Antarctic Research Vessel (ARV)

Engineering Report: Icebreaking Performance Report

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Preliminary Design, @IDR5

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1. Executive Summary

This report discusses the hull form design for the Antarctic Research Vessel (ARV) in accordance with standard practices and team processes in order to maximize icebreaking performance and ice maneuvering, to meet the National Science Foundation (NSF) ARV ship Performance Requirements (P-Spec), Reference (1). Additional discussion of overall hull performance, including open water resistance and powering and bubble sweep down may be found in the Hull Form Trade-Off Study and the ARV Model Test Report, Reference (2) and Reference (3) .

A parametric analysis was performed for a range of existing hull form designs to determine the best ship characteristics to implement in the Preliminary Design (PD) ARV hull form. The analysis provided the target hull Icebreaking (IB) angles for the ARV design. A hull form design was developed, with all target IB angles incorporated into the design.

The hull form was first numerically analyzed to estimate the IB thickness capability and the maneuvering performance in ice. The Objective Key Performance Parameter (KPP) for icebreaking requires the ARV break 4.5 ft of level ice with 12 in of snow at 3 knots; this is equivalent to a total of 4.83 ft of ice. Preliminary IB capabilities were determined using the Tsoy’s Method, detailed in Reference (4), which determines the IB capability based on the hull geometry. Based on the Tsoy’s Method, with a provided Propulsion power of 19.3 MW, the ARV has an IB capability of 4.83 ft, meeting the objective KPP requirement.

In accordance with Reference (1), the ARV ice maneuvering performance is determined by the ship’s ability to break out of its previously broken channel, the Turning Circle (TC) maneuver and the Star Maneuver. Based on the numerical estimates, the ARV will break out of a previously broken channel while moving ahead within 1.0 LWL, break out of a previously broken channel while moving astern in 0.8 to 1.0 LWL, complete a TC maneuver ahead within 5.6 to 6.0 LWL, and perform a Star Maneuver within 1.25 to 1.5 LWL.

Following the numerical analysis, the ARV hull completed Ice Model testing at the Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) Ship Design and Research facility in Hamburg, Germany in March through May of 2023 in three different level ice conditions, the objective 4.83 ft ice thickness, 3.0 ft, and 3.3 ft of ice thickness. Physical Ice Model testing was used to validate the preliminary icebreaking performance and determine the power required to break ice both ahead and astern, as well as validating the ice maneuvering performance for breaking out of a previously broken channel for ahead and astern, the TC capability, and the length required to perform a Star Maneuver.

The Ice Model testing concluded that the ARV will achieve breaking 4.83 ft of ice thickness ahead at 17.4 MW, and astern at 18.4 MW, which fall within the installed propulsion power of 19 MW.

Additionally, the model test concluded that the ARV can break out of a previously broken channel while moving ahead within 2.5 LWL, and to break out while moving astern within 1.0 LWL. The break out ahead length exceeded the numerically predicted 1.0 LWL, but both break out tests were completed within 300 seconds, which meets the objective performance requirements in accordance with Reference (1).

In accordance with the ARV requirements, the maximum TC diameter is required to be within 4 LWL in 3.5 ft of ice thickness. Ice Model Testing concluded that the ARV can complete a TC ahead within 2.0 LWL, and astern within 1.5 LWL, in an ice thickness of 3.0 ft. The tests were not completed at the specified 3.5 ft of ice, however based on the exceptional performance of

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performing a TC ahead within 2.0 LWL, and astern within 1.5 LWL, the ARV can be assessed to perform the TC within the required 4.0 LWL as specified in Reference (1). Ice Model testing determined that the distance to perform a Star Maneuver is within 1 ship length, meeting the requirement to complete the maneuver within 400 ft of the starting position.

The Ice Model testing also verified the vessel's ability to shed ice after it is broken, reducing ice coverage on the hull. This included demonstrating that the rounded ice knife prevents broken ice from passing over the forward edge of the ice knife, and pushes the broken ice from the bow away from centerline. This prevents significant portions of the broken ice from traveling under the vessel and past the bottom shell mounted electronics. When traveling astern, the Azipods may be orientated to push the ice away from the centerline. Ice passing through the Azipods was influenced by the skeg which acted similarly to the ice knife and pushed the ice away from centerline. The results of the ice shedding in the Ice Model tests will be used to further develop the science package protection measures from ice interaction.

The Ice Model Testing demonstrated the ice management capabilities of the ARV when transiting 3.3 ft thickness of unbroken ice and when transiting a brash ice field in order to support scientific equipment towing operations. The total power to break ice at the objective ice thickness does not provide sufficient power margin to direct the thrust outwards to divert the broken ice. As such, the channel clearing demonstration was conducted using an ice thickness of 3.3 ft. The tests demonstrated that angling the pods in both unbroken and brash ice conditions will provide a clear channel to safely support towed operations in ice.

The notional bow thruster location and size for the Ice Model Tests showed that there was no impact on icebreaking performance due to ice ingestion. The location of the seachest continues to be under development. Therefore, the effects of ice on the seachest will be evaluated in subsequent revisions of this report and Model Testing.

1.1. Acronyms

ARV	Antarctic Research Vessel
CNIIMF	Central Marine Research and Design Institute
D/LWL	Diameter vs Length on the Waterline
DWL	Design Waterline
IB	Icebreaking
IN	Inch(es)
FT	Foot or Feet
KPP	Key Performance Parameter
NSF	National Science Foundation
L/B	Length to Beam Ratio
LWL	Length on the Waterline
PD	Preliminary Design
P-SPEC	Performance Requirements
TC	Turning Circle
USCGC	United States Coast Guard Cutter
VFI	Vendor Furnished Information

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2. Introduction

This report documents the icebreaking performance estimation developed for the National Science Foundation (NSF) Antarctic Research Vessel (ARV) during the Preliminary Design (PD) phase. This report details the icebreaking (IB) design considerations, IB maneuvering performance, and methods for clearing ice away from the science mission package based on preliminary predictive methods and physical Ice Model testing.

The location of the seachest continues to be under development. Therefore, the effects of ice on the seachest will be evaluated in subsequent revisions of this report and Model Testing. The Bow Thruster is still under early development, but it is predicted to have minimal effect on icebreaking performance. The size and position are to be determined following Model Testing.

3. Approach

Multiple iterations of the ARV hull form were analyzed to ensure that all icebreaking requirements were met. The optimization of the hull was determined using a combination of design best practices, VFI data from vendors, and established icebreaking estimation methods, as discussed in the following sections.

3.1. Icebreaking Hull Form Design

3.1.1. Icebreaking Hull Form Design Approach

The ARV hull design incorporates hull angles that are proven to be efficient for low ice resistance. The hull angles were determined from a parametric analysis of similar ice breaker hull forms. After developing a hull form with the desired icebreaking hull angles, the total bollard pull was calculated and used to determine the propeller diameter and the required shaft power. These estimates will be inputs to other design factors such as the available displacement and stern geometry to incorporate the Azipods.

3.1.2. Mainstream Icebreaking Hull Design Parameters

Conventional icebreakers built in the last 50 years have similar primary dimension ratios and hull angles. The primary dimension ratio considered in the design was the length to beam (L/B) ratio. The L/B for seagoing icebreakers ranges from 3.8 to 5.0, with a mean of 4.45, as shown in Figure 1. It is common to have specification restrictions for the length or beam, which may lead to a non-optimal hull form in terms of ice performance.

