilation supply recirculation system. Figure 5 depicts a ventilation recirculation system that may be installed in a Machinery Space to limit the amount of cold weather air entering the space in the heating season.

Figure 5: Ventilation Recirculation System



In the heating season, as the outside air starts dropping, Damper A starts closing while Damper B starts opening. This reduces the amount of outside air coming into the Machinery Space while warm air from the space is recirculated back into the space. The return air mixes with the outside cold air to preheat the weather air.

As the HVAC system is designed for the ARV, expected operational conditions of fans will be evaluated to determine if VFD control would provide a meaningful amount of energy savings. It is recommended that spaces such as Main Machinery Spaces, whose fans are sized primarily for the cooling season, utilize VFD control. The decision between single-speed, multi-speed and VFD-controlled fans are dependent on the specific size requirements of each HVAC system. Fan sizing shall be determined through detailed heating and cooling load calculations during the Detail Design phase.

5.1.3. Air to Air Heat Exchangers

Per the ARV Performance Specification, Section 512.1, "Air to air heat exchangers shall be evaluated by the designer as a means of reducing energy loss by extracting heat from exhaust air for preheating supply air."

Air to air heat exchangers bring two air streams of different temperatures into contact, transferring heat from the exhaust air to the incoming supply air from the weather. In accordance with the ARV Performance Specification, Section 044.4.3, the design minimum outdoor air temperature is -49°F.

Exhaust air temperature would need to be maximized to achieve noticeable heating of incoming air. The highest temperature exhaust air will be the engine exhaust. As detailed in Section 5.2.1 below, economizers will be located in the stack to recover waste heat from engine exhaust air. The low availability of hot exhaust air as well as the added space and weight required for air-to-air heat exchangers make this solution undesirable for the purpose of preheating.

For example, the largest capacity heat exchanger from one manufacturer is able to provide 40 watts/°F. A supply air quantity of 3000 CFM would require more than 100 kW to raise its temperature from -49°F to 40°F. If this air were to pass through an air-to-air heat exchanger whose second input was 65°F exhaust air, the exhaust air would only provide 4.6 kW of heat.

Additionally, provision of non-redundant air-to-air heat exchangers creates a single point of failure in the heating system. For these reasons, air to air heat exchangers are not recommended for the ARV.

5.1.4. Heat Pumps

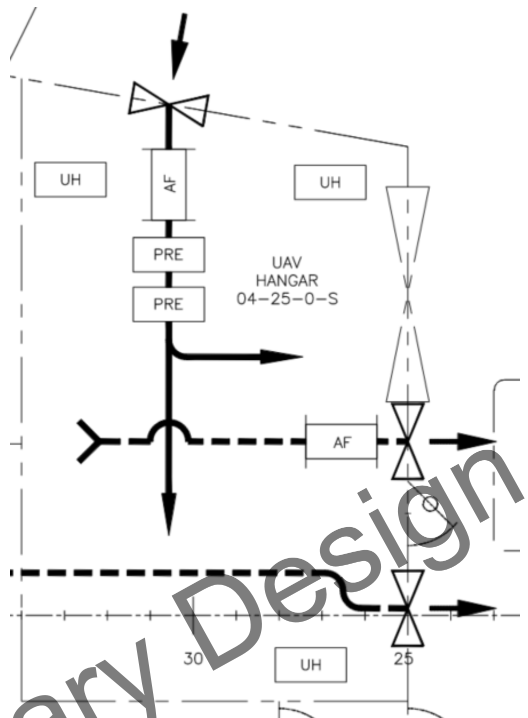
Per the ARV Performance Specification, Section 512.1, "Heat pumps should be evaluated as a means of reducing energy use by utilizing available sources of low temperature waste heat." Heat pumps redistribute heat from the air or water using a refrigerant that circulates between the heating consumer (such as an air handler) and a compressor to transfer the heat. The use of heat pumps to transfer heat between two interior spaces would require a space having excess heat capacity in the heating season. In the heating season, where ventilated spaces are only maintained at 40 to 50°F and most air-conditioned spaces must be heated to achieve space design temperatures, a space with excess heat capacity has not been identified. Because of this, the anticipated output of a heat pump system onboard the ARV would not be expected to have a large enough impact on the overall heating demand of the ship to make its implementation worthwhile. Additionally, with the existing provision of an oil-fired heater, installation of additional heating systems without redundancy would create single points of failure in the heating system. A heat pump system is not recommended for the ARV.

5.1.5. Advanced HVAC Control Systems

Advanced control systems allow passive monitoring of space conditions to allow HVAC equipment to cycle down when full capacity is not required. The first example would be the control system required to carry out the Engine Room recirculation proposed in Section 5.1.2. This concept, which has been integrated into the ARV HVAC design, will require temperature input via temperature sensors and control logic to balance the recirculated and fresh air through the degree to which the dampers are opened and closed.

Sensing the incoming weather air temperature will be of particular importance. As shown in Figure 6 below, mechanical supply systems drawing air from the weather are fitted with two stages preheating. This arrangement will require both preheaters to be energized in the coldest conditions. But in milder conditions, one of the preheaters can be secured, minimizing the electric heating load. Energizing and de-energizing of these units will be automatically handled by the control system.

Figure 6: HVAC Two-Stage Preheating



The Chilled Water System will also require a more advanced control system to enable to system to fully benefit from the provision of VFD-controlled chilled water circulating pumps. The Chilled Water System is designed to be a variable primary flow system. In this design, three-way modulating valves aren't needed to balance the chilled water demands. In a variable primary flow system, two-way flow regulating valves are utilized. These valves create the backpressure in the system that is needed to create the differential pressure required to inform the operation of the VFD-operated chilled water circulating pumps.

Thermostatic control of the chilled water plant can also be used in conjunction with a chilled water to seawater heat exchanger to secure and bypass the chiller during cold water operations where the air-conditioning load is limited. In cold water operations, the chilled water would bypass the chiller and be chilled by the seawater to chilled water heat exchanger. Potential for this installation will depend on the equipment selection of the chiller and expected chiller loads during ship operation when seawater is at a temperature favorable to cool the chilled water to its required low temperature.

5.1.6. Environmentally Friendly Refrigerants

Refrigerants will be required on the ARV for air conditioning, refrigeration and freezer storage, and scientific laboratory equipment. MARPOL 73/78 Annex VI, *Regulations for the Prevention of Air Pollution from Ships*, (Reference 14) prohibits deliberate emissions of ozone depleting substances (ODS) in Regulation 12. The list of prohibited ODS is drawn from the Montreal Protocol and contains chlorofluorocarbons (CFCs) and halons used in older refrigeration systems, as well as hydrochlorofluorocarbons (HCFCs). Per Regulation 12, new installations containing HCFCs were only permitted until 1 January 2020. In order to receive ABS ENVIRO notation, the use of ozone depleting refrigerants are prohibited.

Hydrofluorocarbons (HFCs) became popular in the 1990s as a replacement for ODS. Though HFCs are not classified as ODS, they are greenhouse gases with high global warming potential (GWP). In order to receive ABS ENVIRO+ notation, the use of refrigerants with a GWP greater than 2000 are prohibited. The American Innovation and Manufacturing (AIM) Act of 2020 (Reference 15) was enacted in December of 2020 to address HFCs. It directs the EPA to phase down production and consumption of 18 listed HFCs by 85% over 15 years and facilitate the transition to the next generation of refrigerants technologies. The AIM Act signals a recent shift in the public consideration of HFC use. Several states have implemented GWP limits for new refrigeration and air-conditioning equipment. Mostly recently, the US has ratified the 2016 Kigali Amendment to the Montreal Protocol, which phases down production and consumption of HFCs by 85% over 17 years (Reference 16). With this onset of HFC phasedown, the refrigerant market should be followed closely as more environmentally friendly refrigerants become commercially available.

The EPA maintains a list of acceptable refrigerants for use, organized by sector and end user (chillers, refrigeration units, etc.), under its *Significant New Alternatives Policy* (SNAP) program (Reference 17). It is recommended that refrigerants onboard the ARV be listed as acceptable under the EPA's SNAP program.

Additionally, refrigerant-consuming equipment selections may consider standardization of refrigerant type. Provision of one common refrigerant type would simplify refrigerant storage and disposal.

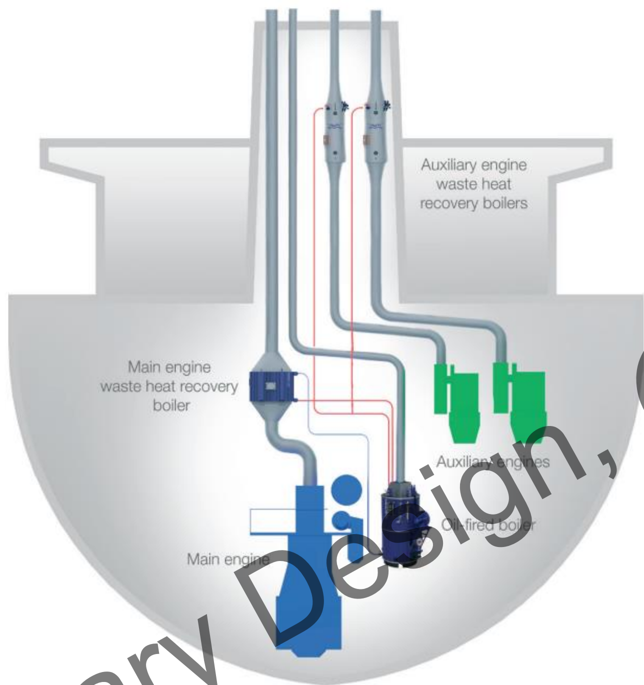
5.2. Waste Heat Recovery

Waste Heat Recovery is discussed throughout the ARV Performance Specification as a beneficial technology to be implemented onboard the ARV. Per the ARV Performance Specification, Section 517, "A heating system shall capture waste heat from the main diesel generators as the primary source of heat and use a diesel oil fired hot water heater(s) as the secondary or supplementary heat source or when the vessel is in port and in zero-emission operation." A 2019 joint study on marine diesel engine efficiency showed that about 25% of the total energy of a diesel engine is lost through exhaust heat (Reference 18). This constitutes the largest energy loss for diesel engines. Additional heat is lost to the cooling water system serving the engines. This waste heat can be recaptured using heat exchangers to provide hot water service to a hydronic (hot water) heating system, augmenting the system's output. Per the Waste Heat Recovery System and Hot Water Heating System diagram, 5E1-517-D001 (Reference 19), the hydronic heating system is currently being used for combustion air intake heating, ventilation pre-heating, compartment heating, tank heating, and potable water heating.

