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Executive Summary

This study investigates and reports on potential propulsor types for the Antarctic Research Vessel (ARV) Performance Specifications. The merits of each regarding characteristics of interest such as performance in open water and ice, mechanical efficiency, underwater radiated noise (URN), and capital and maintenance costs are compared. Systems currently used on recently built Polar research vessels are also presented.

Based on the desire to have a vessel with significantly greater ice going capability than the existing R/V *Nathaniel B. Palmer*, it is recommended that azimuthing propulsors be required by the ARV Performance Specifications. However, if a high-level URN criterion is to be met for open water operations, a hybrid approach should be considered, i.e., using a conventionally shafted "quiet" centerline propeller along with port and starboard wing podded propulsors.

Purpose

The purpose of this study was to investigate propulsor types for the ARV and develop recommendations for how to incorporate the findings to improve the ARV Performance Specifications. The relative performance, cost and reliability are of propulsor options are discussed and inform the recommendations made for propulsor specifications.

Assumptions

The following key assumptions were made:

- Maximum vessel draft of 28'-0" – The draft limitation means that a twin screw arrangement will be favored since maximum propeller diameter will be limited. This maximum draft is dictated by the pier side water depth at Palmer Station.
- Twin propulsors – A twin screw arrangement will be needed to transmit required thrust within the draft limitation. Twin propulsors are also advantageous for dynamic positioning and maneuvering in ice.
- Bow thruster[s] – It was assumed that bow thrusters will be installed to augment dynamic positioning and docking. The bow thrusters are not part of this study.
- Diesel-Electric drive was assumed for this study (Reference 1).

The proposed operating environment for the ARV includes long open water transits from foreign bases such as Punta Arenas, Chile, and Lyttelton, New Zealand. It is assumed that the ARV will spend a significant portion of its mission time in moderate to heavy first-year ice with multi-year ice inclusions (to the extent allowed by its Polar Class 3 classification). Consequently, the ARV must have both excellent open water transiting and maneuvering abilities as well as excellent ice transiting abilities.

Characteristics of Interest

Current propulsor technology for ice going ships covers a wide range of propulsor types, each with their own advantages and disadvantages. For the ARV, the following measures of merit were established for comparing the different propulsor types.

Open Water Performance Characteristics

The open water characteristics of interest for the ARV are:

- Fuel efficiency for long transit legs.
- Dynamic positioning and station keeping capabilities through sea state 6.
- Track line capability within a determined offset deviation.
- Low underwater radiated noise (URN) signature.

Each of these is discussed in the following sections.

Fuel Efficiency for Long Transit Legs

The majority of vessel mission time will be spent in open water conditions. The open water operations will consist of transiting from bases in Chile, Australia, or New Zealand to Antarctica. Additionally, open water science missions are anticipated around Antarctica.

These operating scenarios indicate that propulsor efficiency should be a high priority since fuel consumption will be directly related to propulsor efficiency.

Propellers that are required to meet strict underwater radiated noise requirements as well as ice strength may suffer a significant reduction in propulsive efficiency. A reasonable URN goal dictated by science requirements must be defined (see Reference 2).

Dynamic Positioning and Station Keeping Capabilities

The capability to dynamically position in sea state 6 within a specified watch circle and wind and current forces has a significant impact on the type of propulsor chosen for the ARV. Azimuthing thrusters have a clear advantage in dynamic positioning since they can direct the full thrust of the propulsor through approximately 360 degrees. To achieve acceptable dynamic positioning with conventional shafted propellers requires the addition of high-lift rudders and transverse stern thrusters, in addition to a bow thruster.

Track Line Capability

Track line capability is dependent on longitudinal course stability and high-quality auto-pilot control. Azimuthing type drives can result in directional stability problems due to the lack of rudders unless careful consideration is given to hull/skeg and control system design. This would mean the azimuthing drives would be frequently adjusting their azimuth to maintain a course heading, resulting in a slight zig-zag in the course and additional wear on the steering components of the drive. The zig-zag course will result in greater distance traveled over the track line as well as more propulsion power being expended in course correction maneuvers, both of which will consume additional fuel over the given track.