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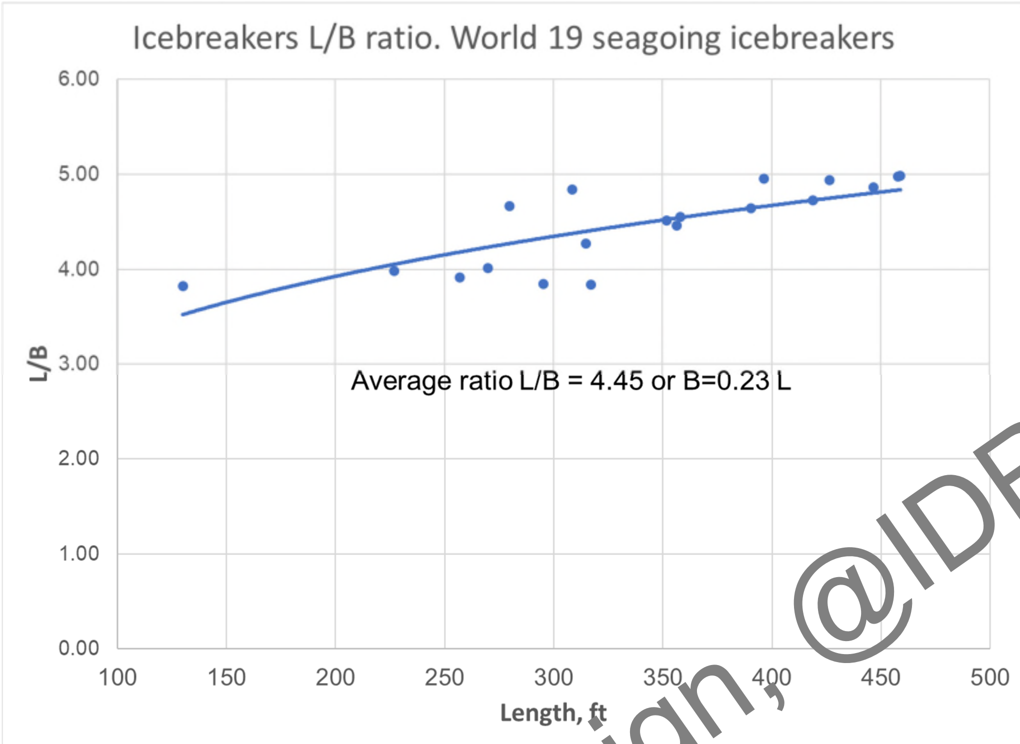
Figure 1: L/B Ratio for Seagoing Icebreakers



The beam and draft have a significant effect on the IB capability. Beam has a linear function relationship with the ship's ice resistance in all methods used to compute IB capability. The ship draft determines the size of the propulsor and its propeller diameter. The propeller diameter is limited to approximately 55% - 60% of the ship's draft. Estimating the IB capability involves the bollard pull calculation which is a function of the shaft power and propeller diameter.

The next critical aspect of icebreakers are the hull angles. For icebreakers, the IB capability and maneuverability in ice is determined by the icebreaking angles along the waterline. These angles are the stem, the half entrance, and the flare at the Forward Perpendicular and midship. As a secondary capability, the rake angle on the transom is also considered for IB going astern. See Table 1 for examples of icebreaking angles from traditional icebreaking hulls when compared to the ARV.

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Table 1: Examples of Critical Icebreaker Hull Form Angles

Angle	Healy	Mackinaw	Henry Larsen	Nathaniel B. Palmer	ARV
Stem	20	19	17	28	20.0
Half Entrance	35	51	35	27	31.7
Flare @ Stem	58	74	50	48	79.7
Flare @ Midship	7	10	7	0	6.4

3.1.3. KPP Requirements Impact

The ARV KPP driving the IB hull design is the requirement to break 4.5 ft of level ice with 12 in of snow at 3 knots; this is equivalent to a total of 4.83 ft of ice. This requires an efficient icebreaking hull form which results in a less favorable ice-free transit efficiency. This icebreaking capability is feasible but requires high bollard pull and installed propulsion power.

3.2. Estimating Required Icebreaking Power

3.2.1. Icebreaking Estimated Power Approach

Calculating the limiting performance (ice thickness) as a function of hull shape, propeller bollard pull, ship dimensions, and ship mass is done by the method developed by Dr. L. G. Tsoy at the Central Marine Research and Design Institute (CNIIMF), per Reference (4). This method does not compute ice resistance versus the ship's speed curve and is only applicable for minimum low steady-state speed (approximately 2 knots) in ice. To ensure applicability to the ARV requirements, the calculation was corrected using a power requirement ratio. A ratio of the 3-knots open water power requirement over the 2-knots open water power requirement was used. This correction has a history of accurately depicting icebreaking capability at full scale sea trials. The main equation of Tsoy's method, Reference (4), is as follows:

$$h = \frac{0.163 \cdot \cos\varphi \cdot \sqrt{\sin\left(\frac{\alpha_0 + \beta_0}{2}\right)}}{\sqrt[3]{\delta} \cdot \sqrt[3]{L/B} \cdot \sqrt[4]{\sin\left(\frac{90 - 0.5\varphi - \beta_{10}}{2}\right)}} \cdot \sqrt{T/B} \cdot \sqrt[6]{\Delta}$$

Where:

h- ice thickness/ icebreaking capability at 2 knots

L – Length (DWL), m

B – Beam (DWL), m

T – Total propeller tow rope pull at 2 knots, Metric Ton

δ – block coefficient

Δ – Displacement, Metric Ton

ϕ - stem angle is measured between the waterline and the tangent line to the stem line drawn at the point of intersection between the stem and waterline.

α - waterline entrance half angle is measured between the centerline and the tangent line to the waterline drawn at the point of intersection between the centerline and waterline.

β_0 - flare angle at station "0" is measured between the vertical centerline and the tangent line to the station line drawn at the point of intersection between the centerline and station line.

β_{10} - flare angle at station "10" is measured between the vertical line and the tangent line to the station line drawn at the point of intersection between the waterline and station line.

The angles measurements are depicted in Figure 2 below:

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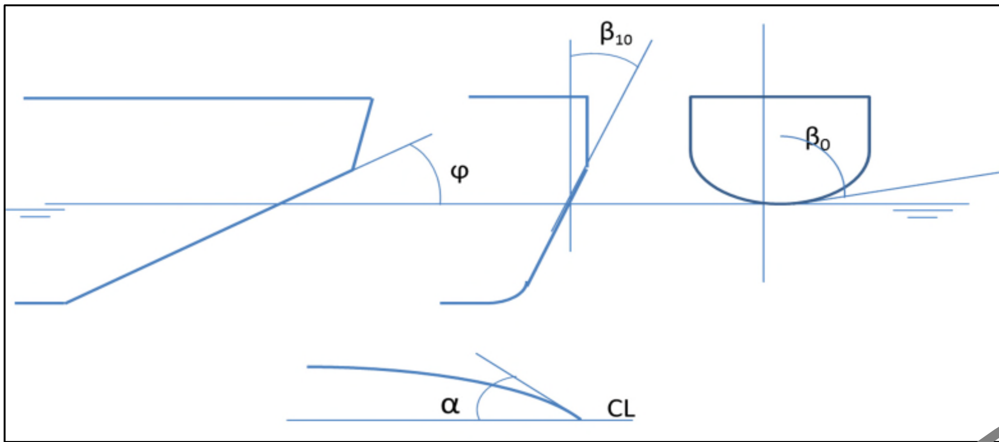
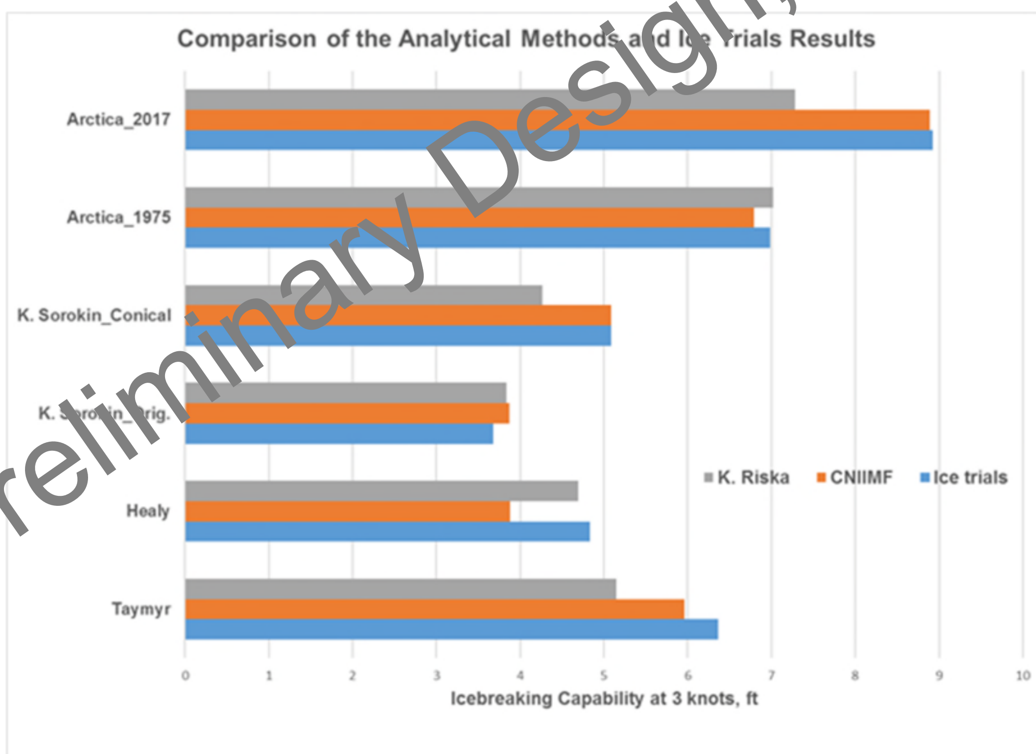
Figure 2: Icebreaking Hull Angles