5.2.1. Economizers

ARV Performance Specification, Section 517 states that waste heat may be taken from the combustion exhaust. In low temperature environments, this exhaust is a valuable source of heat. Exhaust heat can be recovered and used to reduce the load on the oil-fired heaters serving the hydronic system to minimize heater fuel consumption. Economizers, exhaust gas heat exchangers located in the path of the engine exhaust, will be utilized for waste heat recovery of the exhaust system. Economizer sizing is dependent on both space available and output of the diesel engines. An example of the integration of waste heat economizers into a hydronic heating system is depicted in Figure 7 below.

Figure 7: Waste Heat Recovery via Exhaust Gas Economizers



Provided by Alfa Laval (Reference 20)

It is recommended that exhaust gas economizers be used onboard the ARV.

5.2.2. Jacket Water Recirculation

Per the ARV Performance Specification, Section 310, “Main generators sets shall be configured for recovery of waste heat from the jacket water to provide heat to the hot water heating system”. Similarly to the integration of economizers into the hydronic heating system, jacket water recirculation will serve to decrease the load on the oil-fired heaters. For most diesel engines, return temperature of high-temperature cooling water from engines is typically around 180°F or higher. This heat could efficiently be captured via heat exchangers to supplement the hydronic heating system capacity.

Additionally, the warm seawater return from the Jacket Water heat exchanger can be routed to the sea chests to keep the sea chests ice-free.

It is recommended that jacket water recirculation be utilized to supplement the hydronic heating system. Per the Waste Heat Recovery System and Hot Water Heating System diagram, 5E1-517-D001, jacket water recirculation is used to supplement the hydronic heating system. Per the Seawater Service System diagram, 5E1-520-D001, seawater return from heat exchangers is discharged to the sea chests to provide warm water to the sea chests to facilitate melting of accumulated ice

5.3. Low-Flow Water Consumers

Provision of water-efficient appliances and fixtures can reduce both freshwater demand and required capacity of wastewater systems serving freshwater consumers. Reducing the freshwater demand of certain services reduces how often the freshwater generation plants must be run to produce the required freshwater demand, allowing some energy savings.

An item of particular note for reducing the environmental footprint of the ARV would be the reduction in the wastewater produced by the described freshwater consumers. While the provision of low-flow water consumers should not drive a decrease in designed holding capacity or wastewater treatment plant size, it will ultimately decrease the frequency at which wastewater plants are run and will ultimately reduce wastewater discharge.

Low-flow shower heads, laundry washers, and dishwashers are commonly used in the cruise ship industry, making them commercially available for shipboard installation. It is recommended that these technologies be evaluated during Detail Design when specific equipment selections are made.

5.4. Fire Suppression Systems

Several options exist for fixed fire suppression in machinery spaces, including water mist, carbon dioxide (CO_2), inert gas (e.g. Inergen, i3), and chemical agents (e.g. FM-200TM, 3M Novec 1230TM). Each of these systems was evaluated for effectiveness, environmental impact, cost, size, and safety. The outcome of this analysis was used to determine which fire suppression system would be most suitable for the ARV.

5.4.1. 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 ozone depletion potential. Table 8 shows the two most common 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 Physical Science Basis (2013), than the FM-200 systems.

Table 8: Common Clean Agent Fire Suppression Systems

System	Operation	Ozone Depletion Potential	CO_2 Equivalence	Atmospheric Lifetime (years)
FM-200	- Stored as a liquid, vaporizes on discharge - Absorbs heat to extinguish	0	3350 lbs	0.019
Novec 1230	- Stored as a liquid, vaporizes on discharge - Displaces oxygen to extinguish	0	<1 lb	38.9

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 to clean agents 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 global warming potential (GWP) of one. 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 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 takes more space than CO_2, and roughly the same as FM-200. It is slightly higher cost than FM-200 and higher still than CO_2.

5.4.2. Water Mist

Water mist (e.g., HI-FOG by Marioff) systems generate a very fine fog, which removes heat through evaporation and prevents radiative heat transfer. The water mist fog is safe to breathe after discharge (non-lethal) and is safe for equipment, as reported by manufacturers. Installation requires a high-pressure pump skid, piping, controls, and a fresh water storage tank. Regulations require that a 20-minute of supply volume be stored in this tank. After the fresh water from this tank is exhausted, seawater can be used to supply the system as necessary. Unlike the passive, chemical agent fire suppression systems discussed previously, the water mist system requires power with which to drive the pumps. Water mist is inherently the most environmentally friendly fire suppression technology as it does not use any chemical agents. Water mist can be used for small or large spaces and multiple spaces can be served by a single pump skid. Where lithium-ion batteries are included in the ARV, water mist is the preferred solution. It is also advantageous from a design perspective for water mist to serve compartments that are closely co-located.

5.4.3. Discussion

Table 8 provides a summary of fire suppression technology recommendations. Both Novec 1230 and water mist are well-suited for the ARV. Both technologies are more environmentally friendly than similar alternatives. Per the ARV Performance Specifications, water mist was chosen as the fire suppression system for the Battery Room and local application over diesel engines and oil fired heaters. Novec was chosen for the Emergency Generator Room, UAV Hangar, Garbage Treatment Room, Science HAZMAT Locker, AUV Hangar, Paint Locker, Thruster Room, Bow Thruster Room, and Main Engine Room.

5.5. Auxiliary Systems Summary

Table 9: Summary of Auxiliary System Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
HVAC				
Centralized HVAC	- Potential for a lower replenishment air quantity could decreases required heating load - Individual space heating control	- More distributive ductwork required, added weight - Air is recirculated from one space to another; potential for greater transmission of airborne pathogens - Inefficient cooling of spaces	**Further Study**	Upon calculation of individual space cooling and heating loads in the Detail Design phase, the selection of the HVAC system architecture will be re-evaluated to determine if decentralized is the most energy efficient architecture as expected.
Decentralized HVAC	- Higher amount of fresh weather air delivered to each space allowing for a quicker rate of change in the space - Air is only recirculated within space - Individual space heating and cooling control - Less distributive ductwork, lower system weight and less crowding of overhead	- Locating recirculation system within space necessitates additional noise mitigations	**Yes, Incorporated**	–
VFDs	- Energy savings for both reduction in fan power draw and reduction in preheating load	- Harmonic distortions - Electromagnetic interferences	**Yes**	Should only be used for applications with highly variable loading Potential application will be explored in the Detail Design Phase when all fans have been sized
Air to Air Heat Exchangers	- Passive heating requiring no additional power draw	- Heat outputs of units are too low for the high heating demands of the ARV	**No**	–
Heat Pumps	-More energy efficient than electric heating	- Requires a reliable heat source that has not been identified on the ARV	**No**	–

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Advanced HVAC Control Systems	- Allows HVAC systems to cycle down, putting less load on the generators	- More sensors within system provide more points of failure	**Yes**	These controls will be implemented in the Detail Design Phase in the HVAC System and IMACS control schema
Environmentally Friendly Refrigerants	- Reduced global warming potential	- Less commercial availability; higher cost	**Yes**	Environmentally Friendly Refrigerants will be explored in the Detail Design Phase during equipment selection of chillers and refrigeration plants
Waste Heat Recovery	- Reduced fuel consumption - Built in redundancy for	- Highly distributive piping, mitigations need to be put in place for thermal expansion of system - Busy stack when couples with exhaust aftertreatment equipment	**Yes, Incorporated**	–
Low-Flow Water Consumers	- Reduces wastewater discharges - Decreased load on Potable Water Generators and Sewage Treatment Plant	- Market availability is lower for low-flow marine-rated water consuming equipment; more expensive than less water-efficient equivalents	**Yes**	Low-flow consumers will be explored in the Detail Design Phase during equipment selection.
Fire Suppression Systems				
FM-200	-Slightly more efficient on agent volume - Zero ozone depletion potential	- Higher global warming potential - Subject to phasedowns - Requires dedicated space for cylinder storage, cylinders must be located near protected area	**No**	–
Novec 1230	- Reduced global warming potential - Zero ozone depletion potential	- Requires dedicated space for cylinder storage, cylinders must be located near protected area	**Yes, Incorporated**	–
Water Mist	- Zero global warming potential - Zero ozone depletion potential	- Does not extinguish as fast as clean agents - Can cause damage to sensitive electronics	**Yes, Incorporated**	–

6. Pollution Control Systems

6.1. General Environmental Regulations

The anticipated mission area of the ARV will necessitate adherence to several environmental regulations. Major international and federal regulations that will bound the ARV pollution control systems are referenced in Table 10 below.

