Antarctic Research Vessel (ARV)

Engineering Report:

ARV Electric Propulsion Architecture Trade-Off Study

Document No.: 5E1-062-R101
Revision: P1

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	September 1, 2022	All	J.Millard	Initial Issue
P1	January 17, 2023	All	J.Millard	Revised per comments

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1. Executive Summary

The requirements of the ARV project will demand the design of the vessel to be versatile. The propulsion plant, electrical plant, and major auxiliary systems need to perform efficiently while satisfying a challenging set of operations. Based on the size of the vessel at this stage of the design, the recommended propulsion system is a dual azimuth pod electric propulsion system, see reference 1. The manufacturer of the propulsion system will be required to incorporate upgrades to their baseline systems to produce a low underwater radiated noise (URN) signature, and to mitigate the total harmonic distortion produced from the propulsion system for clean power considerations. The electrical plant will provide power to the propulsion system and its auxiliaries as well as to the rest of the vessel including mission systems. A hybrid design consisting of diesel electric generators and Lithium Ion (Li-Ion) battery systems is a flexible design that will fulfil these power requirements, see reference 2. The manufacturer of the propulsion system's power distribution design will require the use of high-pulse VFD's, phase shifting, and power converters to satisfy the clean power requirements and do so without the use of filtering.

Other recommendations to improve the performance and power quality of the vessel involve components and auxiliary systems running off the Ship's Service section of the electrical plant. The use of variable frequency drives (VFD) with higher than standard pulse rates for systems such as sea water systems, and freshwater systems will provide more control over the electrical load of that motor and mitigate the harmonic distortion that variable frequency drives can produce. The use of permanent magnet motors and alternators where applicable, will provide more reliable power, require less power than standard motors, and less maintenance for high use motors such as generators, sea water pumps, and fuel pumps. The use of smart systems that allow for the sensing, actuation, and control of larger systems, such as an advanced HVAC systems will allow for the optimization of power distribution and versatility. These auxiliary systems are essential to building an optimally performing Antarctic Research Vessel (ARV). These auxiliary systems are supporting the propulsion plant and electrical plant via their versatility and ability to automatically adapt to the conditions needed at that time. By taking a component-by-component approach and tracking the effect each has on their systems and the overall power quality of the vessel will allow for the optimization of the systems and the quality of its power that is produced on the vessel.

A less commonly used system and design option is the use of variable speed generators (VSG). These generators may not be a viable solution for the main plant generators as VSG will match their speed to the load required by the vessel. The battery system will be used to keep generators running at their most efficient speed, thus variable speeds are not needed when a battery system is present. Yet a VSG could be used as a harbor generator where efficiency and versatility is a benefit to the vessel, that is if the battery system is not part of the in port electrical plant setup. This report will go into more detail of the use of these types of generators further in 3.6 Electric Plant Systems: Diesel Electric with Variable Speed Generators.

With ARV being a cutting-edge vessel performing industry leading research, there are less commonly used systems and products should be considered. Some such products, such as alternative fuels, demonstrate promise in providing advanced solutions to shipbuilding challenges but are not completely available for full-scale adoption at the time of this study. Alternative fuels such as liquid natural gas, hydrogen and ammonia are fuels that significantly reduce, or in some cases eliminate the carbon footprint and air pollutant emissions of the vessel.

Alternative fuels are in the very early commercial stages of being widely used and available in the marine industry. When considering where the ARV will be operating these alternative fuels will not be readily available in those areas. Alternative non-diesel fuels require specific storage and distribution designs outside the norm of current diesel-based systems, making it impossible to use typical ultra-low sulfur diesel (ULSD) designs without replacing the entire fuel distribution on the vessel. Diesel alternatives like biodiesel, renewable diesel, and synthetic diesels all produce lower carbon footprints and produces lower criteria pollutants than ULSD. Specifically, diesel alternatives offer many advantages and create an appealing solution because they utilize industry standard designs for ULSD with little need for specialized equipment. Diesel alternatives have an abundance of advantages and properties that would be useful towards designing a green ship, however the cost of these fuels and lack of availability, especially in the southern hemisphere are extremely prohibitive. This report does not investigate alternative fuels as they are not a feasible design solution for this project currently. However, they should be considered as these fuels develop and become more available. Alternative fuel sources are explored more in the Green Ship Report, see reference 3.