This method is validated by six modern icebreakers with conventional but varying hull forms and icebreaking capabilities from 3.5 to 9 ft. The Dr. Tsoy/CNIIMF method displays superior alignment with full scale ice trials in comparison to other common icebreaking capacity estimation methods, such as the K. Riska Method. Figure 3 displays how each icebreaking estimation method aligns with full scale ice trials.

Figure 3: CNIIMF vs K. Riska vs Full Scale Ice Trials Icebreaking Estimation



3.2.2. Estimating Ice Maneuvering

In accordance with Reference (1), the ARV ice maneuvering performance is determined by the ship's ability to break out of its previously broken channel, the Turning Circle (TC) maneuver, and the Star Maneuver.

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3.2.2.1. Breaking Out of Channel

Breaking out of a channel ahead is measured in the advance distance from the starting point of the maneuver to the location the ship makes a 90-degree heading turn into the ice sheet from a previously broken ice channel, as shown in Figure 4. Based on icebreaking maneuvering common practices, the break out channel maneuver is calculated in the ice thickness equal to the ship's icebreaking capability at 2 or 3 knots. The break out performance objective for the ARV is based on time of initiating the maneuver to the point where the vessel has turned 90 degrees, which is 300 seconds, in accordance with Reference (1).

Breaking out of the channel requirements based on distance are typically based on experience. Based on icebreaker maneuvering common practice, for ships driven by azimuth thrusters, the common requirement when moving ahead is defined as:

The ARV Shall be able to go ahead to break out of a channel in level ice of 4.5 ft with 12 in of snow within the distance along the track not exceeding 1 ship's length, completing a 90 deg turn, and penetrate the ice off the track for at least 1 ship's length.

Breaking out of the channel going astern is easier than breaking out moving ahead, due to the proximity of the azimuth thrusters. Therefore, the requirement when moving astern is as follows:

The ARV Shall be able to go astern to break out of a channel in level ice of 4.5 ft with 12 in of snow within the distance along the track not exceeding 1 ship's length, completing a 90 deg turn, and penetrate the ice off the track for at least 1 ship's length.

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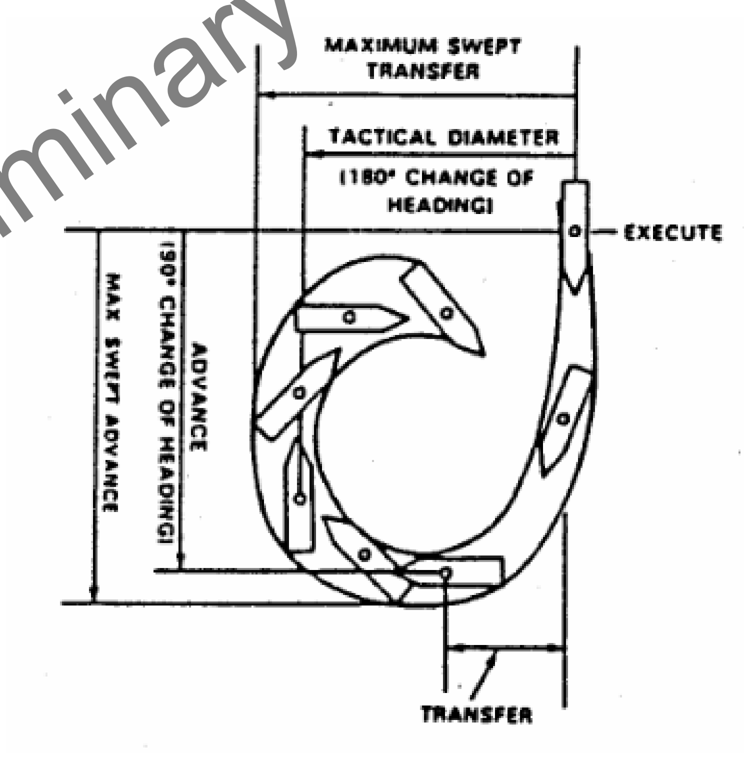
Figure 4: Breaking Out of Channel and Turning Circle



3.2.2.2. Turning Circle Maneuver

The Turning Circle is measured as the diameter distance between the starting point of the vessel traveling ahead, and then turning into the ice until it completes a 180-degree change of heading, as shown in Figure 4. The Turning Circle maneuver is calculated for the ice thickness of 66% to 75% of the maximum ice thickness. A percentage of the maximum ice thickness is used for the TC maneuver calculation because conducting the maneuver is not feasible in the maximum ice thickness capability of the vessel. Initial investigation shows that the ARV requirement for a TC Diameter within 4 LWL at full ice thickness capability is not feasible, per Reference (5).

Defining the turning circle before model testing is very challenging. At the early stage in design, two methods are used to estimate the ARV turning circle. The TC will be verified during Model Testing.

The TC diameter is estimated using the A. Iyerusalimskiy (Reference (6)) and G. Wilkman (Reference (7)) methods. It is observed that icebreakers using azimuth propulsion have superior turning circle capabilities in comparison to conventional shaft-propeller ships, as podded propulsors have the ability to control thrust direction. The G. Wilkman method illustrates this superiority as shown in Figure 6. Breaking out of a channel distance and the star maneuver are determined based on a function of the ship's length. All ice maneuvers were tested and verified during Model Testing.

3.2.2.2.1. A. Iyerusalimskiy Equation Method

The first method was developed during the United States Coast Guard Cutter (USCGC) Mackinaw (WLBB 30) design, Reference (6). This method represents the rough estimate first based on available limited statistics for icebreakers fitted with conventional fixed shaft propulsion systems. Full scale data for 12 icebreakers, with lengths varying from 130 ft to 390 ft, was analyzed. The following ships were considered in the analysis:

1. *Pierre Radisson*
2. *Franklin*
3. *Mudyug*
4. *Kapitan Sorokin*
5. *Bay class*
6. *Moskva*
7. *V. Pronchishev*
8. *Kapitan Chechkin*
9. *Nathaniel B. Palmer*
10. *Juniper*
11. *Karitan-Nikolaev*
12. *Healy*

The data was analyzed to determine the correlation between ice thickness, ship dimensions, and capability of vessels in ice. The objective was to find the impact of maximum icebreaking capability on turning circle diameter in ice thickness below the limit. Figure 5 presents limited statistics of relative turning circle diameter versus relative ice thickness.