Table 10: ARV Environmental Regulations

Title	Regulation Application
IMO Polar Code	Oily Water and Waste Oil, Ballast Water, Sewage, Solid Wastes
MARPOL 73/78	Oily Water and Waste Oil, Ballast Water, Sewage, Solid Wastes, Emissions
IMO Resolution MEPC.227(64)	Sewage
IMO BWM Convention	Ballast Water
Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol)	Oily Water and Waste Oil, Sewage, Solid Wastes, "domestic liquid wastes", Incinerators
33 CFR Subchapter O	Oily Water and Waste Oil, Ballast Water, Sewage, Solid Wastes
40 CFR 1042	Emissions
EPA Vessel General Permit (VGP)	All discharges incidental to the normal operation of the vessel

Requirements within these documents often overlap, such as portions of 33 CFR Subchapter O (Reference 21), which implement regulations of MARPOL 73/78 (Reference 14). Pollution control systems will be designed to meet the regulations of Table 10 for protection of the Antarctic environment and its dependent and associated ecosystems.

MARPOL 73/78 designates "Special Areas" that require more stringent levels of environmental protection under certain Annexes. Special Areas are designated as such due to their oceanographical and ecological conditions, which necessitate special mandatory pollution prevention methods in order to preserve. The Antarctic area is considered a Special Area under Annexes I, II, and V.

The VGP levies predominantly operational requirements. Vessel design requirements for compliance with the VGP are incorporated into 33 CFR and 46 CFR, which the ARV will be designed to meet. By meeting the current system specification, 33 CFR 151, 33 CFR 155, and 46 CFR 162.060, the ARV design meets all equipment related design requirements of the VGP.

Discharges to water shall meet the above regulations. Additionally, to suit the unique mission of the ARV, arrangement and control of overboard discharges shall ensure that underway science surface water sampling systems are not impacted by waste discharges.

6.2. Oily Water and Waste Oil

Prevention of discharge of oil into water is an essential function for an environmental design. Per the ARV Performance Specification, Section 592.1, waste oil tanks shall be provided onboard the ARV with sufficient capacity to hold all waste oil for the full endurance of the vessel. Per

Section 593.2, “An approved oily water separator shall be provided with a minimum separation efficiency of 5 parts per million of oil.”

6.2.1. Environmental Regulations

The IMO Polar Code (Reference 22) only prohibits the discharge of oil and oily mixtures in Arctic waters. Under MARPOL Annex I, Regulation 14, the discharge of oily water mixtures is permitted outside of Special Areas provided:

- the ship is discharging *en-route*;
- the oily mixture is processed through oil filtering equipment meeting requirements of Annex IV, Regulation 14; and
- the oil content does not exceed 15 parts per million (ppm).

Federal regulations contained in 33 CFR 151.10 (Reference 21) enforce these regulations with the added stipulation that discharge must be more than 12 nautical miles (nm) from the nearest land. MARPOL Annex I, Regulation 14, as enforced by 33 CFR 151.13, further prohibits any discharge of oily mixtures in the Antarctic area. The VGP also requires that bilgewater discharges comply with 33 CFR 151.13.

The Madrid Protocol (Reference 23) also prohibits oil and oily mixture discharges in the Antarctic Treaty area. It requires that ships retain all oil and oily mixtures on board for discharge outside of the Antarctic Treaty area, at reception facilities, or as permitted by MARPOL Annex I.

6.2.2. Discussion

6.2.2.1. Treatment

The provision of an oily water separator with a minimum separation efficiency of 5 ppm of oil exceeds the environmental regulations for the areas in which the ARV will operate. A reduction in allowed oil content from 15 ppm to 5 ppm is in line with existing guidance and green ship classification requirements for ship bilge and oily water systems. Canadian Regulations for the Prevention of Pollution from Ships and for Dangerous Chemicals requires 5 ppm bilge alarms for operation on the Great Lakes. In order to receive the Clean(Design) class notation from Det Norske Veritas (DNV), certification must be held confirming that oily water separator discharge does not exceed 5 ppm. The ABS ENVIRO+ notation and Lloyd’s Register Clean Shipping Index verification service also include the 5-ppm discharge standard. Though exceeding current regulations, this requirement aligns with the objective of building a green ship. Separators meeting the 5 ppm separation efficiency are currently commercially available and are recommended for the ARV. Additionally, an incinerator will be provided to burn waste oil.

6.2.2.2. Environmentally Acceptable Lubricants

In November 2011, the United States EPA released the document, *Environmentally Acceptable Lubricants* (Reference 24), setting the scene for the field of environmentally acceptable lubricants (EALs). This document describes the range of EALs, defined by their biodegradation, low toxicity to the marine environment, and low likelihood of bioaccumulation in marine organisms. Adherence to this documentation was required in 2013 to receive a Vessel General Permit, ensuring that EALs are used for any exposed system installed below the waterline and suggests that the use of EALs be expanded to systems installed on deck. The use of EALs will be incorporated into the design where deemed technically feasible and practical for the ARV, although this regulation is only required for vessels operating in the United States. Each type of EAL has different drawbacks. Manufacturer of lube oil-consuming equipment should be engaged to determine the most suitable type of EAL for each application.

6.2.2.3. Oil Leak Prevention

Several mitigations are put in place to prevent leakage of oil onboard the ARV. Drip pans are fitted throughout the ARV at all potential sources of waste oil to be collected and stored in the OWS Sludge Tank. Vents and overflows for fuel oil tanks are located and arranged so that a broken pipe will not lead to the risk of oil discharge into the sea. Fuel tanks will be constructed from H36 steel, and the scantling sizes will be calculated based on the anticipated tank pressure based on the ABS Marine Vessel Rules (MVR) requirements. The tanks will be constructed using a double continuous fillet welded around the perimeter. Additionally, oil stop weld details, which consist of a full penetration plug weld, will be utilized to mitigate the risk of potential leaks between the fillet welds from spreading into adjacent spaces.

MARPOL Annex I, Regulation 12A (Reference 14) requires that fuel tanks be separated from the outer shell by a distance dependent on the ship's breadth and aggregate fuel volume. On the ARV, fuel tanks servicing Fuel Oil and Mission Fuel Systems are protected by separation from the hull via void compartments or ballast tanks, providing a double bottom for protection. For more information on the calculation of the fuel tank distance from the shell, see the Pollution Control Systems and Waste Management Report, 5E1-593-R001 (Reference 25).

6.3. Ballast Water Management

Ballast Water Management Systems (BWMS) are used to inactivate organisms in ballast water as a means of preventing the transference of aquatic invasive species and other non-native species between ecological zones. Per the ARV Performance Specification, Section 529.1, ballast water shall be treated using an IMO and USCG type-approved ballast water treatment system. All current BWMS with USCG type-approval also hold IMO type-approval. These type-approved ballast water treatment systems utilize treatment technologies as described in Table 11 below.

Table 11: BWMS Technologies

Technology	Description
Ultraviolet Light (UV)	UV lamps break down cell membranes and/or disrupting their DNA to neutralize organisms and prevent their reproduction
Electro-chlorination (EC)	A chemical solution is injected into the ballast water for disinfection. Neutralization of the ballast water is required before overboard discharge.
Chemical Injection	A chemical solution is injected into the ballast water for disinfection. Neutralization of the ballast water is required before overboard discharge.
Ozone	Ozone (O3) gas, generated from ship's ambient air, is diffused into the ballast water as a disinfectant to inactivate organisms in the ballast water
Thermal (Heat)	Ballast water is heated to a temperature that will kill organisms in the ballast water
Deoxygenation	Oxygen is removed from ballast water to cause asphyxiation of oxygen-dependent organisms. Oxygen removal is accomplished by injecting inert gases into the ballast water

The majority of the USCG type approved BWMS fall under the first three technologies: UV, EC, and Chemical Injection. Currently only one BMWS solely utilizing thermal treatment and one BWMS utilizing deoxygenation have received USCG type-approval. Two BWMS utilizing Ozone treatment have both USCG and IMO type approval. However, they are two identically sized models from the same manufacturer. All BWMS currently under review for USCG type-approval utilize either UV, EC, or Chemical Injection technologies (Reference 26).

Electro-chlorination, chemical injection, ozone, and deoxygenation treatment technologies all utilize active substances. An active substance is any substance or organism specifically used against nuisance aquatic organisms and pathogens in the ballast water, such as the bulk chemicals used in the Chemical Injection treatment systems.

6.3.1. Environmental Regulations

The *International Convention for the Control and Management of Ships' Ballast Water and Sediments* (IMO BWM Convention) (Reference 27) entered into force in September 2017. The BWM Convention sets the international standard for ballast water treatment. IMO BMWS type approval is detailed in Resolution MEPC.300(72), the *Code for Approval of Ballast Water Management Systems* (BWMS Code), also referred to as the revised G8 Guideline (Reference 28). Systems which make use of Active Substances must also be approved by IMO in accordance with the *Procedure for Approval of Ballast Water Management Systems that Make Use of Active Substances*, also referred to as the G9 Guideline, (Reference 29).

USCG type-approval of BWMS is required by 33 CFR 151.2025 (Reference 21). Requirements for USCG type-approval are found in 46 CFR Subpart 162.060 (Reference 30).

While the IMO and USCG ballast water discharge standards are similar, they are not the same. The BWM Convention discharge standard is written in terms of number of "viable" (able to reproduce) organisms in ballast water discharge, while the Coast Guard's discharge standard is written in terms of "living" organisms. Additionally, the testing requirements to prove compliance with discharge standards are different. Provision of a USCG and IMO type approved BWMS ensures adherence to both IMO and federal standards and regulations.

Currently, the Polar Code only addresses ballast water management in accordance with the BWM Convention as a recommendation in Part II-B of the Polar Code. Should the Polar Code require adherence to the BWM Convention in the future, the ARV will already be compliant.