Often a track line may be best achieved by crabbing, where vessel heading, and course heading are different.

Low URN Signature

URN values require non-cavitating propellers through the speed range of interest. All azimuthing type thrusters will have difficulty meeting stringent URN criteria, such as ICES 209 or DNV Silent R, in the low frequency end of the noise spectrum (see Reference 2 for further discussion). If a significant part of the open water leg of ARV missions requires very low URN, consideration should be given to a conventional or hybrid arrangement, e.g., azimuthing thrusters with a centerline conventional propeller that is capable of meeting noise goals in the low frequency end of the spectrum.

Ice Operations Performance Characteristics

The propulsor's ice operations characteristics of interest for the ARV are:

- Adequate strength to operate in ice conditions.
- Ability to maneuver well in ice.
- Ability to provide a relatively ice-free wake.
- Adequate low speed and bollard thrust for ice breaking.

Polar Class 3 strength requirements will dictate certain propeller design features such as thicker blade scantlings, thicker propeller tips, larger propeller hubs. For azimuthing units, the leg lengths may be limited due to structural limitations thereby reducing the maximum propeller diameter that can be accommodated. A smaller propeller diameter can result in higher blade loading and higher tip speeds having an adverse effect on efficiency and noise.

The actual power requirements needed for transiting and maneuvering in the environment prescribed for a Polar Class 3 vessel will depend on several influencing factors in addition to power available to the propulsors:

- Hull form influences such as the angle of buttocks and waterlines at the bow.
- The hull form's ability to shed ice away from propeller discs thereby reducing propeller-ice interaction.
- The shape of buttocks and waterlines at the stern to facilitate breaking ice astern which is an important attribute for maneuvering.
- The shape and extent of any parallel mid-body.

Maneuverability in Ice

A significant aspect of ice navigation involves "ice avoidance." This is the use of open leads in the ice to facilitate transiting to a desired destination. This activity can be enhanced by having a highly maneuverable vessel with a low turning radius and the ability to quickly reverse course and change direction. There are some features of hull geometry that can be included in the design to improve maneuverability in ice, but azimuthing drives have proven in recent years to offer significantly more maneuverability to ice breaking vessels than hull optimization alone can provide.

Ice-Free Wake

An important attribute of the propulsors is the ability to leave a relatively ice-free wake, especially for over-stern science operations in ice. Azimuthing propellers have a clear advantage for producing ice-free wakes as the thrusters can be angled away from centerline to push ice away from the transom.

Ice Breaking Low Speed and Bollard Thrust

Bollard, and low speed thrust is needed for efficient ice breaking. The thrust can be improved using propeller nozzles. However, nozzles may have a negative impact on higher open water speeds as well as URN if not specifically designed around noise criteria. Nozzles have also been shown to easily clog with ice during ice transiting.

Other Characteristics

In addition to the desired performance characteristics described above, the following measures of merit apply generally:

- Reliability and maintainability. Considering the remote operating areas, this is imperative. Ideally, the selected propulsor manufacturer will have service facilities in key southern hemisphere locations such as Chile, Australia, and New Zealand. A certain number of strategic spares could be warehoused in Chile.
- Cost. Capitol cost, operating cost, and maintenance cost.

Propulsor Comparison

Various suitable candidate propulsor arrangements were examined for this study, including systems used on recently built or planned polar vessels, system efficiencies, and costs.

Propulsor types

There are two basic types of propulsor alternatives suitable for the ARV: conventional shafting (with propellers, rudders, and transverse thrusters) and azimuthing stern drives. Both alternatives have variations that may be of advantage to a polar research vessel.

Conventional Shaft Lines

Conventional twin screw shaft arrangements are common on many research vessels and ice breakers. This type of propulsor arrangement has the advantage of lower capital cost, high reliability, and lower contribution to URN. However, capital costs are offset by the additional equipment needed to provide an acceptable level of dynamic positioning performance (equivalent to azimuthing drives): transverse tunnel thruster(s) at the stern, high-lift rudders, and rotary vane steering gears that allow higher rudder angles.