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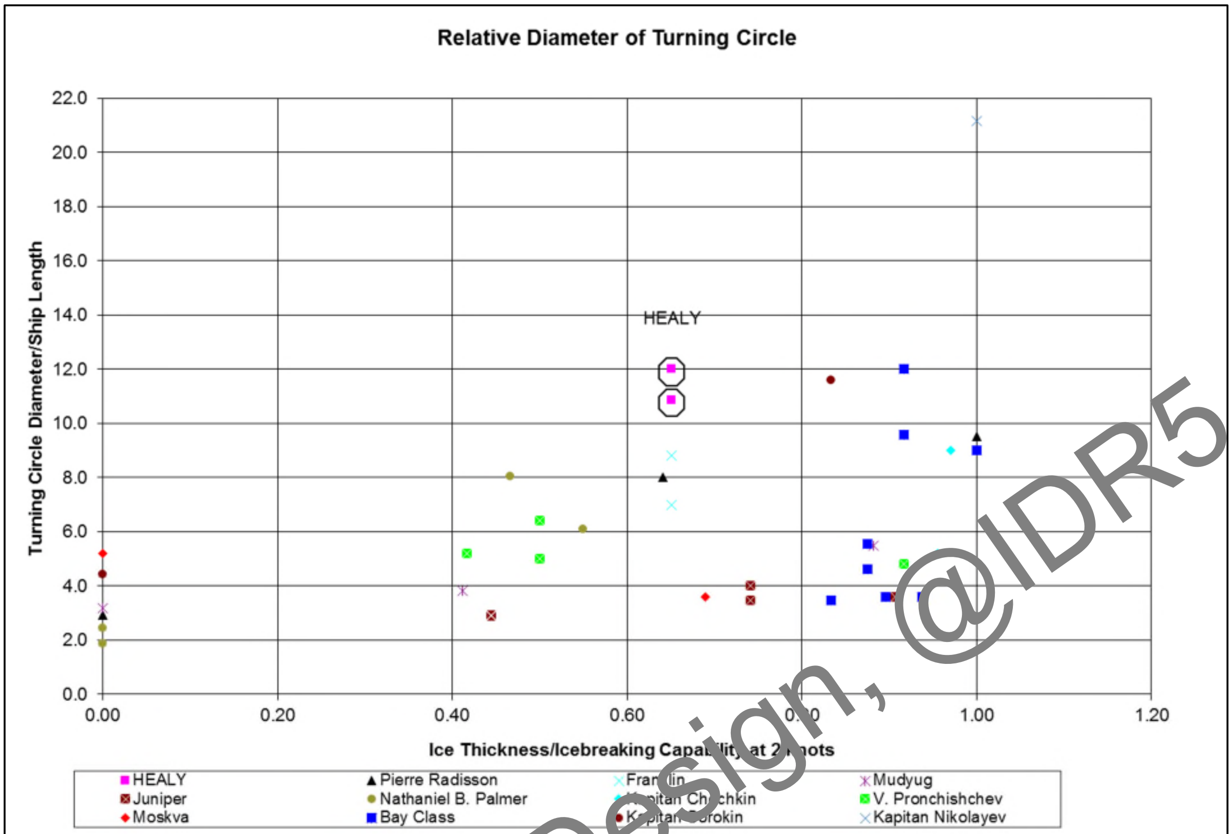
Figure 5: Turning Circle Diameter versus Relative Ice Thickness



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Using the conservative approach, the upper bound of the data set can be presented by the following equation:

$$D_C = \left(5.2\frac{h}{h_L} + 16\right)L_{BP}$$

Where:
D – Turning Circle Diameter, m
H – Ice Thickness, m
h_L – Icebreaking Capability of vessel at 2 knots, m
L_{BP} – length between perpendiculars, m

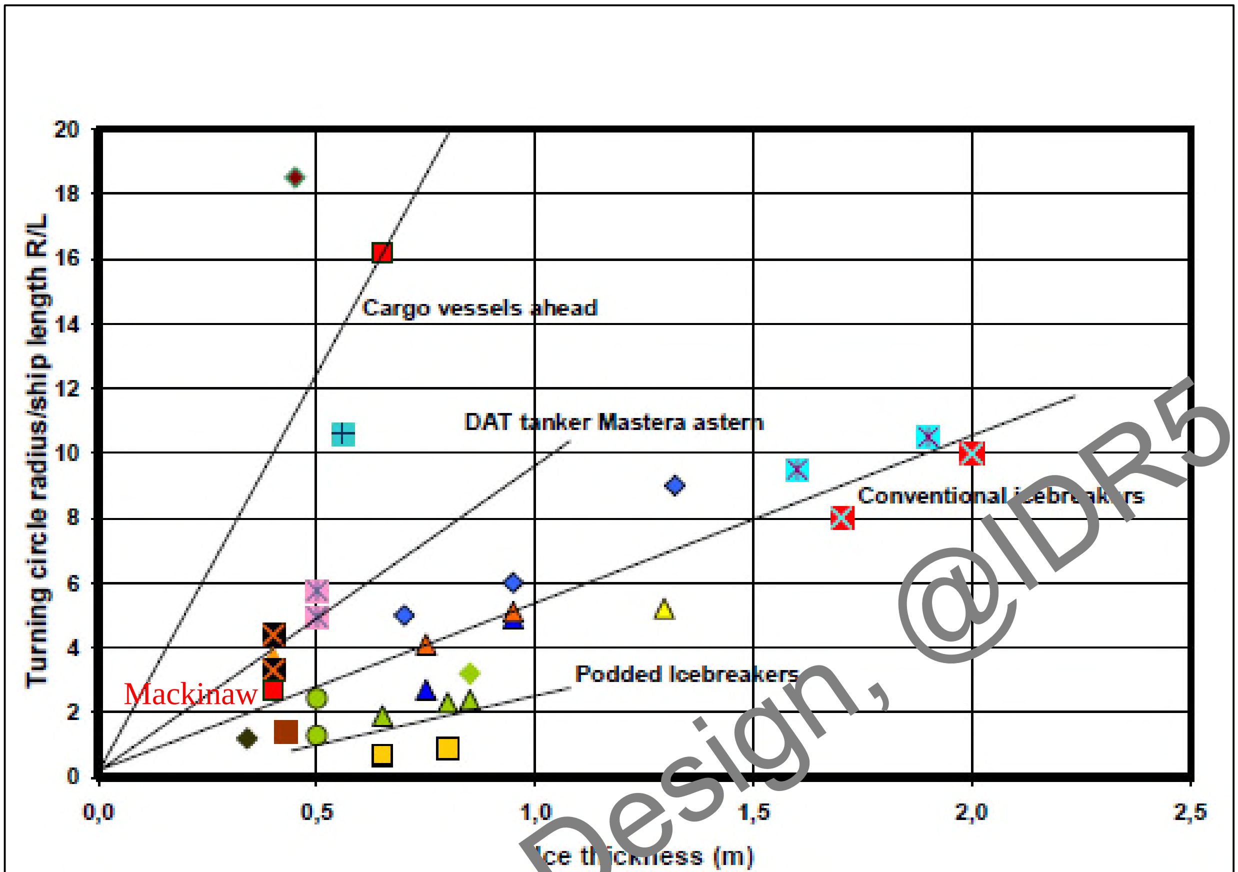
The study was later refined to better estimate ships fitted with azimuth propulsion. The resulting equation is as follows:

$$D_C = \left(20.4\frac{h}{h_L} - 8.1\right)L_{BP}$$

3.2.2.2.2. G. Wilkman Equation Method

Goran Wilkman created another study to determine the turning ability of cargo vessels and conventional icebreakers with shafted propulsion and azimuth propulsion, as detailed in Reference (7). Data collected for this method is found in Figure 6 with the USCGC Mackinaw called out to show compliance with the Conventional Icebreaker Turning Circle vs Ice Thickness estimation.

Figure 6: Turning Circle Comparison by Wilkman



The resulting trendline equation for the Conventional Icebreakers is as follows:

$$D_C = (6.897h - 1.448)L_{BP}$$

The A Iyerusalimskiy and Wilkman results for the USCGC Mackinaw show agreement providing a preliminary approach to estimate the turning circle of the ARV hull form.

3.2.2.3. *Star Maneuver*

The Star Maneuver is performed by breaking out of the channel and making consecutive changes in heading moving ahead and astern, until the ship completes a full cast about. The maneuver is typically performed in the spots where a turning circle is restricted by the fairway or other operational limitations. The Star Maneuver is typically completed within an ice field with the diameter of 1.25 to 1.5 of the ship's Length on the Waterline (LWL) for twin podded ships. Based on icebreaking maneuvering common practices, the Star Maneuver is calculated in the ice thickness equal to the ship's icebreaking capability at 2 or 3 knots.