The use of an electric dual azimuth pod propulsion system, power by a hybrid diesel electric plant with a Lithium Ion (Li-Ion) battery system will provide the appropriate propulsion and power for the ARV. Incorporating high pulse VFDs, permanent magnet motors, and smart systems into the auxiliary systems, will complement the electrical plant and help efficiently distribute the power on the vessel. The recommendations made here, and the considerations of what may become available in the future are important in obtaining the goal of having a state of the art, versatile, and optimally performing Arctic Research Vessel.

1.1. Objective

This report investigates the advantages and disadvantages of electric propulsion drive and pod systems, conventional shaft line diesel-electric drive systems and hybrid system designs that incorporate both propulsion types. The report will also cover the auxiliary systems on the vessel that complement the propulsion and electrical plant designs.

1.2. Acronyms

AC	Alternating Current
ARV	Antarctic Research Vessel
ASC	Antarctic Support Contractor
DC	Direct Current
DPS	Dynamic Positioning System
EPA	Environment Protection Agency
G&C	Gibbs & Cox, a division of Leidos
HVAC	Heating, Ventilation and Air Conditioning
LED	Light Emitting Diode
Li-Ion	Lithium Ion
THD	Total Harmonic Distortion
URN	Underwater Radiated Noise
ULSD	Ultra-low Sulfur Diesel
VFD	Variable Speed Drive
VSG	Variable Speed Generator

2. Requirements

There are very specific requirements that the ARV design must adhere to due to the variety of tasks the vessel must accomplish and the operating environments. The vessel will need to meet ABS Ice Class PC3 requirements that affect the propeller design, the transiting and maneuverability of the vessel, and the hull design. In addition to the ARV properly performing in ice breaking operations, the vessel will also need to perform well in open water operations to accomplish a wide variety of scientific missions. For many missions, a dynamic position positioning system (DPS) and bow thrusters will be required to perform position keeping, loitering and auto tracking operations.

The ARV will need to meet some elements of the underwater radiated noise (URN) requirements, such as DNV Silent R, and elements associated with a modified ICES 209 requirements to limit environmental impacts of ARV operations. The challenge will be finding a propulsion plant design that will meet the URN requirements in the low frequency end of the noise spectrum, see references 4 & 5. main is specifically a concern because it is more difficult to filter or block than high frequency noise**.**

The ARV has specific operating conditions the vessel must meet, each with their own requirements. The open water condition requires fuel efficiency for long transit legs, track line ability, and station keeping. Ice breaking operations will require adequate propulsion power to provide high maneuverability in ice, achieve adequate low speed bollard thrust for ice breaking and create a relatively ice-free wake.

When selecting the manufacturer of the propulsion system and/or propulsor, they must have the ability to support the ARV for maintenance and repair from Chile, Australia and/or New Zealand regions of the world.

The ARV will need to perform a multitude of different operations, tests, and studies. This creates a multitude of different operating conditions in which the ARV is expected to perform efficiently. The challenge will be to find the best equipment that allows for versatility, efficiency, and the ability to perform under the various operating conditions.

3. Description and Comparison of Propulsion, Electric Plant, and Auxiliary Systems

A research vessel such as the ARV requires specialized criteria to be met. As noted in the requirements, the electrical propulsion architecture needs to perform properly under many operating conditions. To provide the higher torque at lower speeds needed in ice breaking operations, electric motors driven directly from the generators are recommended. Laboratory work and precise testing will be conducted on this vessel; therefore, electrical harmonics produced by large propulsion motors and power generating engines must be kept at a minimum to ensure clean power is distributed throughout the vessel.