Conventionally shafted propellers may be fixed-pitch propellers (FPPs) or controllable-pitch propellers (CPPs). The propellers can be driven by AC or DC motors or driven directly from a diesel prime mover. For ice breaking service the propellers are normally driven by electric motors that can provide high torque through the full range of propeller rpm.

Azimuthing Thrusters

There are three possible options for azimuthing propulsors (Figure 1). Z-drives have an upper and lower right-angle gear set between the motor input flange and the propeller. L-drives have the propulsion motor situated vertically directly driving the vertical shaft of the drive, thereby eliminating the upper right angle gear set. Podded drives (e.g., ABB's Azipod®) have the drive motor directly connected to the propeller with the motor housed in a pod at the lower portion of the unit, thereby eliminating gear sets altogether.

Figure 1 Azimuthing propulsor alternatives (Kongsberg and ABB)

Azimuthing drives have been used on research vessels for a number of years. Due to their ability to direct the full propulsion thrust through 360 degrees, they provide excellent maneuvering, and, when combined with bow thrusters, excellent dynamic positioning capability.

Azimuthing drives provide additional benefits for operating in ice. The high degree of maneuverability and reduced tactical turning diameter in ice is an advantage. The ability to direct the thrust at outboard angles can provide a relatively ice-free wake which makes over the stern launching and towing operations possible in ice covered conditions. The thrust can be directed forward along the port or starboard side of the vessel to create an open water area for deploying instruments over the side.

Azimuthing drives can be arranged with propellers facing forward (pulling) or aft (pushing). Pulling propellers may offer higher efficiency since they have unobstructed flow into the blades. Nozzles can be fitted on either type of azimuthing drive and can provide higher low speed thrust. However, nozzled propellers have a sharper cavitation incidence which may be detrimental to URN mitigation. They can also easily clog with ice requiring propeller reversing to free the nozzle of ice.

Geared azimuthing drives have been in use in United State research vessels for many years including on the AGOR 23 class vessels, the University of Delaware's *Hugh R. Sharp*, the Regional Class vessels currently under construction, and on the NSF/University of Alaska Fairbanks icebreaking research vessel, R/V *Sikuliaq*.

A.1 Z-Drives

All of the above vessels are diesel electric with electric propulsion motors driving an input shaft to the Z-drive which transmits power through an upper right-angle gear set down to a lower right-angle gear set which drives the propeller. The drives are capable of 360-degree rotation with the rotational movement provided by geared hydraulic motors driving the azimuthing gear.

Although Z-drives provide the excellent maneuverability and dynamic positioning needed in oceanographic vessels, the upper and lower right-angle gear sets are a contributing factor to URN. The British research vessel RRS *Discovery* is fitted with Z-drives and is purported to meet the URN standards of DnV Silent R, although this vessel does not have a high ice class, Lloyds Ice Class 1D (very light ice conditions). The *Sikuliaq* design goal was to meet a modified ICES 209 requirement at a reduced speed of 8 knots with somewhat higher URN permitted in the low frequency end of the spectrum. As built the *Sikuliaq* exceeds the modified ICES standards below 250 Hz.

A.2 L-Drives

A variation of the Z-drive that eliminates the upper gear set is the L-drive. This type of drive has the propulsion drive motor arranged vertically on top of the drive thereby eliminating the upper right-angle gear set. This type of drive may provide for a somewhat reduced gear noise contribution to URN. However, L-drives may require additional overhead space in the drive room to provide clearance for the electric motor. This may result in an undesired increase in freeboard. Initial arrangement offered by manufacturer indicates that the overall height of an L-drive unit exceeds available height. Further investigation in the next design phase will be needed to determine if low-profile drive motors can be supplied in the power range needed.