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3.3. Numerically Estimated Icebreaking Performance

3.3.1. Estimated Icebreaking Capability

As outlined in Section 3.2.1, the objective icebreaking capability will be achieved by incorporating the necessary propulsion arrangement. Based on the Tsoy's Method, with a provided Propulsion power of 19.3 MW, the ARV has an IB capability of 4.83 ft, meeting the objective KPP requirement. This shall be met by providing two ABB VI1800 Azipods. Table 2 provides the hull angles for the ARV hull form design.

Table 2: ARV Hull Angles

Angle	ARV
Stem	20.0
Half Entrance	31.7
Flare @ Stem	79.7
Flare @ Midship	6.4

3.3.2. Estimated Ice Maneuvering

3.3.2.1. Breaking out of the Channel

The ARV is required to break out of the channel ahead and astern at the objective ice thickness of 4.5 ft and 12 in of snow, equivalent to 4.83 ft of ice, Reference (1). The ARV is estimated to achieve breaking out of the channel ahead in approximately 345 ft of the initial position in the channel, equaling 1.0 ship's LWL. The ARV is estimated to break out of the channel astern within approximately 276 ft to 345 ft, equaling 0.8 to 1.0 of the ship's LWL. Both estimates confirm compliance with Reference (1) requirements to break out of a channel.

3.3.2.1. Star Maneuver

The Star Maneuver is not a required maneuver but is included based on common icebreaking practices. The ARV is estimated to complete the 180-degree turn Star Maneuver within approximately 430 ft to 518 ft, equaling 1.25 to 1.50 of the ship's LWL.

3.3.2.2. Turning Circle Diameter

The ARV is required to have a maximum turning diameter ahead and astern of 4 LWL in 4.5 ft of level ice, or 3x LWL in 1.6 ft of ice, Reference (1). Based on icebreaker maneuvering common practices in preliminary design, the Turning Circle Diameter was estimated using an ice thickness of 3.33 ft (69% of Objective KPP ice thickness of 4.83 ft). The turning circles at this thickness were found to be larger than the Reference (1) required diameter for 4.5 feet of level ice. Research investigating the TC diameter at the Objective KPP ice thickness shows that the current requirement for the ARV TC diameter is not feasible, Reference (5).

Using the Iyerusalimskiy and the Wilkman method, the ARV turning circle is estimated and shown in Table 3, the results are shown in total diameter, and Diameter vs LWL (D/LWL).

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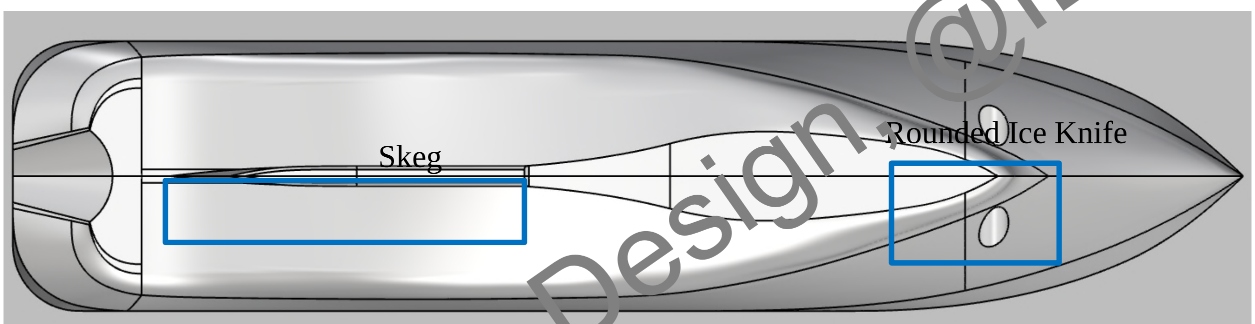
Table 3: Turning Circle Results

Angle	ARV
LOA (ft)	365
LWL (ft)	345
Icebreaking Capability @ 3 knots with 12 in of snow (ft)	4.83
Turning Circle Ice Thickness (ft)	3.33
Turning Circle Diameter; A Iyerusalimskiy (ft)	2,060
Turning Circle Diameter; G. Wilkman (ft)	2,024
Turning Circle Diameter as Ships LWL; A. Iyerusalimskiy (D/LWL)	6.0
Turning Circle Diameter as Ships LWL; G. Wilkman (D/LWL)	5.6

3.3.3. Clearing Ice from Science Package

Clearing ice from the science package is achieved with the use of the rounded ice knife for ahead operations, and the Azipods and skeg for astern operations. Figure 7 displays the Rounded Ice Knife and Skeg.

Figure 7: ARV Hull Bottom View



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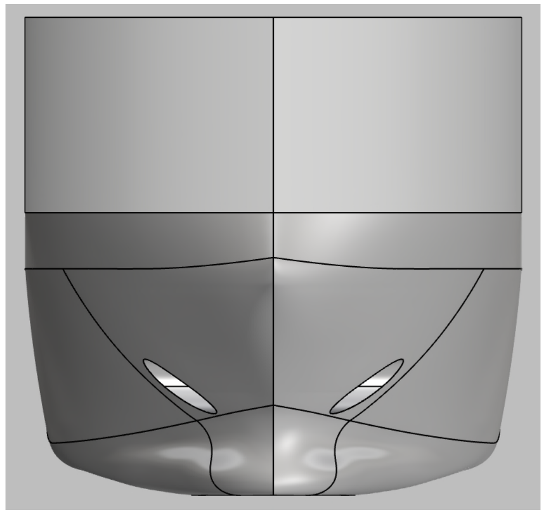
3.3.4. Clearing Ice Going Ahead

The ARV hull form possesses a Rounded Ice Knife, which is used to spread the broken ice outwards towards the side shell as the hull travels through the ice sheet. The broken ice during ahead operations will come down the hull and interact with the rounded ice knife, which primary purpose is to mitigate bubble sweepdown, but it also assists in breaking the brash ice further and pushing it outwards before it goes below the hull bottom. Parts of the ice traveling along the hull waterlines will clear upwards with the continuous flare at the waterline. The flare also allows the ice sheet to break wider than the hull itself, with an ice channel having a maximum width of approximately 1.15 – 1.20 of the ARV's waterline beam. See Figure 8 for the bow view of the ARV Hull.

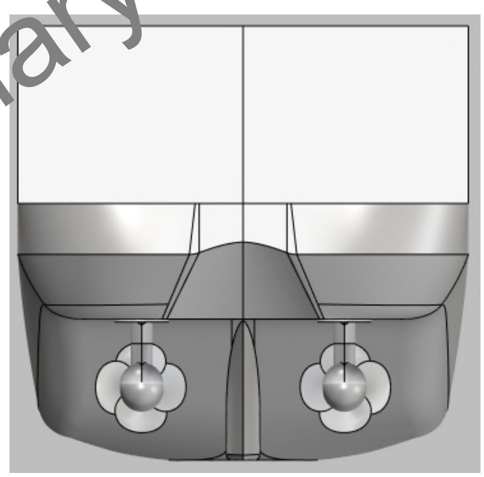
Figure 8: ARV Bow View Displaying Rounded Ice Knife



3.3.5. Clearing Ice Going Astern

The ARV has two Azipods which can be utilized to push the ice away from the hull during operations moving astern. When in operation in brash ice, the Azipods can be orientated to push the ice away from the hull, assisting in clearing the ice before it runs below the hull. If the ice passes the Azipods, it will be in contact with the skeg, which will act similarly to the ice knife. The skeg will direct the ice outwards, and the ice will travel along the skeg before it interacts with the trailing transition between the skeg and the box keel. The widening between the skeg and the box keel will aid in continuously pushing the ice away from the sonar equipment. Figure 9 shows the transom view of the ARV Hull.