Scientific instrumentation must be deployed from the boat and into the water to monitor and retrieve data. These tests will require drilling operations, ROV launches, and the ability to communicate with and monitor equipment while under water. The vessel must be able to hold tight positioning while scanning the ocean floor, requiring station keeping being implemented with as little noise and interference as possible. While conducting all these operations, considerations to the impacts to the environment and the marine life in the area is top priority. This requires the electrical architecture to adhere to all URN regulations and rules as well as stringent emission standards.

3.1. Propulsion Systems: Conventional Diesel-Electric Shaft Lines

The conventional twin screw shaft arrangements are the most common propulsion system used in current and past ice breaker vessels, and research vessels. This consist of two conventional diesel-electric shaft lines on the port and starboard sides of the vessel. A twin screw propulsion system has relatively low initial cost, high reliability, and lower URN levels than other propulsion systems (See reference 1). Incorporating a dynamic positioning system (DPS) into the conventional twin screw shaft propulsion system would increase the cost of the system (See reference 1). To improve the maneuverability and ice breaking capabilities of a vessel using conventional twin screw shaft propulsions systems; transverse tunnel thrusters, high lift rudders, and design allowances for high rudder angles will be required as well. Control-pitch propellers can be used with this propulsion system, and while fixed-pitched propeller are acceptable for this design, control-pitch propellers would be the most feasible design considering a conventional shaft line.

3.2. Propulsion Systems: Azimuthing Thrusters

Z-Drive
(shown with nozzle)

L-Drive

Podded Drive

Azimuth propulsors are electric propulsors that are popular in ice breaking vessels because of their ability to direct the full propulsion thrust though 360 degrees and provide excellent maneuvering. When the azimuth propulsors Aare paired with bow thrusters, the propulsion plant can provide very efficient and precise DPS capability. This increased maneuverability provided by azimuth propulsors is valuable when operating in ice. The propulsors allow for a high degree of maneuverability and reduced tactical turning diameter in ice compared to conventional twin screw shaft arrangements. The azimuth propulsors can produce a relatively ice-free wake by directing the thrust at outboard angles, allowing for stern launching and towing operations. With their ability to direct thrust forward along the port side or starboard side of the vessel, these propulsors allow for creating ice-free areas along the side of the vessel for the deployment of instruments.

There are three main types of azimuth propulsors, Z-Drives, L-Drives, and podded Drives. Z-Drives have two right angle gears coming from the prime mover which transfer power to the propeller at the end of the drive. L-Drives have a single right-angle gear to transfer power to the propeller with the prime mover situated directly on top of the drive. L-Drives do require a lot of overhead space. Podded drives do not have any right-angle gears, as the main motor is situated within the pod connected to the propeller.

When looking at Z-Drives, and L-Drive azimuth propulsors, manufacturers of these types of drives have facilities in Chile, Australia, and South Africa to supply support. These drives require more fuel, have less mechanical efficiency, higher fuel costs, and higher maintenance costs than podded drives (See reference 1).

Conventional twin screw shaft arrangements are the most common propulsor however azimuthing propulsor are commonly used relative to current ice breaking designs. There are ninety or more podded drive ice breaker vessels currently in use around the globe. Manufactures of podded drives have service facilities in Miami, Singapore, Brazil, South Africa, Australia, and New Zealand. These drives require less fuel, have more mechanical efficiency, lower fuel costs, and lower maintenance costs than Z-drives and L-drives.

While the podded drives reduce gear noise and URN, off-the shelf pods that meet the stricter elements associated with a modified ICES 209 requirements for URN are hard to find. Since the electric motors are in the pods and in contact with the water, noise is an issue. Discussions between our team and the manufacturers of these types of pods will be required. The manufacturer will need to understand the URN requirements of elements associated with the modified ICES 209 requirements and what modifications to the pods will be needed to better meet that standard. The pods can produce noise on the AC bus if not properly filtered. The harmonic distortion produced by the system needs to be monitored and kept within the limits required for the ARV. The ARV will require all methods to reduce noise within the manufacturer's system should be implemented into the design for the ARV. Additional modifications to the "off the shelf" designs that manufactures provide that include phase shifting, harmonic filters, and any additional filters will be requested by G&C to ensure the cleanest power we can have on the vessel**.**