A.3 Podded Drives

Podded drives, such as ABB's Azipod, have similar maneuvering characteristics to those described above for Z-drives and L-drives. The primary difference is that the drive motor is located in the lower part of the drive in a "pod" such that the propeller is directly driven by the electric motor, thus eliminating the upper and lower right angle gear sets found in Z-drives.

Podded drives on icebreaking vessels are becoming increasingly common. ABB, one of the major podded drive manufacturers, claims over 90 icebreaking vessels are fitted with their drives. Notable installations on polar vessels include the recently built R/V *Xue Long 2*, the USCG Polar Security Cutter (PSC), the USCG Great Lakes Ice Breaker (GLIB), and the new Finnish Baltic Icebreaker *Polaris*.

Although podded drives eliminate the gear noise contribution to URN, the unfiltered AC motor noise has been an issue. The leading manufacturer of podded drives, and the only manufacturer offering ice strengthened drives in the power range needed for the ARV, is ABB's Azipod drive system. To date there are no ABB Azipod-equipped vessels that meet the ICES 209 requirements for URN. However, ABB claims to be developing solutions to mitigate URN to meet ICES 209 requirements.

Recent Polar Vessel Propulsors

Recently built or planned Antarctic research/resupply vessels and their propulsion characteristics are shown in Table 1. Note that, with the exception of Australia's new vessel RSV *Nuyina*, these vessels are diesel-electric drive.

Table 1 Recent Antarctic/Arctic Vessels

Vessel	Country	Polar Class	Built	Displacement MT	Power kW	Propulsor Type
R/V *Kronprins Haakon*	Norway	3	2017	10,000	17,000	Twin Z-drives with nozzles
R/V *Xue Long 2*	PRC	3	2019	14,300	15,000	Twin Azipods
RRS *Attenborough*	UK	4, 5	2020	12,790	18,000	Twin Promas[1] conventional
RSV *Nuyina*	Australia	3	2020	25,500	26,600	Twin conventional controllable pitch propellers
CCG *Diefenbaker*	Canada	2	2029[2]	23,325	36,000	Triple: Azipod on centerline with fixed wing propellers
USCG Polar Security Cutter	USA	2	2024[2]	23,300	45,200	Triple: Azipod wings with direct drive on centerline

1 Promas type propeller/rudder arrangement features a stern bulb located on the rudder directly aft of the propeller hub. This type of arrangement is estimated to gain 2-6% in open water propulsive efficiency.

2 Planned.

Relative Efficiencies

Given the long transit distances, propulsor system efficiency is an important measure of merit. Table 2 below gives basic estimates of the propulsion train efficiency from the power generation source (e.g. diesel generator) to the propeller.

Propeller efficiency is not considered here; given the requirements for limiting URN, the propeller design and efficiency will be subject to detailed analysis and design beyond the scope of this study. The *Sikuliaq* propellers are fixed-pitch open wheel Z-drives with the propeller design parameters requiring Polar Class 5 strength, high thrust and cavitation inception limited to speeds above 8 knots. Although the propellers met these demanding design criteria, they sacrifice efficiency. Propeller hydrodynamic efficiency can be thought of as the amount of useful work obtained from the propeller divided by the work expended. The propeller efficiency for the *Sikuliaq* is 0.41 (or 41%), compared to an open water propeller optimized for low cavitation and noise such as the propeller on the NOAA fisheries research vessels that have an efficiency on the order of 0.65 (65%).

As shown in Table 2, the mechanical efficiency of the candidate systems varies from a low of 87% for the Z-drives to a high of 97% for the conventionally shafted CPPs. These efficiencies represent the mechanical losses from gears, bearings, etc.