Figure 9: ARV Transom View Displaying Azipods and Skeg



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4. Ice Model Testing Results

The ARV hull form was physically modeled and tested at the Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) Ship design and research facility in Hamburg, Germany. Icebreaking performance tests, including powering, ice management, and ice maneuvering were completed in March through May of 2023. Additional details of the model testing can be found in the ARV Model Test Report (Open Water and Ice), Reference (3).

4.1. Icebreaking Capability

According to the model test results, the ARV will achieve 3 knots ahead in 4.83 ft of level ice at a power of 17.4 MW, a reduction in the estimated requirement of 19.3 MW The ARV will achieve 3 knots astern in 4.83 ft of level ice at a power of 18.4 MW. Figure 10 and Figure 11 show model ice breaking tests at objective ice thickness for Ahead and Astern, respectively. Further details regarding other level icebreaking performance are available in the Reference (3).

Figure 10: Icebreaking Ahead in Objective Ice Thickness

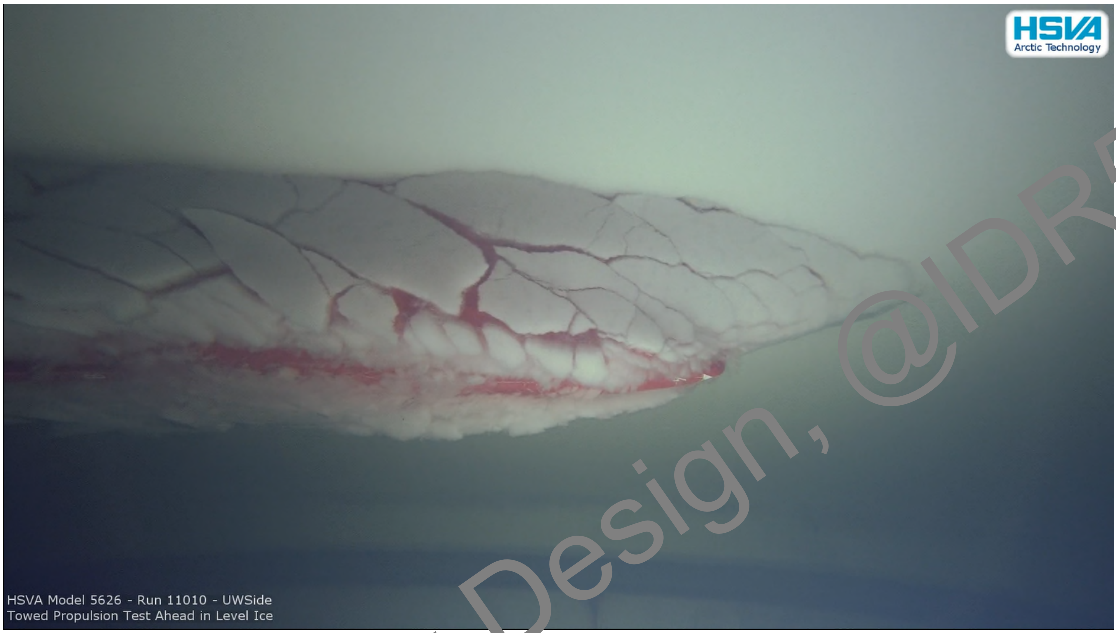

Figure 11: Ice Breaking Astern in Objective Ice Thickness

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4.2. Ice Maneuvering

4.2.1. Breaking out of the Channel

The model test demonstrated that the ARV can break out of the channel traveling ahead in approximate 2.5 LWL. Though this exceeds the numerically predicted 1.0 LWL, it meets the time required to break out of a channel of 300 seconds as required in Reference (1). Figure 12 below shows three moments in time during the ahead channel break out test.

Figure 12: Break Out Test Ahead in Objective Ice Thickness

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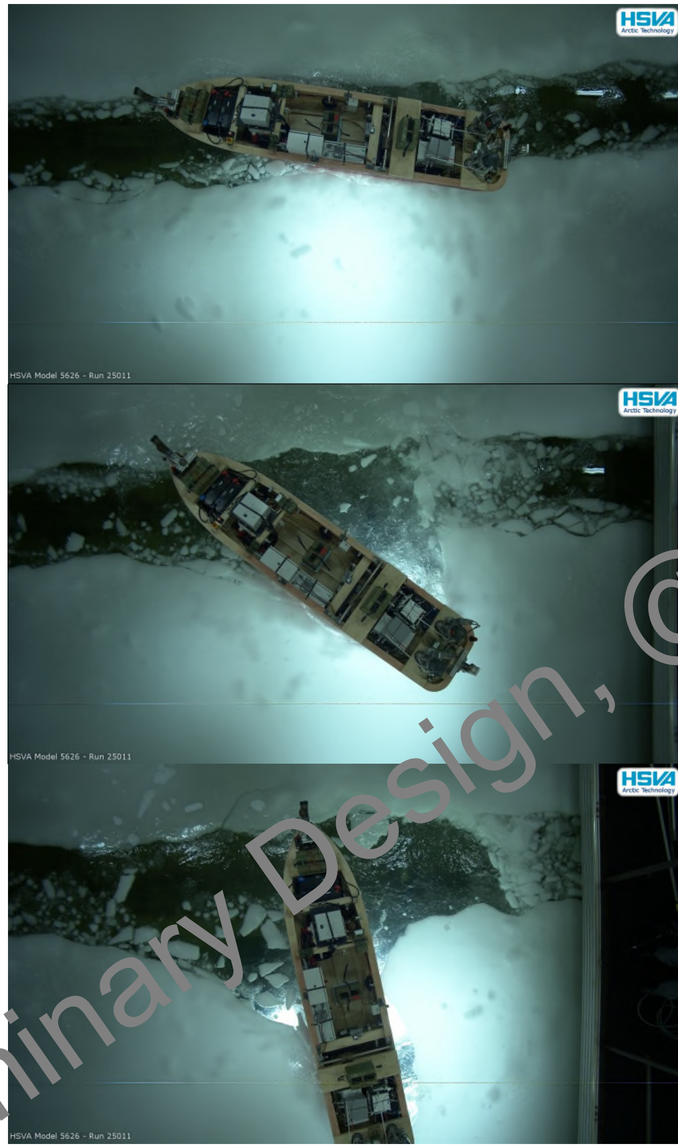
The ARV will break out of the channel traveling astern in approximately 1.0 LWL and completed within the required 300 seconds, Reference (1). This meets the numerically predicted 0.8 to 1.0 LWL for astern break out. Figure 13 below shows three moments in time during the astern channel break out test.

Figure 13: Break Out Test Astern in Objective Ice Thickness



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4.2.2. Star Maneuver

The Ice Model Test demonstrated that the ARV can perform a Star Maneuver in the objective 4.83 ft of ice within 1 LWL, achieving greater capability than the estimated 1.25 to 1.50 of the ship's LWL. Figure 14 below which shows three moments in time during the star maneuver test.

Figure 14: Star Maneuver in Objective Ice Thickness

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4.2.3. Turning Circle Diameter

The Ice Model Test demonstrated that the ARV can perform a 180-degree turning circle traveling ahead in 3.0 ft of ice within the model basin, which illustrates the hull can turn in within 2.0 LWL. The tests were not completed at the specified 3.5 ft of ice, however based on the exceptional performance in 3.0 ft ice, the ARV is anticipated not to have any issues meeting the required 4.0 LWL as specified in Reference (1). Figure 15 shows three moments in time during the ahead turning circle diameter test.

Figure 15: Turning Circle Ahead 3.0 ft Ice Thickness

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The Ice Model Test also demonstrated that the hull can perform a 180-degree turning circle traveling astern in 3.0 ft of ice in a smaller span, which results in approximately 1.5 LWL. Figure 16 shows three moments in time during the astern turning circle diameter test.