The EPA VGP provides operational requirements for ballast water discharge. Provision of a USCG type-approved allows the ARV to meet VGP discharge limitations for ballast water.

6.3.2. Discussion

Selection of a BWMS must consider the following parameters: weight, electric load, and availability and environmental friendliness of the technology. Increased weight and electric load lead to increased fuel consumption and, consequently, higher emissions. Selection of a BWMS technology with multiple type-approved options for manufacturers and equipment models allows the ship designer to select a BWMS tailored to the needs of the ARV. By choosing a BWMS technology with limited market availability, the BWMS may not be optimized to suit the required capacity and available machinery footprint of the ARV. Because of this, it may be favorable to select a BWMS that utilizes Ultraviolet, Electro-chlorination, or Chemical Injection treatment technologies.

Between Ultraviolet, Electro-chlorination, and Chemical Injection, only Ultraviolet does not make use of active substances. While systems utilizing active substances must meet the additional standards of the G9 Guideline, there still remains skepticism as to how environmentally friendly these systems are. Once ballast water treated by Chemical Injection and EC systems is disinfected, the chemicals that remain in the water must be neutralized prior to overboard discharge. This can be done with counteracting chemicals or allowing additional holding time for the chemicals to break down naturally. Despite this, the *2018 Assessment of the Efficacy, Availability, and Environmental Impacts of Ballast Water Treatment Technologies for Use in California Waters* produced by the California State Lands Commission (Reference 31) found that “residual chlorine from BWMS is a serious problem, as multiple vessels reported chlorine levels that exceed the California Total Residual Chlorine limits”.

Provision of a Chemical Injection system requires storage of bulk chemicals for BWMS use. Bulk chemical storage necessitates additional safety provisions such as increased ventilation requirements, a gas detection system, and chemical level indication and alarm systems.

For these reasons, similar ship programs have specified that selected BMWS not make use of active substances. It is recommended that the ARV is provided with a BWMS that does not make use of active substances. Final BWMS selection shall be based on initial costs, lifecycle costs, space, and weight. At this time, a BWMS utilizing UV technology has been notionally selected for the ARV.

6.4. Wastewater Treatment

Per the ARV Performance Specification, Section 593.3, “An [marine sanitation device] MSD shall process blackwater from the sewage tank to effluent standards that comply with IMO Resolution MEPC.227(64).” Additionally, “The designer shall consider both biological and electrolytic wastewater treatment systems as greener treatment options.”

While treatment of greywater is not required in the ARV Performance Specification, its regulation should be considered due to the harmful particulates that can be found in greywater. Per a 2011 EPA report (Reference 32), greywater discharges can contain bacteria, pathogens, oil and grease, detergent and soap residue, metals, solids, and nutrients. These pollutants can be disruptive to local environments, particularly in an area of high sensitivity like the Antarctic area.

The ARV will also maintain holding capacities for both Sewage and Greywater. In accordance with the ARV Performance Specifications, the ARV will have Sewage Tank sized for at least a 20-day holding capacity. While a minimum Greywater holding capacity was not specified for the ARV, the ARV will maintain a minimum of 4 days of Greywater storage. See the Pollution Control Systems and Waste Management Report (Reference 25) for more details on the sizing of these waste tanks.

6.4.1. Environmental Regulations

6.4.1.1. Sewage

The Polar Code prohibits discharges of sewage into the polar waters except when performed in accordance with MARPOL Annex IV (Reference 14) and the following requirements:

- sewage has been treated by a sewage treatment plant in accordance with MEPC.227(64); and

- discharges are as far as practicable from the nearest land, any ice shelf, fast ice or areas of ice concentration exceeding 1/10.

When operating in areas of ice concentration exceeding 1/10 for extended periods of time, discharge of treated sewage is only permitted subject to the approval of the administration. MARPOL Annex IV further adds that effluent shall not produce visible floating solids nor cause discoloration of the surrounding water. MARPOL Annex IV allows discharge of sewage into the sea when the ship is operating a sewage treatment plant in accordance with MEPC.227(64).

These requirements exceed those set in 33 CFR 151.79 (Reference 21), which allows untreated sewage to be discharged at a moderate rate 12 nm of Antarctic land or ice shelves, while the ship is *en-route* at a speed of no less than 4 knots.

Federal regulation 33 CFR 159 (Reference 21) requires that all vessels equipped with toilets also install a Type II or III Marine Sanitation Device (MSD). Type II MSDs are equivalent to sewage treatment plants while Type III MSDs are sewage holding tanks. The MSD acceptance standards provided in 33 CFR 159 fall below those of MEPC.227(64). In 2015, the Coast Guard announced its acceptance of sewage treatment plants holding IMO type-approval as meeting the requirements for Type II MSDs.

Though the US is not a signatory to Annex IV, recognition of MARPOL Annex IV standards demonstrates the NSF’s commitment to preserving polar ecosystems.

6.4.1.2. Greywater

The VGP requires that untreated graywater be discharged greater than 1 nm from shore while the vessel is underway. Neither the Polar Code, MARPOL, nor 33 CFR Subchapter O provide overarching discharge restrictions for greywater. The Madrid Protocol allows discharge of “domestic liquid wastes” directly to the sea. However, greywater restrictions are beginning to be introduced in the marine sector. Federal regulation 33 CFR 159.309 restricts greywater discharge from cruise vessels in certain waters of Alaska. Cruise vessels operating in US waters must be 1 or 3 nm from shore, dependent on ship size, and traveling at 6 knots or greater in order to discharge untreated greywater. The California Clean Coast Act prohibits discharge of greywater within state marine waters (within 3 nm of shore, including offshore California islands) (Reference 33).

In 2018, the Frank LoBiondo Coast Guard Authorization Act was passed, which charged the EPA and Coast Guard to develop new regulations to manage vessels’ incidental discharges, including greywater (Reference 33). In 2020, the EPA's *Notice of Proposed Rulemaking - Vessel Incidental Discharge National Standards of Performance* (Reference 35) was published for public comment. The EPA proposes to prohibit the discharge of greywater within 1 nm from shore from any vessel that voyages at least 1 nm but not more than 3 nm from shore, unless the discharge meets a set of standards contained in the proposed rule. The EPA further proposes that discharge of greywater from any new vessel of 400 gross tons or greater be required to meet the new discharge standards. This would necessitate either treatment of greywater prior to discharge or provision of sufficient storage capacity to retain all greywater onboard while operating in waters protected by the rule.

While sweeping international and federal regulations are not currently in place, it is apparent that the US is trending toward stricter regulations.

6.4.2. Discussion

6.4.2.1. Sewage

Provision of a Type II MSD ensures compliance with both Federal and International regulations for sewage treatment and discharge. MEPC.227(64) defines sewage treatment plant effluent standards for fecal coliform, total suspended solids (TSS), biochemical oxygen demand, chemical oxygen demand, pH, total nitrogen, and total phosphorous. Discharge standards for microplastics are covered by the TSS effluent standard. Provision of a sewage treatment plant under the guidelines of MEPC.227(64) is required to receive ABS ENVIRO or ENVIRO+ notation.

There are several Type II biological and electrolytic sewage treatment plants that hold both IMO and USCG approval. Both technologies hold their own costs and benefits.

While electrolytic systems may boast being chemical-free, they also require strict influent temperatures and salinity to function properly. Biological systems do not depend on salinity and do not have as strict of temperature ranges. However, these systems require a longer processing time and produce a higher amount of sludge. Membrane bioreactors (MBRs) require large chemistry sets, and longer processing times for sewage to reach an appropriate effluent standard for overboard discharge. Furthermore, MBRs have a large footprint, both in terms of weight and volume. Sludge holding tanks must also be factored in, as approximately 2% of MBR input material will be converted to sludge. Membranes only last approximately ten years, meaning there will be four service requirements to change membranes over the service life of the ARV.

Compared to MBRs, electrolytic systems are not as labor intensive, nor do they have such a large footprint. However, salinity requirements for electrolytic systems have been found to be around 32 Practical Salinity Units (PSU). The ARV will often encounter waters below of a salinity below this requirement. In these instances, the electrolytic system would not function properly. To maintain flexibility between the ARV missions and the handling of sewage, it is recommended that a biological-type sewage treatment plant be selected for the ARV.

6.4.2.2. Greywater

In response to the EPA's proposed changes to commercial vessel discharge standards, consideration should be given to treating greywater using the sewage treatment plant or sizing greywater holding capacity to minimize discharge while underway. As a mark of designing an environmentally conscious ship, ABS requires that sewage treatment plants are to be equipped with means to treat greywater in order to receive ABS ENVIRO+ notation. Similarly, DNV requires greywater to be treated either with the sewage treatment plant or a dedicated treatment system in order to receive their Clean(Design) notation (Reference 36). Use of a biological-type sewage treatment plant requires a specified amount of hydration water, typically greywater, to carry out the treatment process. In the selection of a biological-type sewage treatment plant, both greywater and sewage will be directed to the plant for treatment prior to overboard discharge.

Laboratory chemical waste streams should not be handled by the Greywater System. As such, laboratory sinks drain covers should be provided on sinks in laboratory areas to prevent chemical spills from entering the Greywater System. Management of laboratory chemical waste is covered in the Hazardous Material Management Plan, 5E1-077-P101.

Consideration should also be given to maximizing environmental friendliness of expected waste streams. Soaps and detergents should be non-toxic, phosphate-free, and biodegradable where possible.