Table 2 Comparative mechanical efficiencies of propulsors

Major Components	Z-Drive	L-Drive	Azipods	Hybrid[1] Direct Diesel Drive	Direct Diesel-Electric Drive
Generator	0.97	0.97	0.97	0.985	0.97
Switch Boards	0.998	0.998	0.998	0.999	0.998
Converters	0.985	0.985	0.985	0.9925	0.985
Electric Motor	0.96-0.97	0.96-0.97	0.9546	0.98-0.985	0.96-0.97
Gearbox – Single Stage	-	-	-	0.97-0.98	0.98-0.99
Gearbox – Multi-Stage	-	-	-	0.94-0.96	0.95-0.97
Shaft & Bearings	-	-	-	0.97-0.99	0.97-0.99
Upper Drive	0.975	-	-	-	-
Lower Drive	0.975	0.975	-	-	-
Propeller bearing	0.999	0.999	0.999	-	-
TOTALS	**0.869-0.878**	**0.892-0.901**	**0.909**	**0.873-0.933**	**0.912-0.970**

[1] Combination of azimuthing thrusters with a centerline conventional propeller.

To illustrate how these efficiencies translate into fuel consumption, average efficiency values were used to calculate relative fuel consumption for an example case: an 8-day mission leg in calm open water at a transit speed of 12 knots. Table 3 summarizes the results and shows an incremental fuel cost increase of between 2.7% and 6.0% over the baseline case of direct motor driven conventional shafts with CPPs.

Table 3 Fuel consumption comparison

Configuration	Mechanical Efficiency	Fuel Used	Fuel Cost	Incremental Cost Increase	% Increase
Direct Diesel-Electric	0.941	97,973 gal	$148,480	Baseline$	
Azipods	0.909	100,627 gal	$152,501	$4,021	2.7%
L-Drives	0.897	101,769 gal	$153,334	$4,854	3.3%
Z-Drives	0.874	103,818 gal	$157,338	$8,858	6.0%

Costs

Relative Unit Costs

Suppliers able to manufacture propulsors with high ice class were approached for rough order-of-magnitude (ROM) costs for a ship set of propulsors complying with the following criteria:

- 5 MW power per propulsor
- ABS Polar Class 3
- Electric Motor Drive
- Low URN

Suppliers offering feedback, information, and costs for the propulsors able to meet these requirements were:

- Kongsberg Maritime
  - Contact: Bruce Trent (bruce.trent@km.kongsberg.com)
  - Z- and L- Drives
  - Conventional Shaft + CPPs
- ABB Azipod
  - Contact: Samuli Hanninen (samuli.hanninen@us.abb,com)
  - Podded propulsors
- Siemens
  - Contact: Luke Briant (luke.briant@siemens.com)
  - AC electric propulsion motors for all but Azipod drives

To do a consistent comparison between the propulsor types, the cost of the electric motor was added to the cost of each, except for Azipods since the motors are included as an integral component of the system.

The cost of the conventional shafted configuration includes the additional cost of high lift rudders, steering gears, and two transverse tunnel thrusters. These additional components are needed to approach the dynamic positioning capability offered by the azimuthing drives.

Table 4 compares ROM capital cost estimates for a ship set of each propulsor type.

Table 4 ROM unit costs for a ship set of candidate propulsors (References 3, 4, 5, and 6)

Candidate Propulsors	Vendor	ROM Cost USD[1,2]
Two Azipod units (includes motors)	ABB	$15,000,000
Two Z-drives + Two Motors	Kongsberg/Siemens	$12,500,000
Two L-drives + Two Motors	Kongsberg/Siemens	$12,800,000
Two Shafted CPP Promas Props + Two Motors[3]	Kongsberg/Siemens	$7,900,000

1. Costs assume one Euro = 1.19 USD.
2. ABS Standard spares are included in costs.
3. The shafted arrangement costs include the costs of the following:
   -Two high lift rudders with steering gear.
   -Two transverse tunnel stern thrusters.

Relative Operating Costs

Suppliers provided standard operating and maintenance costs for a ten-year service period (Table 5). Costs include unit parts but assume servicing labor comes from ship's crew. Drydocking and other yard costs are not included in these numbers.