Figure 16: Turning Circle Astern in 3.0 ft Ice Thickness

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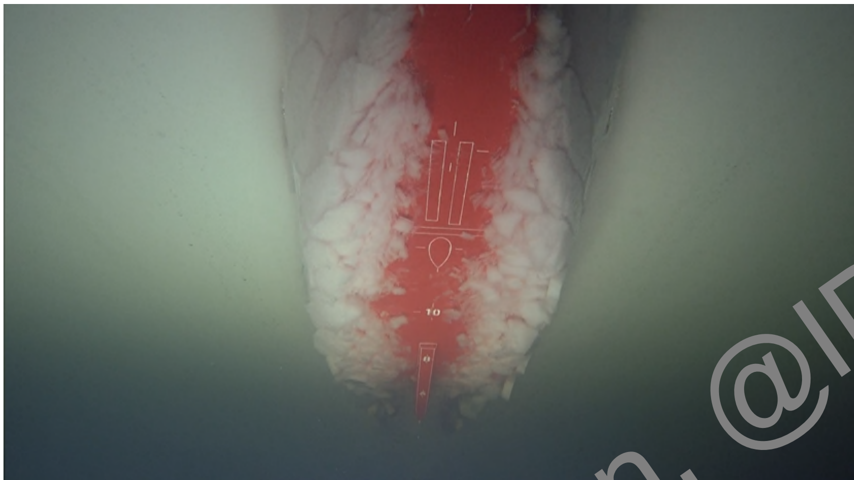
4.2.4. Clearing Ice from Science Package

The Ice Model testing shows that clearing ice from the science package is successfully achieved with the use of the rounded ice knife for ahead operations, and the Azipods and skeg for astern operations. Figure 17 displays the freshly broken ice is pushed outwards of the science equipment during the objective 4.83 ft thick ice breaking operations.

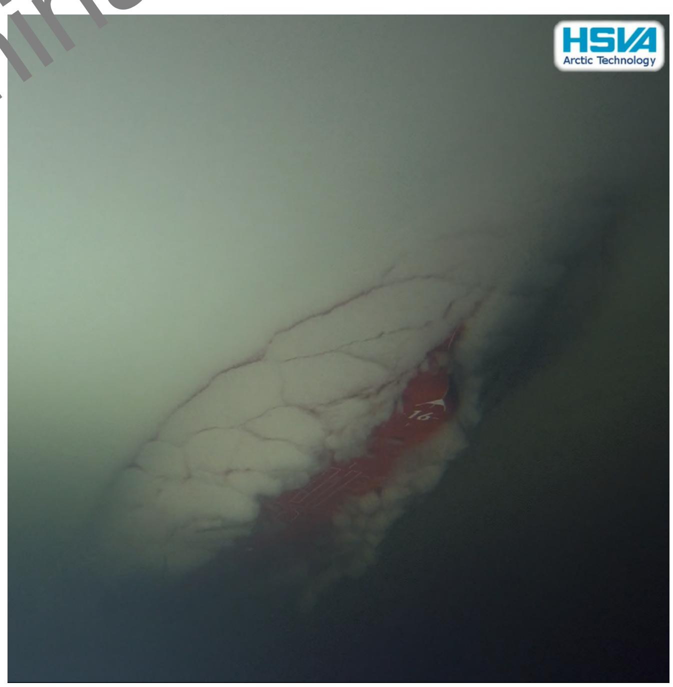
Figure 17: Ice Cleared from Science Package at Objective Ice Thickness



4.2.5. Clearing Ice Going Ahead

The model testing demonstrated that the ARV has the ability to clear ice from the hull, preventing it from traveling under the ARV and past the bottom shell mounted electronics. It was observed that the rounded ice knife keeps the ice from traveling in front of its forward edge and pushes it outward away from the bottom shell-mounted electronics. The ice clearing performance ahead can be seen in Figure 18.

Figure 18: Ice Clearing Ahead at Objective Ice Thickness



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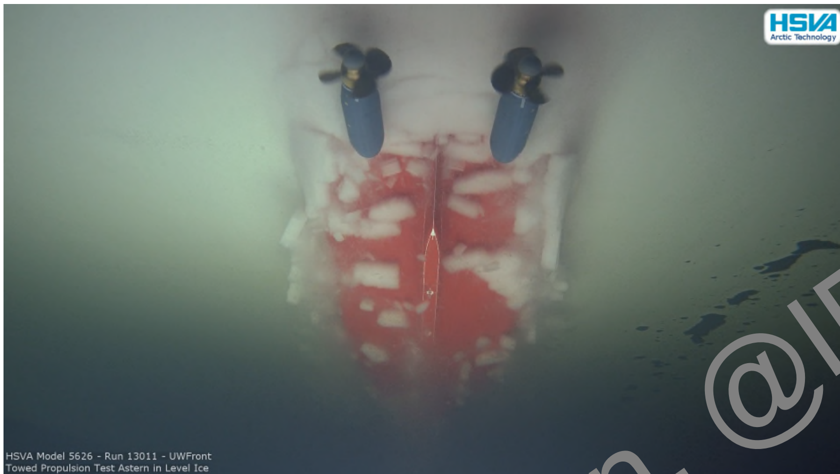
4.2.6. Clearing Ice Going Astern

The ice clearing for the ARV traveling astern performed exceptionally well with the freshly broken ice being cleared from the ARV by the water flow from the propellers. Rectangular ice floes are split by the aft skeg. At the outer hull area, small floes are further broken, which allows them to be easily cleared by the propeller wash. Ice clearing performance astern can be seen in Figure 19.

Figure 19: Ice Clearing Astern at Objective Ice Thickness



4.3. Ice Management Performance

The ARV will perform extensive scientific missions which require the ability to manage the ice surrounding and trailing the ARV after breaking through it. During model testing, three scenarios were tested to demonstrate the ice management abilities of the ARV:

- Maintenance of clear channel during unbroken ice transit
- Maintenance of clear channel during brash ice transit
- Execution of the “side step maneuver”

4.3.1. Clear Channel during Unbroken Ice Transit

The first ice management tests investigated how well the ARV hull can maintain a clear ice channel while orientating the Azipods at opposing angles in unbroken ice at 60 degrees towards centerline, then 60 degrees away from centerline, and then alternating the pods in parallel from one side to another. Pod orientations can be seen in Figure 20. Configuration 1 depicts a toe-in orientation, Configuration 2 depicts a toe-out configuration, and Configuration 3 alternates both thruster angles continuously in a parallel motion. These configurations will allow the ARV to maintain its required forward thrust to break ice and still have additional outward thrust to push the broken ice away from the channel. The total power to break ice at the objective ice thickness does not provide sufficient power margin to direct the thrust outwards to divert the broken ice. As such, the channel clearing demonstration was conducted using an ice thickness of 3.3 ft. An Azipod angle of 60 degrees was demonstrated to produce the necessary forward thrust for continuous icebreaking, while also maintaining a channel clear of the broken ice. Of the three tests, the pods in a toe-in configuration oriented 60 degrees towards centerline provided the clearest channel. Figure 21 shows the clear channel trailing the ARV in the 60-degree toe-in configuration.

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Figure 20: Pod Orientation for Clear Channel Test

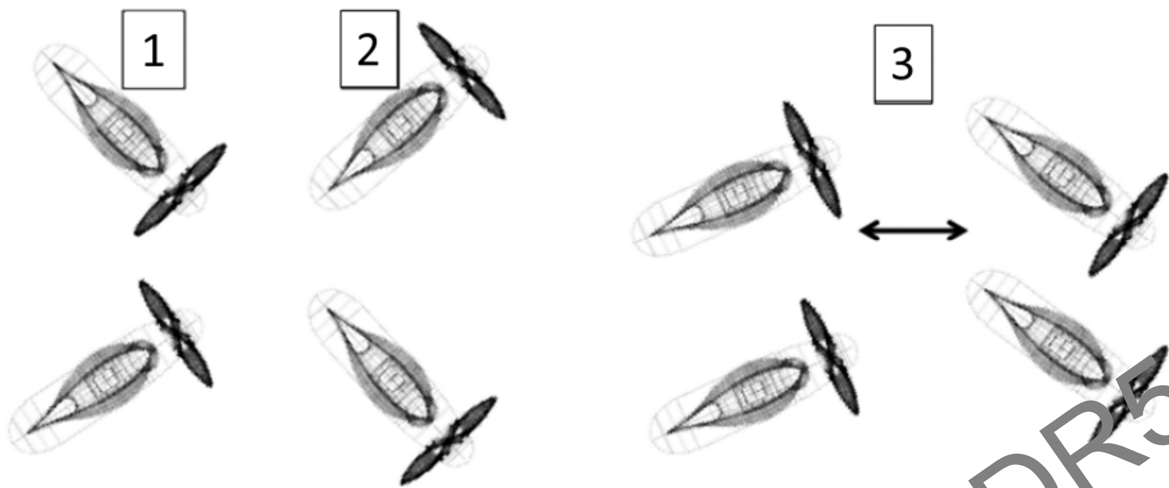

Figure 21: Clear Channel in 3.3 ft of Unbroken Ice

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4.3.1. Clear Channel during Brash Ice Transit