6.5. Solid Waste Management

Per the ARV Performance Specification, Section 593.4, the ARV must develop a comprehensive plan for the collection, separation, conveyance, storage, and disposal of all types of organic and inorganic waste generated on the vessel. MARPOL Annex V, the Polar Code, the Madrid Protocol, and 33 CFR Subchapter O refer to these waste streams generally as “garbage”, while this report uses “solid waste” to describe food waste, glass, metal, plastics, cardboard, paper, and other daily wastes.

MARPOL Annex V, Regulation 5 states that the flag state shall ensure that all ships entitled to fly its flag have sufficient capacity on board for the retention of all garbage while operating in the Antarctic area and have made arrangements to discharge stored garbage at a reception facility after leaving the area.

6.5.1. Environmental Regulations

6.5.1.1. Food Waste

The Polar Code prohibits food waste from being disposed into the water within 12 nm of ice-shelves, 12 nm of fast ice, or near areas of ice concentration exceeding 1/10. Discharged food waste must be comminuted, shall be capable of passing through a screen with openings no greater than 25 mm, and shall not be discharged onto the ice. The Madrid Protocol supports these regulations, requiring that disposal of comminuted food waste occur no less than 12 nm from the nearest land or ice shelf.

In both Special and Non-Special areas, MARPOL Annex V, Regulation 3 allows disposal of non-comminuted food waste in the water no less than 12 nm from the nearest land. Comminuted food waste that can pass through a screen with openings no greater than 25 mm may be disposed of in non-Special area waters at a distance of at least 3 nm from the nearest land. In order to receive ABS ENVIRO+ notation, vessels may not dispose of food waste into the sea except when it has passed through a comminuter or grinder.

Federal Regulation 33 CFR 151.66 prohibits all discharge of garbage, including food waste, into navigable waters of the United States.

6.5.1.2. Other Solid Wastes

The Polar Code requires that disposal of garbage into the sea is permitted in accordance with regulation 6 of MARPOL Annex V provided discharges are as far as practicable from areas of ice concentration exceeding 1/10 and not less than 12 nm for the nearest fast ice. Plastics are not permitted to be disposed of into the sea.

The Madrid Protocol, Annex IV, Article 5 prohibits the disposal into the sea of plastics and all other garbage (paper products, glass, metal, incinerator ash, etc.).

MARPOL Annex V, Regulation 3 prohibits the disposal of plastics into the sea. It also requires that disposal of dunnage, living, and packing materials that will float be disposed of 25 nm from the nearest land. Paper products, rags, glass, metal, bottles, and the like are permitted to be disposed of 12 nm from the nearest land.

Federal Regulation 33 CFR 151.66 prohibits all discharge of garbage, including food waste, into navigable waters of the United States.

6.5.1.3. Incinerators

The ARV Performance Specification suggests the use of an incinerator for management of shipboard wastes. In accordance with MARPOL Annex VI, Regulation 16, incinerators must be approved by the administration, considering the standard specification for shipboard incineration developed by IMO and contained in IMO Resolution MEPC.76(40) (Reference 37). MEPC.76(40) contains a number of requirements for shipboard incinerators including materials for manufacturing, operating requirements, and emissions standards.

6.5.2. Discussion

6.5.2.1. Food Waste

Ship generated food waste has three disposal routes: disposal to the sea, incineration, and transfer to a reception facility. There are drawbacks to each of these methods. Disposal to the sea introduces food-based nutrients that are potentially harmful to aquatic ecosystems. A case study at the Latvian Maritime Academy assessed the food waste management plans of different vessels to calculate the expected daily nutrient content of their discharge. The study found that “the discharging of food waste into the sea and of mixtures of shredded food waste and greywater into seawater has a high probability of producing an unacceptable or severe [daily nutrient content] DNC load impact” (Reference 38). Access to food waste can also cause a disruption in the food chain at the site of disposal. Incineration increases gas emissions but is carried out in small enough intervals that exhaust heat recovery would be impractical. To transfer waste to a reception facility, the ARV will require a larger area for waste storage than if other disposal methods were used.

Since first being piloted in 2019, biodigesters have become popular in the cruise ship industry. Biodigesters use anaerobic digestion to break down food wastes to create what amounts to liquid fertilizer. Biodigesters have both a power demand and a water demand to carry out their function. The space, weight, and service demand of the biodigesters should be analyzed to determine if use of a biodigester is suitable for the ARV.

Additional types of food waste processors include macerators/pulpers and dehydrators. The available footprint for food waste storage will ultimately drive the necessity for processing equipment. Per the Pollution Control Systems and Waste Management Report (Reference 25), an incinerator will be provided to incinerate any food waste in excess of the ARV’s food waste storage capabilities. Larger scale food waste processors like biodigesters and dehydrators will not be required.

6.5.2.2. Other Solid Wastes

While disposal of solid wastes such as cardboard, glass, and metal into the sea are permitted in non-Special Areas with some restriction, efforts should be made to recycle and store solid wastes onboard. Space for waste storage and processing should be provided. The amount of waste storage and processing space available will drive the need for waste processing equipment as described in the ARV Performance Specification, Section 593.4, to compact shipboard solid wastes. In order to receive ABS ENVIRO+ notation, dedicated arrangements must be provided for storage of garbage. Processing equipment could include name balers, metal shredders, glass crushers, and trash compactors. Per the Pollution Control Systems and Waste Management Report, of these solid waste processors, only a glass crusher will be required. All other waste stream will be able to be stored or incinerated onboard for 90 days.

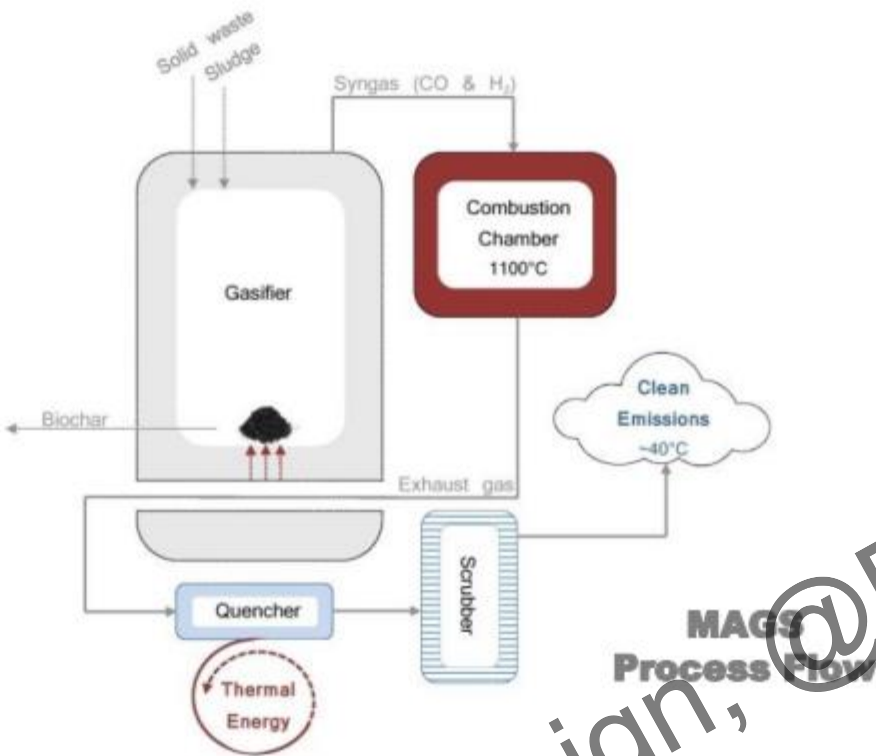
6.5.2.3. Incinerators

In order to receive ABS ENVIRO notation, where installed onboard, incinerators are to be type-approved in accordance with IMO Resolution MEPC.244(66). The ABS Guide of Environmental Protection Notations for Vessels also includes a list of shipboard wastes that may not be incinerated. For ABS ENVIRO+ notation, at least one incinerator is to be installed onboard unless stowage arrangements for all garbage and shipboard wastes are provided until able to be offloaded to shore. The ARV will be provided with an incinerator for processing of waste streams.

6.5.2.4. Gasification Systems

One emerging incineration-type technology of interest is the Terragon-patented technology, the Micro Auto Gasification System (MAGS). The MAGS breaks down hydrocarbons in waste and transforms them into energy and a byproduct of bio-char. A flow path of the process is shown below in . During the Auto Gasification Process, the synthesis gas of the waste is used as fuel. So, the waste is converted into inert carbon products when cooked using the vapors generated by the waste itself. Once the hot gasses transfer heat to the gasifier, they are quenched with water to eliminate the potential for dioxins and furans, both toxic substances that share a similar chemical structure. The gas is then sent through a scrubber that removes all acid gases and particulates prior to discharging clean emissions.

Figure 8: MAGS Flow Path



The main benefit of the installing a MAGS aboard the ARV is the availability to reduce the volume of solid waste and oily sludge that is stored on the ship. When in use, the MAGS has a 95% waste volume reduction and emissions that are invisible, safe, and meet all environmental air standards. The MAGS itself operates at a capacity of >50kg/hr of solid waste, 15-20L/hr for oily sludge, and generates more than 100 kWh per hour of thermal energy that can be harnessed. The self-fueling process leads to a lower reliance on fossil fuels. Another benefit of the MAGS is that it is a leader in IMO incinerator verification. The MAGS is certified with both IMO resolution MEPC.76(40) and MEPC.244(66) – Standard Specifications of Shipboard Incinerators.

While helpful for reducing the volume of garbage, the incinerator itself can be a space and weight restraint. The MAGS system weighs 9,700 lbs (4,400 kg) with a volume of ~360 ft^3 (~10 m^3). The byproduct of bio – char, must also be routinely emptied and stored somewhere on the ship. Due to the lower carbon emissions and superior environmental friendliness of the system, the MAGS incinerator has been incorporated into the ARV design.