3.3. Propulsion Systems: Hybrid Arrangement

The hybrid arrangement for propulsors is a combination of podded drives and conventional twin screw shaft arrangements. This design incorporates a port and starboard azimuth podded drive, and a centerline conventional propeller. This would allow for the propulsion plant to meet the high-level URN criterion required of the vessel by way of using the conventionally shafted "quiet" centerline propeller as the main propulsor in open water and using the podded drives at low thrust levels. The centerline propeller would be providing most of the propulsion power, and the podded drives would be used mainly for steering and maneuvering. The beam of the vessel restricts the ability to have the hybrid arrangement setup noted in this section of the report. This design would require the ARV to be at least 10 feet wider, and there would need to be room for the third propulsor, and its supporting equipment.

3.4. Electric Plant Systems: Diesel Electric

Diesel Electric is the baseline architecture for the electrical plant for the ARV. This type provides the full rated torque at lower propeller speeds that is critical for ice breaking vessels. The ARV design consists of six main diesel generators, four of the gensets rated at 4.05MW, two of the gensets rated at 3.04MW, and a single 1.20MW emergency generator.

This baseline design would rely on the paralleling, load sharing, and a power management system to run this plant as efficiently as possible. Diesel combustion engines typically run optimally when loaded to around 85% of their capacity. Running generators at a high load increases fuel burn and stress on the engine of the generator and running the generators at a lower load reduces the generators efficiency, wastes fuel, and requires unneeded wear and tear on the engines as well. The limitations on how the generators can handle the different loads conditions that will be present on the vessel for its many tasks, conditions and operations will be challenging with this design.

3.5. Electric Plant Systems: Hybrid Diesel Electric with Batteries.

The hybrid diesel electric plant would consist of the baseline diesel electric architecture with the addition of a Li-Ion battery system. The battery system can be used as a replacement for a spinning reserve, perform peak shaving, and potentially be used as the main power source for the vessel for a limited period. Using the battery system in this way will add reliability, improve efficiency of the electrical plant, and reduce emissions. The addition of the battery bank does come with a higher initial cost, and will add complexity to the electrical plant, yet is the least polluting, and least expensive service life cost design. This is due to the ability to maintain the generators at optimal efficiency, and therefore reducing emissions, and fuel usage. The battery systems have a service life of approximately 10 years, and the batteries have some small degradation over time based on use yet will perform the necessary functions needed over the service life of the system.

The peak shaving function of the battery system will allow the generators to always run at or close to 85% capacity. When the electrical load of the plant has power surges and temporary high amperage states where the vessel's load is more than 85% of all operating generators, the battery bank can take on this extra load allowing the generators to stay at 85% capacity. If the electrical load of the plant is lower than 85% of the operating generator capacity then the available power will be used to charge the battery bank, again keeping the generators running at 85%. This would result in the gensets running at their optimal load, and increases their fuel burning efficiency, as well as lowers maintenance costs on the genset by not putting stress on the gensets. A secondary benefit of this peak shaving function allows the battery system to assist the vessel while operating in an ice breaking condition. When the propulsors need additional power from the power plant while breaking ice, the battery system can take on this extra load allowing the gensets to continue to run at 85% capacity.

The ability to use the battery bank as a replacement for a spinning reserve increases the efficiency and lowers maintenance costs for the plant. If the battery system is properly sized to take on the full electrical load of the vessel for the required amount of time to allow an offline generator to be brought online then the battery system removes the need to have a secondary generator online and running in case of an emergency such as the main generator having a failure and shutting down. The battery system can take on the electrical load at the time of the operating generator's failure and power that load until another generator is started up and brought online. This will result in needing to run the gensets less, burn less fuel, and reduce the wear and tear on the gensets.