The second ice management test investigated how well the ARV hull can maintain a clear ice channel while orientating the Azipods at opposing angles in brash ice. Because the power required to transit brash ice is far less than unbroken ice, there is more margin for propulsion power required to transit the ice and maintain a clear channel. Three toe-in pod angles were tested at 60 degrees, 45 degrees, and 30 degrees, as shown in Figure 22. All three angles successfully provided a clear channel, but in varying widths. While the 60-degree pod angle test did provide sufficient thrust to keep the ARV moving ahead, it was much slower than the other two pod orientations. The tested pod angles are shown in Figure 22; while Figure 23, Figure 24, and Figure 25 depict the resulting cleared channels.

Figure 22: Clear Channel Pod Angles

Figure 23: Clear Brash Ice Channel with 60 Deg Pod Angle

Figure 24: Clear Brash Ice Channel with 45 Deg Pod Angle

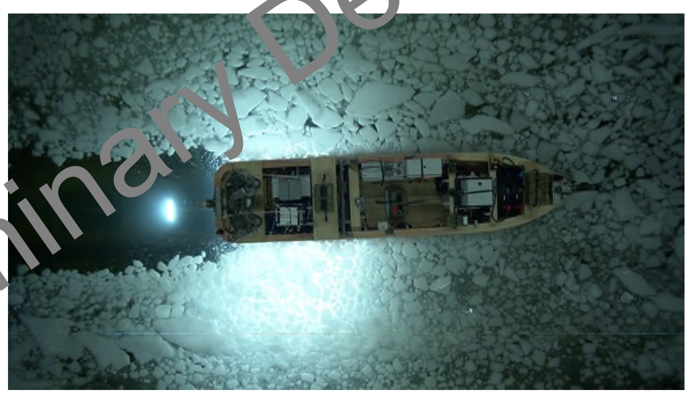

Figure 25: Clear Brash Ice Channel with 30 Deg Pod Angle

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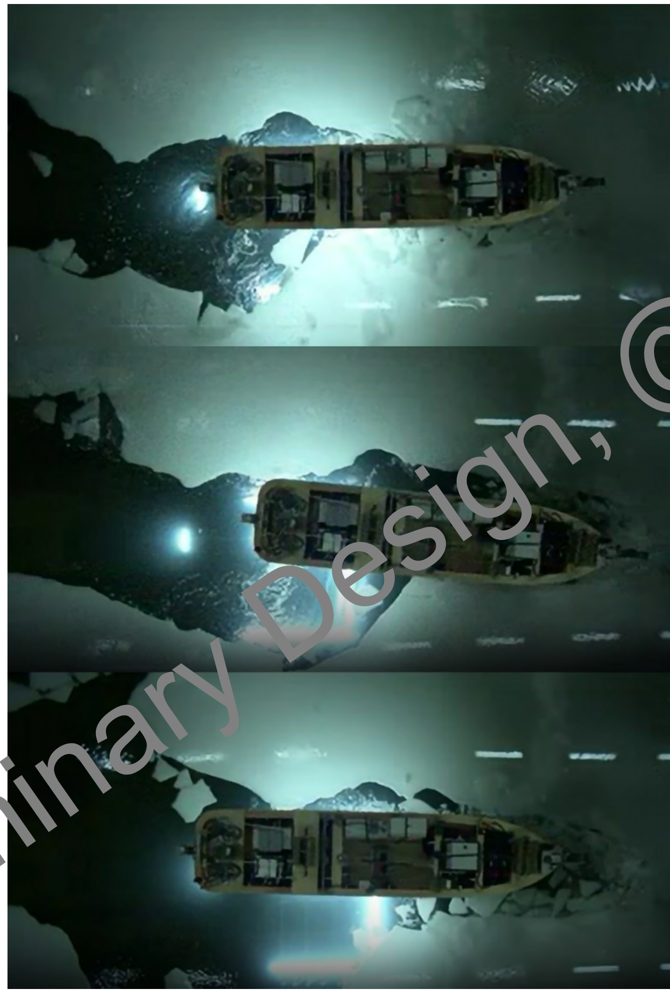
4.3.2. Side Step Maneuver

The third ice management test was to create an open pool adjacent to the working deck to support overboard science missions in unbroken ice. This maneuver, known as the Side Step Maneuver, requires the ARV to widen the channel from an already broken ice path, and then push the broken ice to one side, allowing an ice-free track on one side of the ARV. Figure 26 shows three moments in time during the Side Step Maneuver test.

Figure 26: Side Step Maneuver Test



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5. Ice Ingestion into Seachests and Bow Thruster

The Bow Thruster experiences minimal ice ingestion, but it does not result in any adverse effects in icebreaking performance. The ice sheet flows over the bow thruster opening and continues down the ARV length without creating ice damns. The location of the seachest continues to be under development. Therefore, the effects of ice on the seachest will be evaluated in subsequent revisions of this report and Model Testing.

6. Conclusions and Recommendations

The ARV hull form design was analyzed in accordance with standard practices and team processes in order to maximize icebreaking performance and ice maneuvering. The Tsoy's Method equation predicts the ARV hull form will break the KPP Ice Thickness of 4.83 ft with 19.3 MW of propulsion power. KPP icebreaking capability has been confirmed with the Ice Model testing at HSVA which predicts that the power required to break the KPP ice thickness ahead is 17.4 MW, and to break the KPP ice thickness astern is 18.4 MW.

The Ice Model test predicts that the distance to break out of a channel going ahead is 2.5 LWL, and the distance to break out of a channel going astern is 1.0 LWL. The time to break out of the channel was within 300 seconds is achieved, as required in Reference (1). The ARV hull form model testing has demonstrated that a star maneuver, 180-degree turn, can be completed in 1 LWL. The Ice Model testing also shows that the ARV hull is able to complete a TC in 3.0 ft of ice ahead within 2.0 LWL, and astern within 1.5 LWL. The tests were not completed at the specified 3.5 ft of ice, however, based on the exceptional performance in 3.0 ft ice, the ARV is anticipated not to have any issues meeting the required 4.0 LWL as specified in Reference (1).

The Ice Model tests demonstrated the ice management capabilities of the ARV can clear a channel in 3.3 ft of unbroken ice, and brash ice, by rotating the pods in opposing angles to provide enough forward thrust to maintain a forward heading, and outward thrust to push the broken ice aside. The model tests also show that the ARV can push brash ice outwards at varying degrees of the pods to maintain an ice-free channel. The ARV can additionally perform a Side Step maneuver to create an ice-free pool adjacent to the working deck to perform overboard science operations.

Further discussion on Ice Model Testing results can be found in the Model Test Report (Open Water and Ice), Reference (3).

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7. References

(1) *ARV Performance Specifications*, Rev. A Change 04, 19 May 2023.

(2) *ARV Hull Form Trade-Off Study,* Rev P3, File 5E1-051-R001, 28 July 2023.

(3) *ARV Model Test Report (Open Water and Ice)*, Rev. P2, File No. 5E1-098-R101, 23 December 2022.

(4) *Formula for the determination of the icebreaking capability and recommendations for the choice of the shape of hull lines of icebreakers and ice ships*, Tsoy L.G., Central Marine Research and Design Institute (CNIIMF), 1990

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(6) *Relative Performance Model for Great Lakes Ice Transit Simulations*, Aleksandr V. Iyerusalimskiy, James St. Jon, Chrisopher Cleary, CDR Jon Nickerson, ICETECH 2000 6th International Conference on Ships and Marine Structures in Cold Regions 2000.

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