Table 5 ROM costs for 10-year maintenance of Candidate Propulsors (References 5, 7, and 8)

Candidate Propulsors	Vendor	ROM Cost USD[1]
Two Azipod units (includes motor)	ABB	$7,740,000
Two Z-drives + Two Motors	Kongsberg/Siemens	$3,900,000
Two L-drives + Two Motors	Kongsberg/Siemens	$3,900,000
Two Shafted CPP Promas Props[2]	Kongsberg/Siemens	$1,000,000

1. Costs assume one Euro = 1.19 USD.
2. The shafted arrangement maintenance costs include the costs of the following:
   -Two high lift rudders with steering gear.
   -Two transverse tunnel stern thrusters.

Recommended significant service (i.e., drydocking) intervals are typically required at five-, ten-, and twenty-year periods for all of the candidate propulsor types.

All of the candidate propulsors may benefit from a condition monitoring system (CMS) which will predictively identify parts needing replacement or service. ABB offers remote monitoring via their CMS program as well as a remote diagnostics program.

The manufacturers have varying degrees of service facilities and support in the ARV operating areas:

- Kongsberg Maritime has service facilities in Chile, Australia, New Zealand and South Africa. Global service is available.
- ABB Azipod also is also prepared for global servicing and has several first-tier support centers, the closest to the ARV operations area being Singapore and Miami (Reference 9).

Risk mitigation

Given the remote operating area and distance to qualified service centers, a risk mitigation program for the propulsors is advised and recommended for inclusion in the Performance pecifications. Such a program may consist of the following components:

- **Enhanced propulsor specification for Z, L drives.** Experience on the U.S. Navy's AGOR 23 class vessels have shown that right-angle gear sets may be vulnerable to damage from inadequate tooth contact combined with inadequate case hardening depth. A thorough review of the selected manufacturers machining and testing program is recommended.
- **Continuous monitoring system (CMS).** A CMS is recommended. These systems can provide predictive maintenance guidance and generally identify potential mechanical issues well enough in advance to facilitate correction ahead of failure.
- **Strategic spares (depot spares).** In addition to spares recommended by the propulsor manufacturers it is recommended that a certain inventory of parts otherwise requiring a long manufacturing lead time be purchased and warehoused at the vessel's advance base, e.g., Valparaiso. These "depot" spares will vary depending on the type of propulsor. Example depot spares are given below:

Table 6 Recommended depot spare parts inventories

Propulsor Type	Recommended Spare Parts Inventory	Estimated Cost
Conventionally shafted CPP	Spare propeller blades, P/S Spare CPP hub	$1,190,000
Z-Drives	Upper right-angle gear set, P/S Lower right-angle gear set, P/S Propellers, P/S	$1,404,000
L-Drives	Lower right-angle gear set Propellers, P/S	$795,000
Azipods	Slewing bearing Thrust bearing Propeller bearing Propeller bearing adapter sleeve Propellers, P/S (not in above cost)	$781,000

Noise

The candidate azimuthing propulsor systems will have an impact on URN to varying degrees. The Z-drive configuration will have noise contributions from both the upper and lower gear sets. For example, the R/V *Kronprins Haakon*, which has twin 5.5MW Z-drives, exceeds the DNV Silent R criteria in the low end of the requirement spectrum (below 1,000 Hz).

The L-drive configuration could theoretically have a reduced impact on URN due to the elimination of the upper gear set. However, no recent installations where URN was tested for this configuration were identified.

ABB Azipods have recently worked to decrease the URN attributed to the AC motors located in the pods, which are in direct contact with the water. Although full scale trials data is not available, in-house simulations conducted by ABB show that lower levels of URN can theoretically be achieved.

If meeting a relatively onerous URN level, such as DNV Silent R is deemed essential for open water missions, a hybrid triple screw propulsor arrangement should be considered. Such an arrangement may consist of a conventionally shafted centerline propeller optimized for quiet open water propulsion with two azimuthing wing propellers to provide the needed thrust and maneuvering characteristics required for ice transit as well as open water dynamic positioning. While operating in the quiet open water mode the wing propellers would be operated at low thrust levels to provide steering forces. ABB Azipod has previously simulated this type of arrangement and reports that they are able to keep the steering forces provided by the wing propellers while staying under ICES noise level requirements. If this design path is to be considered in the next phase these claims would need to be validated.