One of the more challenging requirements for the ARV is to have the vessel run off strictly battery power for a given condition or test, for a given period of time. A Li-Ion battery system can power the entire vessel for a given period, but considerations must be made to allow the system to accomplish this task. The size of the battery bank in the battery system must be big enough to handle the total electrical and propulsion load for the time required for the task, test or condition required, see Reference 6. This may require a battery bank larger than the vessel can permanently fit into the vessel. Consideration will have to be made towards having an electrical plant that can add and remove battery banks as needed. This would allow the ARV to be more versatile and allow the vessel to meet the requirements of running off battery power for certain conditions and not have to permanently sacrifice the space to store the extra battery banks to achieve the requirement.

The power in a hybrid diesel electric plant distribution system will be important to the overall design. This plant has a main distribution bus that consists of switchboards that control the battery power, generator power, and shore power. The switchboard allows for the distribution of these power sources to the propulsion plant, and Ship's Service loads on the vessel. The distribution bus can be DC powered or AC powered, and which type of power that will be used will be based on the total electrical load of the vessel. G&C is recommending a medium AC voltage bus system as the total electrical load will be over 20MW. This will not affect battery storage or the approximate 10-year (mattering on use of batteries) life span of the batteries.

3.6. Electric Plant Systems: Diesel Electric with Variable Speed Generators

The diesel electrical plant with variable speed generators would consist of the baseline diesel electric architecture except the generators would be variable speed generators (VSG). A variable speed generator has a broader range of operating points, each with its own fuel consumption value. A VSG control system can optimize speed and power for maximizing engine efficiency and fuel efficiency. The largest benefit being when the electrical load is below 50% of the gensets capacity, which is where standard gensets are very inefficient. With the VSG ability to run efficiently at lower speeds that correspond with the electrical load, these gensets have lower maintenance costs and lower emissions.

It should be noted that having a large battery system with VSG's would be redundant. A battery system works with the generators to maintain a constant load on the generators, while a VSG's benefit is that it can work more efficiently at lower loads, so a battery bank would negate the benefits of a VSG. A standard DC power setup (no batteries) is used with a VSG electrical plant design. If the emergency generator can be used as a harbor generator in port, then a VSG may also be considered for the emergency/harbor generator. It would be more efficient at lower loads, which would be the case while in port. As required by SOLAS MSC.1 Circ 1464/Rev. 1, an emergency generator can be used as a harbor generator but one of the requirements is that there are procedures and instructions for setting up the generator as a harbor generator while in port and as an emergency generator while under way, see reference 7. Before the vessel is under way the VSG would have to be setup to work as a standard genset to work efficiently with the battery system.

G&C does not recommend using VSR generators for main gensets. The concern with variable speed generators is the commercial availability and initial costs. This may cause problems with resolving maintenance issues, finding parts, and replacement gensets. The specifications for this project call for a battery bank system to be part of the electrical plant. A design including Li-Ion batteries plus VSG would increase costs for only marginal benefit.

3.7. Auxiliary Systems Considerations that Compliment the ARV Propulsion and Electrical Plants

There are auxiliary systems considered for this design that will complement the electrical and propulsion plants for the ARV. The systems discussed are large with very large electrical loads.

The better these systems can be implemented the more the systems can help the vessel operate more efficiently and provide more versatility to the electrical plant.

The use of Variable Speed Drives (VFD) to run motors for pumps and fans will allow for more control over these components. The use of sensor feedback loops with the VFDs will allow for the control of the speed of these motors and allow for the reduction of the electrical load of these motors. For example, a 25% reduction in the speed of a pump could result in a 58% power reduction for the same pump. Pumps and fans that do not have to run at 100% all the time, a VFD should be considered. Using VFDs does not come without a cost. VFDs create harmonic distortion. As the P-Spec specified the harmonic filters shall not be used as the primary means of achieving the power quality requirements, G&C recommends the use of variable frequency drives (VFD) with higher than standard pulse rates, such as 12 or 16-pulse rates, for systems such as sea water systems, and freshwater systems will provide more control over the electrical load of that motor and mitigate the harmonic distortion that variable frequency drives can produce. The mounts for motors will need finer and more complicated mounts to work with the variations in excitation frequency that will be caused by the VFDs as well. VFD motors that cannot be specified to be higher than standard pulse rate will require line reactors if their use contributes negatively to the power quality of connected systems.