6.6. Air Emissions Reduction

6.6.1. Environmental Regulations

The ARV Performance Specification requires the use of at least four diesel engines. Emissions standards have been tightened on the allowable levels of NOx and SOx emissions. MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships, establishes Emission Control Areas (ECAs) that require stricter emissions standards. Although waters off North

American coasts have been designated as ECAs, the Antarctic region has not yet been designated as such.

MARPOL Annex VI, Regulation 13, as enforced by 40 CFR 1043 (Reference 39), is applicable to all marine diesel engines with a power output greater than 130 kW installed on a ship. Such power output is significantly smaller than what will be required for the ARV. Emergency diesel generators are exempted from the regulation. The regulations stipulate that marine diesel engines on a ship constructed after 1 January 2021 must meet IMO Tier III emissions requirements when operating in Special Areas. When operating in water other than Special Areas, the engines must meet Tier II exhaust emissions.

Engines on U.S. flagged vessels that do not operate in waters subject to the jurisdiction of another country may comply with the EPA's domestic emission standards (EPA Tiers 1, 2, 3, and 4) in lieu of compliance with MARPOL Annex VI. However, as ARV will be operating in international waters, it must meet MARPOL Annex VI emissions requirements.

In the US, in addition to EPA requirements, the California Air Resources Board (CARB) must be adhered to for ocean going vessels while docked at berth at a California port. These regulations require a reduction of engine emissions through either:

1. A reduction of engine power generation by at least of 80% from the vessel's baseline power generation while in-port, or
2. Use of emission reduction technology to reduce NOx and particulate matter emissions by 80% from the vessel's baseline emissions.

The regulations also place a time limit on how long vessel-based power can be used in-port. However, per the At Berth regulation, government vessel are exempt from these regulations (Reference 40).

Additionally, Annex VI, Regulation 14 directs that the sulfur content of fuel oil used or carried for use on board a ship shall not exceed 0.50% m/m. This requirement drops to 0.10% m/m while a ship is operating within an emission control area. MARPOL Annex I, Regulation 43, which entered into force in 2011, prohibits the use of heavy fuels in the Antarctic area. This prohibition aims to reduce pollution in the Antarctic region.

6.6.2. Discussion

6.6.2.1. Emissions Aftertreatment

The diesel generator sets installed onboard the ARV for propulsion and ship service loads will need to meet IMO Tier III emissions standards. If the Antarctic area is named an Emissions Control Area, the ARV will already be compliant with the requirement for Tier III engines. Consideration must be given when arranging Main Machinery Spaces and engine intakes and uptakes to account for the space and weight required for the technologies used to achieve IMO Tier III emissions criteria. There are several technologies which may be used to meet IMO Tier III emissions standards. Market research of engines that will suit the power demands of the ARV was performed and determined that the two emissions reduction technologies that are available for diesel engines of the appropriate power output are Selective Catalytic reduction (SCR) and Exhaust Gas Recirculation (EGR). For a discussion on these types of treatment technologies, see the Pollution Control Systems and Waste Management Report, 5E1-593-R001 (Reference 25).

6.6.2.2. Ultra Low Sulfur Fuel

MARPOL Annex I, Regulation 43 (Reference 14) restricts the carriage in bulk as cargo, ballast, or carriage and use of heavy fuel oils on ships operating in the Antarctic area. MARPOL Annex VI, Regulation 14, restricts the sulfur content of any fuel oil used on board ships. Outside of ECAs, this shall not exceed 0.50% m/m (5000 ppm). While inside ECAs, this value is restricted further to 0.10% m/m (1000 ppm). Using these lower sulfur fuels can significantly reduce the emissions, specifically SO_x and soot from diesel engine exhaust. Additional benefits include low sulfur fuels being better for aftertreatment systems that use catalyst materials that are susceptible to sulfur poisoning. The ARV Performance Specification, Section 310, states that the diesel engines and emergency generators shall be capable of operation with all grades of Nos. 1 and 2-D diesel fuel oils, including the ultra-low sulfur diesel (2-D S15) and renewable or synthetic diesel meeting the same specification. The availability of these fuels is not widespread and is more expensive compared to marine diesel oil fuel. As the 0.10% m/m sulphur content MARPOL requirement for North America only took effect in January of 2020 and as new ECAs continue to be designated, bunkering availability of fuel oils meeting the sulfur content restriction is expected to become more widely available in the coming years.

6.7. Pollution Control Systems Summary

Table 12: Summary of Pollution Control Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Oily Water Treatment *5 ppm OWS*	- Reduces required Oily Water storage capacity - Provides better protection than required by IMO outside of Polar waters	- Less market availability of USCG/IMO type-approved 5 ppm OWS; cost	**Yes, Incorporated**	–
Environmentally Acceptable Lubricants	- Higher biodegradability - Low aquatic toxicity	- Different drawbacks dependent on EAL type – poorer performance at temperature poles, more prone to hydrolysis	**Yes**	Engine, propulsor, and handling systems vendors will be engaged in Detail Design to determine the suitable EAL selection for these applications
Ballast Water Management System				
Electro-chlorination	- Smaller footprint - Not effected by turbidity	- Strict salinity requirements - Use of chemical, requires chemical storage	**No**	–
Chemical Injection	- Simple, easy systems not prone to disrepairs - Not dependent on salinity	- Use of chemical, requires chemical storage - Longer holding times	**No**	–
Thermal (Heat)	- Does not use active substances	- Less market availability of USCG/IMO type-approved; cost	**No**	–
Ultraviolet Light (UV)	- Does not use active substances - Not dependent on salinity	- Lamps have to be replaced regularly - Longer hold times	**Yes, Incorporated**	–
Solid Waste Management *Sewage Treatment Plant*				
Electrolytic	- Smaller footprint	- Strict temperature and salinity requirements	**No**	–
Biological Membrane	- Not dependent on salinity - Treats both Sewage and Greywater	- Bulk chemical storage - Larger footprint	**Yes, Incorporated**	Sewage Treatment Plant should be sized to treat both Sewage and Greywater waste streams

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Solid Waste Management *Gasification Systems*	- Reduced carbon emissions - Ability to combust hazardous materials safely - Produces thermal energy that can be re-captured	- Larger footprint	**Yes, Incorporated**	–
Air Emissions Reduction				
Selective Catalytic Reduction	- More market availability - More fuel efficient	- Have to bunker, store, and potentially heat urea - More equipment to fit in the stack	**Conditional**	*Both emissions reduction systems are considered acceptable for the ARV. While the footprint of EGR engines may be larger than SCR engines, selection of SCR engines necessitates volume to be taken back for urea.
Exhaust Gas Recirculation	- No need to bunker, store, or heat urea	- Engines utilizing EGR tend to have higher cooling water requirements - Point design solution	**Conditional, Incorporated**	
Ultra Low Sulfur Fuel	- Decrease in SO_x emissions - Required by MARPOL	- Bunkering availability - Potential need to segregate if different fuel types are used	**Yes, Incorporated**	–

7. Outfitting

7.1. Thermal Insulation

Per the ABS LTE (Reference 9), Appendix 4/8, “An increase in the amount of approved insulation for the steel structure inside the accommodations area to support the efficiency of the HVAC system may be necessary. The associated increase in thickness and weight must be considered in the design.” While an increase in the amount of thermal insulation used onboard the ARV comes with an associated increase in weight, its addition will yield lower degree of heat transfer between spaces. Space heating and cooling loads drive the size of the HVAC and Chilled Water systems serving the compartments. Heat gains or losses due to transmission between adjacent space boundaries is expressed as follows:

$$q = U \times A \times \Delta T$$

Where q is the transmission heat gain or loss of the space, U is the coefficient of heat transmission, A is the shared area between the spaces, and ΔT is the temperature difference across the boundary[1].

For a given boundary, increasing the width of insulation will eventually plateau. As an example, the heat transfer between the Auxiliary Machinery Space and the Wet Lab will be analyzed with varying thicknesses of insulation. In the heating season, the temperature differential between these spaces is 20°F in accordance with the temperatures listed in the ARV Performance Specification, Section 044.4.4, Table 5 for Laboratories and Table 6 for Machinery Spaces. The eventual plateau of the amount of heat transfer is illustrated in the calculation results in Table 13 below.

Table 13: Heat Transfer from Wet Lab at Various Insulation Thicknesses

Insulation Thickness	Insulation Type	Insulation U-Value[2]	Heat Loss[3] (BTU/HR)	Heat Loss (kW)
0”	Type 0	0.695	5004	1.467
1”	Type 22	0.179	1289	0.378
2”	Type 52	0.122	878	0.257
3”	Type 93	0.081	583	0.171
4”	Type 113	0.064	461	0.135
6”	Type 146	0.047	338	0.099

In this scenario, increasing insulation thickness has the highest impact when adding 1” to 3” of insulation. At insulations greater than this, heat losses start to plateau while weight of insulation increases. As demonstrated above, increasing insulation thickness should be evaluated in all areas to determine the value added by providing additional insulation. Added weight should be balanced against the potential reductions in required heating and cooling capacity.

[1] Retrieved from SNAME Technical & Research Bulletin 4-7 (Reference 41)
[2] Retrieved from SNAME Technical & Research Bulletin 4-16 (Reference 42)
[3] Using square footage of 360 ft^2 from the ARV General Arrangement, 5E1-001-D001, Rev. P0 (Reference 43)

7.2. Green Material Selection

The ARV Performance Specification, Section 600, states: “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.” Volatile organic compounds (VOC) are emitted as gases from certain solids or liquid, like paints and coatings. Release of VOCs in painting operations poses a health hazard to workers. Concentration limits for VOC / volatile organic hazardous air pollutants (VOHAP) in marine coatings used in shipbuilding operations are defined 40 CFR 63, Subpart II (Reference 44). The Coast Guard has further tightened these restrictions in the Coatings and Color Manual, COMDTINST M10360.3D, prescribing a maximum VOC content limit of 400 grams/liter for antifouling bottom paint and 340 grams/liter for all other marine paints. It appends this requirement stating that “VOC regulations are expected to be significantly reduced in the near future to 340 grams/liter for antifouling bottom paint and 250 grams/liter for all other marine paints.” These limits may be used as a baseline for the ARV.