The centerline propeller optimized for quiet open-water low noise and propulsive efficiency would contribute to the overall efficiency of the vessel while on long transit legs. It would allow the design of the wing thruster propellers to be optimized for thrust in ice conditions. Given the significant amount of time that the vessel will be in open water the addition of a centerline propeller could result in significant life-cycle cost savings. However, the addition of a third propulsion motor, shaft line, and center propeller will result in undesirable space constraints, particularly in the main engine room where the third motor would need to be located.

Hybrid triple screw installations are proposed for the new Canadian icebreaker CCG *Diefenbaker* as well as the new USCG Polar Security cutters.

An abbreviated design cycle would be recommended to explore the triple screw option. Given the machinery arrangement in the current concept design it is estimated that an additional mid-body length of at least 10 feet would be needed to accommodate the additional drive motor. This will impact arrangements throughout the vessel and the added cost would need to be compared to any life-cycle cost savings that accrue to improvements in open water efficiency.

This type of arrangement would increase both capital and maintenance costs. The following is an estimate of the incremental cost increases:

- Capital cost increase, approximately $3M.
- Maintenance cost increase, 10 year, approximately $0.5M.

Findings

A review of anticipated science missions and past experience with the *Nathaniel B. Palmer* indicates a high value is placed on ice going ability (Reference 10). Based on the ARV's anticipated areas of research, azimuthing drives are favored due to their ability to provide efficient ice breaking, maneuvering and wake clearing characteristics. The azimuthing drives will increase the ability to perform science operations in ice covered and open waters due to their ability to:

- Reach areas that would otherwise be difficult for a conventionally shafted vessel to reach.
- Produce a clear, ice-free wake easing launch, recovery and towing from the stern of the vessel.
- Push ice away from the starboard side of the vessel to allow instrumentation to be lowered over the side.
- Provide superior dynamic positioning and station-keeping capability.

We recommend azimuthing propulsors for this vessel as they are essential for effective ice-going transits to and from the areas of interest for anticipated science missions. Additionally, azimuthing drives provide an effective way to conduct on-station work in ice and open water. An experienced operator's perspective on the use of azimuthing drives in ice operations from Capt. Dan Oliver (USCG, retired) is offered in Appendix A (Reference 11).

Dependent on the degree of URN that may be tolerated for open water missions, the following ranking from lowest URN contribution to highest is suggested:

- Podded propulsors.
- L-Drive propulsors.
- Z-drive propulsors.

Should URN in open water conditions be critical to anticipated missions we recommend that the hybrid triple screw option be considered.

Specification Changes

Recommended Changes

The following changes to the ARV Performance Specifications are recommended:

- Specify twin azimuthing propulsors of a power suitable for the stated ice performance and ABS class but a minimum of 5.5 MW each.
- Specify minimum azimuthing rate.

- Specify noise/cavitation requirements.
- Specify over-torque capability and timeframe.
- Specify (as a goal) the UNOLS specifications for right angle gear sets.
- Specify that shop tests of the propulsors must include full scale maximum torque testing.
- Specify stainless steel propellers meeting ABS PC3 requirements.

Required Owner Decisions

1. Would the Owner like to investigate the feasibility of a hybrid triple-screw propulsor arrangement? This would require another iteration through the design spiral to ascertain, at a conceptual level, impacts to:
    a. Principal dimensions.
    b. Capital and life-cycle costs.
    c. Maintenance costs.
2. A decision is needed whether to specify azimuthing drives or conventional shafts and rudders.
3. If azimuthing drives are selected, a decision is needed whether to specify Z-drives or podded drives, or leave that decision to the discretion of the designer. Both types of drives have been shown to be reliable in ice service. Z-drives have lower maintenance costs and can, with the right vessel design features, be removed for servicing while the vessel is in the water, however few research vessels are designed to achieve this. Podded drives typically require dry-docking the vessel for servicing the pods and moors. If the triple screw arrangement is pursued, we would recommend that podded drives be used in conjunction with the centerline propeller since the podded drives would be quieter that the Z-drives while freewheeling or providing steering forces at low power.
4. A decision is needed on what maximum URN, if any, should be specified.