There are options available for the motors used for the ARV. Premium efficiency motors and permanent magnet motors & alternators should be considered for frequently used pumps, and high use machines. For frequently used, vital pumps, and fans, premium efficiency motors are to be considered. There is a small increased cost associated with these premium efficiency motors along with an increase is weight, but for vital pumps and fans that are used frequently the benefits of having a pump that is more efficient, requires less maintenance, and provides better reliability negates that initial cost. Permanent magnet motors are recommended by G&C for larger motors such as propulsors and generators as they are more efficient than standard motors and offer more precise speed control. Permanent magnet motors are also physically smaller which helps save space in locations where space is a premium, such as generator and engine rooms. Permanent magnet motors are more expensive and less available, however with these benefits, consideration for using these types of motors should be made wherever feasible.

Smart control systems for lighting and HVAC systems, advancements in lighting systems and lighting technology have created the opportunity to use these smart systems to better control the overall electrical load for all lighting on a vessel. The use of LED lighting drastically reduces the electrical load for lighting and allows for more control over the lighting by efficiently suppling appropriate lighting, at the appropriate times. Implementing a lighting control system with the LED lighting, can modify lighting scenarios on the boat as needed. G&C recommends implementing a lighting control system with the LED lighting, can modify lighting scenarios on the boat as needed. Ability to control the overall lighting on the boat allows for easy load sharing and load shedding to be done in a controlled and nuanced manor. A similar smart control system is available for HVAC equipment. For a vessel that will find itself in extreme temperatures that also requires specific temperatures and environments for scientific facilities, this type of control over the HVAC system will be a necessity. The ability to modify and control the HVAC system to better control the total electrical load adds versatility and efficiency to the overall vessel operations and optimize the use of the electrical load on the boat.

4. Conclusions and Recommendations

The requirements and specification for the ARV are the main criteria used to determine what the best design and system to use on the ARV. The request that the vessel be state of the art and include a battery system dictates many of the recommendations made for the ARV.

Based on the current width of the boat, and the requirements for maneuverability and ice breaking capabilities, podded drives are recommended for propulsion plant for the ARV. The advantages podded drives provide being a long-term low-cost option, fuel efficient, and high performing for both DPS operations and ice breaking operations makes this the optimal propulsor to use for the vessel (See reference 1).

A hybrid diesel electric and Li-Ion battery system electrical plant will satisfy the requirements noted in the specifications for the ARV. It will allow for the efficient use of gensets, increase the reliability of the plant, and allow for the possible expansion of the size of the battery system to run the boat off strictly battery power. It is recommended to give strong consideration towards using the smallest Ship's Service generator as the harbor generator to save space, and further consideration into this specific Ship's Service generator to be a variable speed generator to allow for the generator to run efficiently while being used as a harbor generator and powering a lower load than 85% of the capacity of the genset.

Vendors typically have distribution system designs that incorporate battery systems and generators which allows for the efficient operation of their podded drives. As the ARV design continues to increase in size, a medium AC powered distribution bus and switchboards should be used to control the electrical plant and propulsion plant. This design will allow for the use of the battery system for peak shaving, replacement for spinning reserves, and powering the vessel off batteries.

Other recommendations are made for auxiliary systems that will help the performance of the electrical and propulsion plants. Using VFD's with sensor feedback loops is recommended to help control motors and reduce excessive and unneeded electrical loads by controlling the pump speeds for what the system needs. Using premium efficiency motors where available and possible for frequently used pumps and fans will help with maintenance costs, with reliability, and overall efficiency. Using permanent magnet motors for larger high use motors like propulsion, gensets and alternators improves efficiency, reliability, speed control, and saves physical space could be done if commercially available. Smart controllers for large boat wide systems like lighting and HVAC is recommended as it would optimize those loads while having control over the system to ensure the systems are efficient yet do not disrupt the work being done on the research vessel.

5. References

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