As the ARV outfitting design develops, use of sustainably sourced, recycled, or low environmental impact outfitting materials will be further explored. Incorporation of these materials would be captured in the Detail Design phase in deliverables such as the Paint Schedule, Furniture and Outfit List, Deck Covering Schedule.

7.3. Outfitting Summary

Table 14: Summary of Outfitting Technologies

Technology	Benefits	Drawbacks	Recommended for ARV?	Comments
Thermal Insulation	- Decrease in heating and air-conditioning loads in shell-adjacent spaces	- Added weight and cost	**Further Study**	Tradeoff should be further studied in Detail Design phase, when detailed space heating and cooling load calculations are performed
Green Material Selection	- Lower toxicity - More environmentally friendly	**-** Market availability; cost	**Further Study**	Outfitting details will be further explored in Detail Design and captured in various outfitting lists and schedule

8. ABS ENVIRO and ENVIRO+ Notations

Per the ARV Performance Specifications (ARV Performance Specifications, Section 070.1, the ABS ENVIRO notation is a threshold requirement for the ARV while ENVIRO+ is the objective. ABS ENVIRO+ is a notation that builds on the ENVIRO and adds procedures that are more restrictive toward environmental factors. The differences between the two include procedure changes, equipment adjustment, and support. The differences are outlined below in Table 15 with indication for its incorporation status for the ARV design.

Table 15: ABS ENVIRO vs. ENVIRO+ Notation

Technology	Section	ABS ENVIRO	ABS ENVIRO+	Planned Incorporation on ARV
Hull Construction				
Anti-fouling Coating	2.2.2.1	Coating must not contain organotin compounds or are to bear a coating that forms a barrier to prevent leaching of organotin compounds from an underlying non-compliant system. Small quantities of organotin compounds are allowed as a chemical catalyst. The levels of these compounds are not to be present above 2,500 milligram (mg) total tin per kilogram (kg) of dry paint.	No additional requirements.	**ENVIRO+ Conditional** If an anti-fouling overcoating is used, it is recommended that the selected coating meet the listed ENVIRO standard..
Auxiliary Systems				
Environmentally Friendly Refrigerants	5.1.6	The use of ozone depleting refrigerants is prohibited.	The use of ozone depleting refrigerants is prohibited other than hydro-chlorofluorocarbons. The use of refrigerants with global warming potential (GWP) greater than 2000 are prohibited other than for the notation, EP2020+.	**ENVIRO+**
Fire Suppression Systems	5.4	No Halons or Perfluorocarbon Mediums unless; they contain no ozone depleting substances and a GWP less than 4000	GWP must be <2000.	**ENVIRO+**
Pollution Control Systems				
Waste Oil	6.2.2	The total capacity of sludge tanks is to meet the criteria specified in MARPOL Annex I, Unified Interpretations 16.1 and 16.2, as applicable, based on the maximum period of voyage between ports.	No additional requirements.	**ENVIRO+**
Oily Water Separator	6.2.2.1	15 ppm effluent standard	5 ppm effluent standard	**ENVIRO+**
Oil Leak Prevention	6.2.2.3	Arrangements of fuel oil tanks are to comply with 4-6-4/17.1 and 4-6-4/17.3 of the Marine Vessel Rules	Arrangements of fuel oil tanks and lubricating oil tanks are to comply with the requirements for the class notation POT.	**ENVIRO+**

Technology	Section	ABS ENVIRO	ABS ENVIRO+	Planned Incorporation on ARV
Ballast Water Management System	6.3.2	Vessels are to comply with the requirement of the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWM Convention). Methods of ballast water management are to consist of ballast water exchange or ballast water management systems in accordance with the BWM Convention.	No additional requirements.	**ENVIRO+**
Sewage Treatment Plant	6.4.2	Provision of Sewage Treatment Plant or Sewage Holding Tank	Sewage Treatment Plant treats both sewage and greywater	**ENVIRO+**
Incinerators	6.5.2.3	Where installed onboard, incinerators are to be type-approved in accordance with IMO Resolution MEPC.244(66)	At least one incinerator is to be installed onboard and is to comply with the ENVIRO guide air discharge - incinerators requirements	**ENVIRO+**
Main Diesel Engine Emissions	6.6.2	Exhaust Gas is complicit with ABS guide for Exhaust Emission Abatement. Complicit with the requirements of the IMO Guidelines for Exhaust Gas Cleaning Systems, Resolution MEPC.170(57) prior to 1 July 2010, the requirements of MEPC.184(59) prior to 15 May 2015 and MEPC.259(68), as amended, thereafter.	The sulfur content of fuel oil used on board globally (Excluding ECA Zones) is not to exceed the limit of 0.5% mass/mass. The sulfur content of fuel oil used onboard in ECA Zones is not to exceed the limit of 0.1% mass/mass.	**ENVIRO+**
Solid Waste Management				
Garbage	6.5	Hold a Garbage Management Plan in accordance with MEPC/Circular 317	Dedicated arrangements are to be provided for storage of garbage. If overboarding food waste, unless comminuted.	**ENVIRO+** Currently, there is no plan to overboard food waste.
Recycling	6.5	No requirement.	Vessels are to hold and maintain the Inventory of Hazardous Material (IHM) class notation.	**ENVIRO+** It is recommended that the ARV pursue obtaining the IHM notation.

9. Conclusions and Recommendations

The ARV Performance Specification creates a baseline of required technological implementation for a green ship design. There is still room to build upon that baseline as emerging technologies become more commercially available, as detailed in this report. The majority of the proposed technologies and practices aim to minimize discharges into the water, minimize energy use and fuel consumption, and minimize use of environmental contaminants. The feasibility of green technology and practice implementation will depend on several input parameters that will continue to be explored and balanced including space, weight, power, cost, and the degree of positive environmental impact. These input parameters will continue to be defined as the ARV design matures. A summary of incorporated and recommended green technologies for installation onboard the ARV are summarized in Table 16 and Table 17 below. These tables shall be updated as the design matures.

9.1. Incorporated Technologies

Table 16 summarizes green ship technologies that have been implemented into the ARV design.

Table 16: Incorporated Technologies

Technology	Report Section
Hull Technologies	
Hull Form balancing Icebreaking and Open Water Performance	2.1
Electric Systems	
IEPS	3.1
Hybrid Battery	3.2
Father-Son Generator Configuration	3.3
VFDs	3.4
LEDs	3.7.1
Propulsion Plant	
Podded Electric Drive Propulsors	4.1.1
Auxiliary Systems	
Decentralized HVAC	5.1.1
Waste Heat Recovery	5.2
NOVEC 1230	5.4.1
Water Mist	5.4.2
Pollution Control Systems	
Oily Water Separator (5 ppm)	6.2.2.1
Ballast Water Management System (UV)	6.3.2
Sewage Treatment Plant (Biological Membrane)	6.4.2.1
Incinerator (Gasification System)	6.5.2.4
Exhaust Gas Recirculation	6.6.2.1
Ultra Low Sulfur Fuel	6.6.2.2

9.2. Recommended and Further Study Technologies

Table 17 lists recommended technologies or technologies whose potential incorporation warrants further study in the Detail Design Phase. The table details where technology implementation is expected to be reflected and the timeline for incorporation.

Table 17: Recommended and Further Study Technologies

Technology	Report Section	Remarks
Hull Technologies		
Hull Lubrication	2.1	Benefits of hull lubrication will be explored once a final hull form has been converged upon.
Anti-Fouling Hull Coating	2.2.2.1	This would be documented in the detail Design Phase in a Paint Schedule.
Abrasion-Resistant, Low Friction Hull Coating	2.2.2.2	This would be documented in the detail Design Phase in a Paint Schedule.
Hull Cleaning (both divers and ROVs)	2.3	Hull cleaning method can be selected or modified at any time during ship's lifetime.
Electrical Systems		
Premium Efficiency Motors	3.5	Availability will be explored during the Detail Design phase during equipment selection.
PM and SR Motors	3.6	Availability will be explored during the Detail Design phase during equipment selection.
Lighting Controls	3.7.2	Lighting controls will be implemented in the Detail Design Phase in the Lighting Plan and IMACS control schema.
Propulsion Systems		
Biodiesel	4.3.1	In the future, should bunkering become available, biodiesel could be used as a drop-in fuel. Should heating of fuel tanks be required, use of biodiesel is not recommended as tank heating would be accomplished using the oil-fired heater which would lead to higher fuel consumption of oil-fired heater.
Auxiliary Systems		
Centralized HVAC	5.1.1	At this time, decentralized is expected to be more energy efficient than a centralized system. Upon calculation of individual space cooling and heating loads in the Detail Design phase, the selection of the HVAC system architecture will be re-evaluated to determine if decentralized is the most energy efficient architecture as expected.
VFDs (HVAC)	5.1.2	Potential application will be explored in the Detail Design Phase when all fans have been sized.
Advanced HVAC Control Systems	5.1.5	These controls will be implemented in the Detail Design Phase in the HVAC System and IMACS control schema.