Appendix A Operational Opinion on Shaft Versus Azimuth Drives For Icebreaker Propulsion

05 April 2021

Subj: OPERATIONAL OPINION ON SHAFT VERSUS AZIMUTH DRIVES FOR ICEBREAKER PROPULSION

From: Daniel K. Oliver, Captain USCG Retired
To: Glosten Associates

Ref: Your ASC Research Vessel Replacement Program Propulsor Study, Rev P0, dtd 30 Dec 2020

I am providing this memo in support of Glosten's conclusion in the referenced study that the ARV Performance Specification should require the ARV to use azimuth propulsors. I believe the the operational advantages provided by azimuth propulsors over conventional shafting and rudders for a research icebreaker more than off-set the higher acquisition and life-cycle costs of the azimuth propulsors, providing a best value ARV. This is based on my operational experience in USCG on various USCG icebreakers (all with shaft driven propulsors and rudder(s)), my experience with the PC5 class R/V SIKULIAQ (which uses Z-drive azimuth propulsors), broad maintenance/operational experience from having worked with every USCG icebreaker class built since the 1940's (including the design of the USCG's new azipod driven heavy icebreaker currently under contract) along with experience working with a number of foreign icebreakers. The improvement you get in icebreaking capability due to the added maneuverability of using azimuth propulsors gives you a ship that matches the icebreaking capability of a shaft driven icebreaker of greater displacement and power.

The operational advantages that azimuth propulsors provide a ship for maneuvering is well documented so I won't reiterate them here. Suffice to say that those advantages provide excellent operational capability to a research ship in open water. It can be equally said that a well-designed ship with shaft driven propellers and rudders combined with bow and stern thrusters can provide similar open water maneuverability. The big difference between the two types of propulsion though is most of those maneuvering capabilities in open water translates well into use in ice for azimuth propulsors while any ship with rudders loses most of its backing maneuverability because of the susceptibility of the rudders to damage in the ice when backing. Azimuth propulsors also provide significant improvement in capability over shaft driven propellors for two key science operations: clearing of ice from the side of the ship for over the side work and clearing ice astern of the ship for towing operations in ice.

A successful icebreaker depends on four broad attributes: hull form, displacement, power, and maneuverability. For a given class of icebreaker, a lessor capability in any of the attributes can be largely overcome by enhancement in the other attributes. USCGC HEALY does a good job breaking ice ahead because it has heavy displacement with moderate power. It doesn't maneuver well in ice because of the hull form (long parallel mid-body) and has essentially no maneuverability when backing other than straight back or to weathervane into the wind. The USCG Polar Class icebreakers don't have the displacement of HEALY (approx. 3,000 LT less), but much higher power and a hull form that provides for better maneuverability when going ahead. A Polar Class is still limited in its ability to back though because of its rudder. SIKULIAQ has a relatively light displacement and power for a PC5 class icebreaker, but because of its maneuverability due to azimuth propulsors it has excellent ability to avoid (or get out of) trouble in the ice, giving it the equivalent capability of a larger and more powerful PC5 class ship with shaft driven propulsors.

NSF wants the ARV to have PC3 capability, but also wants to keep the size and power in the range of the ARV concept design which is at the light end of the scale for PC3 capability. To offset limitations in displacement and power, I believe the ARV will need to optimize hull form and maneuverability. Azimuth propulsors combined with a good icebreaking hull form will provide the ARV with the level of icebreaking performance NSF is striving for while staying in the same magnitude of displacement and power of the concept ship. I believe a concept design size ARV with azimuth propulsors could closely match HEALY's capability in all but the heaviest of ice under pressure despite it being roughly 60% the displacement of HEALY.