Technology	Report Section	Remarks
Environmentally Friendly Refrigerants	5.1.6	Environmentally Friendly Refrigerants will be explored in the Detail Design Phase during equipment selection of chillers and refrigeration plants.
Low-Flow Water Consumers	5.3	Low-flow consumers will be explored in the Detail Design Phase during equipment selection.
Pollution Control Systems		
Environmentally Acceptable Lubricants	6.2.2.2	Engine, propulsor, and handling systems vendors will be engaged in Detail Design to determine the suitable EAL selection for these applications.
Air Emissions Reduction *Selective Catalytic*	6.6.2.1	While the currently selected engines utilize Exhaust Gas return for emissions reduction, other diesel engine suitable for the ARV utilize Selective Catalytic Reduction.
Outfitting		
Increased Thermal Insulation	7.1	Tradeoff should be further studied in Detail Design phase, when detailed space heating and cooling load calculations are performed.
Green Material Selection	7.2	Outfitting details will be further explored in Detail Design and captured in various outfitting lists and schedule.

9.3. Eliminated Technologies

Table 18 lists technologies that have been eliminated from consideration for implementation into the ARV design. The table details the key reasons why incorporation into ARV design is impractical or surpassed by better options.

Table 18: Eliminated Technologies

Technology	Report Section	Remarks
Electrical Systems		
Generator Set Configuration *Equally Sized*	3.3	Eliminated in favor of a father-son configuration that has lower space, weight, and fuel consumption.
Propulsion Systems		
Azimuthing Propulsors *Mechanical Drive*	4.1.1	Eliminated in favor of electric drive propulsors which have lower mechanical losses and better reliability.
Wind Power	4.2	Eliminated due to expected low output of system and compromises to ship stability, lines of sight, science operations.
Alternative Fuels *Methanol and Hydrogen* *Ammonia*	4.3	Eliminated due to low bunkering availability and required increases in fuel storage capacity that would be unmanageable on the ARV given its power needs and allotted space for fuel tankage.

Technology	Report Section	Remarks
Auxiliary Systems		
Air to Air Heat Exchangers	5.1.3	Eliminated due to its inefficiency in meeting the high heating demands of the ARV.
Heat Pumps	5.1.4	Eliminated due to lack of reliable heat source for transferring of heat via heat pump.
FM-200	5.4	Eliminated in favor of NOVEC and water mist which have significantly lower global warming potentials.
Pollution Control Systems		
Ballast Water Management System *Electro-chlorination* *Chemical Injection* *Thermal (Heat)*	6.3.2	Eliminated in favor of UV-type BWMS for its established place in the market, its non-reliance on active substances, and its independence from ballast water salinity
Sewage Treatment Plant *Electrolytic*	6.4.2.1	Eliminated due to its reliance on water salinity that may not be met in all areas of ship operation

10. References

1) ARV Performance Specifications, Rev. -, File No. 19136.01, 30 November 2021.

2) *Green Vessel Design*, USCG Proceedings, Vol. 65, Number 4, King, B., Roberts, R., Payne, J., & Villiot, C., 2008.

3) Green Ship Alternatives Study, Rev. P0, ASC Research Vessel Replacement Program, Leidos, ASC, 26 January 2021

4) ARV Icebreaking Performance Report, 5E1-050-R201, Rev. P1

5) ARV Hull Form Trade-Off Study, 5E1-051-R001, Rev. P2

6) ARV Bubble Sweepdown Computational Fluid Dynamics Report, 5E1-050-R101, Rev. P2

7) *ABS Guide for the Inventory of Hazardous Materials*, October 2018.

8) *International Convention on the Control of Harmful Anti-fouling Systems on Ships*, IMO, https://www.imo.org/en/OurWork/Environment/Pages/Anti-fouling.aspx, accessed 14 March 2022.

9) *ABS Guide for Vessels Operating in Low Temperature Environments* (LTE), September 2021.

10) *ABS Guide for the Environmental Protection Notations for Vessels*, January 2021.

11) ARV Electric Propulsion Architecture and Trade-off Study, 5E1-062-R001, Rev. P1

12) ARV Battery Sizing for Lithium-Ion Batteries, 5E1-313-P001, Rev. P0

13) Underwater Radiated Noise Requirements Study, Rev. -, ASC Research Vessel Replacement Program, Leidos, ASC, 12 May 2021

14) *International Convention for the Prevention of Pollution from Ships* (MARPOL), IMO, as amended.

15) *American Innovation and Manufacturing (AIM) Act*, H.R. 133, 116th Congress, 2020, https://www.epa.gov/sites/default/files/2021-03/documents/aim_act_section_103_of_h.r._133_consolidated_appropriations_act_2021.pdf, accessed 23 February 2022.

16) *Hydrofluorocarbons and the Kigali Amendment*, Harvard Law School, https://eelp.law.harvard.edu/2017/09/hydrofluorocarbons-and-kigali-amendment-to-montreal-protocol/, accessed 27 September 2022.

17) *Significant New Alternatives Policy (SNAP) Substitutes in Refrigeration and Air Conditioning*, US Environmental Protection Agency (EPA), https://www.epa.gov/snap/substitutes-refrigeration-and-air-conditioning, last updated 28 December 2021.

18) *Energy efficiency analysis of marine high-powered medium-speed diesel engine base on energy balance and exergy*, Yao, Z.M., Qian, Z.Q., Li, R., & Hu, E., Energy, Volume 176, 1 June 2019.

19) ARV Waste Heat Recovery System and Hot Water Heating System, 5E1-517-D001, Rev. P2

20) *Efficiency in boilers and beyond*, Alfa Laval, https://www.alfalaval.com/globalassets/documents/products/heat-transfer/boilers/exhaust-gas-economizer/steam-production-and-waste-heat-recovery.pdf, accessed 15 February 2022.

21) 33 CFR Subchapter O, *Pollution*

22) *International Code for Ships Operating in Polar Waters* (Polar Code), IMO, https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/POLAR%20CODE%20TEXT%20AS%20ADOPTED.pdf, accessed 17 March 2022.

23) *Protocol on Environmental Protection to the Antarctic Treaty* (Madrid Protocol), https://www.ats.aq/e/protocol.html, accessed 14 March 2022.

24) *Environmentally Acceptable Lubricants*, EPA 800-R-11-002, EPA, November 2011.

25) ARV Pollution Control System and Waste Management Report, 5E1-593-R001, Rev. P2

26) *BWMS Type Approval Status*, Marine Safety Center, https://www.dco.uscg.mil/Portals/9/MSC/BWMS/BWMS_Approval_Status_7APR22.pdf, 7 April 2022.

27) *International Convention for the Control and Management of Ships' Ballast Water and Sediments* (BWM Convention), IMO, https://www.imo.org/en/MediaCentre/HotTopics/Pages/Implementing-the-BWM-Convention.aspx, accessed 3 March 2022.

28) *Code for Approval of Ballast Water Management Systems* (BWMS Code), Resolution MEPC.300(72), IMO, adopted 13 April 2018.

29) *Procedure for Approval of Ballast Water Management Systems that Make Use of Active Substances* (G9), Resolution MEPC.169(57), IMO, adopted 4 April 2008.

30) 46 CFR Subpart 162.060, *Ballast Water Management Systems*

31) *2018 Assessment of the Efficacy, Availability, and Environmental Impacts of Ballast Water Treatment Technologies for Use in California Waters*, California State Lands Commission, December 2018, https://www.slc.ca.gov/wp-content/uploads/2019/01/2018.pdf, accessed 10 February 2022.

32) *Graywater Discharges from Vessels*, US EPA, November 2011, https://www3.epa.gov/npdes/pubs/vgp_graywater.pdf, accessed 8 February 2022.

33) *California Clean Coast Act of 2005 FAQ*, California Water Boards, https://www.waterboards.ca.gov/water_issues/programs/npdes/docs/sb771/faq.pdf, accessed 30 September, 2022.

34) *Frank LoBiondo Coast Guard Authorization Act*, 115th Congress, 2018, https://www.congress.gov/bill/115th-congress/senate-bill/140/text, accessed 11 March 2022.

35) *Notice of Proposed Rulemaking - Vessel Incidental Discharge National Standards of Performance*, US EPA, 26 October 2020,

https://www.federalregister.gov/documents/2020/10/26/2020-22385/vessel-incidental-discharge-national-standards-of-performance, accessed 11 March 2022.

36) *Rules for Classification*, Part 6, Chapter 7 Environmental protection and pollution control, DNV GL, July 2019, https://rules.dnv.com/docs/pdf/DNV/RU-SHIP/2019-07/DNVGL-RU-SHIP-Pt6Ch7.pdf, accessed 7 March 2022.

37) *Standard Specification for Shipboard Incinerators*, Resolution MEPC.76(40), IMO, adopted on 25 September 1997.

38) *Nutrient Analysis of Food Waste from Ships' Greywater in the Baltic Sea*, Kalnia, R., Demjaneko, I., Gorbacenko, D., Priednieks, V., & Baronins, J., Water, Volume 13, Issue 17, 03 September 2021.

39) 40 CFR 1043, *Control of* NO_x, SO_x, *and PM Emissions from Marine Engines and Vessels Subject to the MARPOL Protocol*

40) *Ocean-Going Vessel At Berth Regulation, California Air Resources Board*, https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation, accessed 30 September 2022.

41) SNAME Technical & Research Bulletin 4-7, *Thermal Insulation Report*, 1974.

42) SNAME Technical & Research Bulletin 4-16, *Recommended Practices for Merchant Ship Heating, Ventilation and Air Conditioning Design Calculations*, August 1980.

43) ARV General Arrangement, 5E1-001-D001, Rev. P0

44) 40 CFR 63, Subpart II, *National Emission Standards for Shipbuilding and Ship Repair (Surface Coating)*