Antarctic Research Vessel (ARV)

Engineering Report: Hull Form Trade-Off Study

Document No.: 5E1-051-R001

Revision: P3

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
P0-2	June 20, 2022	All	S. Sweeney	Initial draft for ASC peer review
P1	September 20, 2022	All	S. Sweeney	Updated information for DR3 Included Discussion on Resizing Study
P2	November 25, 2022	All	S. Sweeney	Incorporated ASC Rev P1 Comments
P3	July 28, 2023	All	S. Sweeney	Updated information for DR5 Included discussion of Hull Optimization Study Incorporated ASC Rev P2 Comments

Prepared by:

Sean Sweeney	Sean Sweeney	07/28/2023
Signature	Print Name	Date

Naval Architect III, Leidos / Gibbs & Cox

Checked by:

Dan Kopera	Dan Kopera	07/28/2023
Signature	Print Name	Date

Senior Principal Naval Architect, Leidos / Gibbs & Cox

Engineered/Managed by:

Justin Klag	Justin Klag	07/28/2023
Signature	Print Name	Date

Manager, Naval Architecture Department, Leidos / Gibbs & Cox

Approved by:

Dave Rosenthal	Dave Rosenthal	07/28/2023
Signature	Print Name	Date

Assistant Vice President, Engineering Group, Leidos / Gibbs & Cox

Table of Contents

List of Figures

List of Tables

1. Executive Summary

The Antarctic Research Vessel (ARV) hull form design was matured from initial Concept Design principal characteristics to a Preliminary Design hull form through a series of studies, model basin testing, and evaluations. These processes were conducted to verify the hull form meets the KPPs defined in the ARV ship Performance Requirements (P-Spec), Reference (1), and supports the science mission of the vessel.

The hull form development process for the preliminary design of the ARV commenced with the principal characteristics and constraints established by the Concept Design phase. These initial constraints limited the vessel size, which resulted in a hull form that was deemed insufficient to meet the combined requirements of the ARV.

To determine the principal characteristics needed to meet all KPPs, a hull sizing study was conducted to re-evaluate and revise the initial assumptions and constraints, which primarily originated from the presumed mooring restrictions at Palmer Station. With these revised assumptions, a total of six hull form variations were studied and it was determined that a ship with a length of 365 ft would be required. The hull form also incorporated the use of a box keel appendage to assist in minimizing bubble sweepdown over select areas of the hull where underwater sensors would be located. From the length and draft, a corresponding beam of 80 ft was selected based on the parametric analysis conducted from similar sized and Ice Breaking (IB) capable icebreaker hulls.

In addition to the computational evaluation of the hull form, the resized vessel was physically model tested and the results were compared to the icebreaking KPP and bubble sweepdown requirements. The model tests determined that the icebreaking KPP was met, but identified an opportunity to modify the hull form to improve bubble sweepdown and open water performance.

In order to improve the bubble sweepdown and open water performance, while maintaining required icebreaking performance, a total of seven additional hull form variations were computationally studied. This cycle resulted in the removal of the box keel and featured iterative reshaping of the ice knife and lower ice belt geometry forward of midship. The resultant hull form was then selected for additional model testing and has been incorporated into design products to be delivered in the design iteration culminating in DR5.

Computational and Physical Model Testing Results indicate that the selected ARV hull form can meet the icebreaking KPP while achieving improved bubble sweepdown performance and open water resistance. These improvements were made while maintaining the ability to balance the hull displacement with estimated ship weights and loads, and provide a foundation for the design to accommodate the facilities required to support the research and scientific missions.

1.1. Acronyms

ABL	Above Baseline
AP	Aft Perpendicular
ARV	Antarctic Research Vessel
CFD	Computational Fluid Dynamics
CNIIMF	Central Marine Research and Design Institute
DRMC	Design Reference Missions Candidate
DR	Design Review
DWL	Design Waterline
EOSL	End of Service Life
FT	Feet
FP	Forward Perpendicular
G&C	Gibbs & Cox, a division of Leidos
GHS	General HydroStatics software
IB	Icebreaking
IN	Inches
KPP	Key Performance Parameters
LT	Long Ton
L/B	Length to Beam Ratio
MCR	Main Control Room
NM	Nautical Mile
PD	Preliminary Design
PDR	Preliminary Design Review
P-Spec	Performance Requirements
VCG	Vertical Center of Gravity

2. Introduction

This report documents the approach and trade space that developed the Antarctic Research Vessel (ARV) hull form during the Preliminary Design (PD) phase. This report outlines details for the following:

- Icebreaking (IB) capabilities
- Draft considerations
- Bubble sweepdown mitigation considerations
- Stern rise geometry
- Working deck considerations
- Effects on the hull form due to the integration of the Azipods and propellers

3. Approach

A total of 17 iterations of the ARV hull form were considered to meet the Key Performance Parameters (KPPs) outlined in Reference (1); four iterations investigated the ships size, detailed in Appendix 2: Initial Hull Sizing and Resizing Study, six iterations evaluated the box keel bubble sweepdown performance, detailed in Appendix 3: Box Keel Design Considerations, and seven additional iterations modifying the ice knife size and geometry to optimize bubble sweepdown and maintain icebreaking capability are detailed in Section 4.2.2. Several mission requirements were taken into consideration with priority on the following:

- Icebreaking Capability
- Bubble Sweepdown Performance
- Open Water Performance and Maneuvering
- Hull Stability
- Support Ship Weights and Fuel Loads

To meet these requirements, the hull form must be capable of both breaking the required amount of ice and meeting range and endurance requirements, necessitating the need to balance icebreaking and open water performance. In addition, the hull form must also provide sufficient means to mitigate sweepdown to support science missions, be sufficiently stable, and able to balance displacement and weight.

Typical icebreaking hull features are in contrast to typical open water performance features and bubble sweepdown mitigations, necessitating careful evaluation and consideration of the trade-offs between the features.

Icebreaking vessels may be categorized into two groups, conventional and modern. While both are naturally inefficient in open water, modern icebreakers that are designed to optimize the icebreaking capability further decreases the open water efficiency. For the ARV, a hull with conventional icebreaker features selected over the modern icebreaker features in order to improve the open water performance and ice maneuverability.

To minimize bubble sweepdown, modifications to conventional icebreaking lines below the bilge radius were investigated. This included investigation of the ice knife size and shape, as well as deadrise angles, to divert water surface away from the science package.

The optimization process utilized a combination of design best practices, vendor furnished information, and computational analysis, then was validated with Model Testing. The process prior to model testing included:

- Estimating IB capability using established industry calculations for icebreakers.
- A Computational Fluid Dynamics (CFD) Analysis was conducted using StarCCM+ to determine the effects of bubble sweepdown on the hull.
- A Hydrostatic analysis was conducted using General HydroStatics (GHS) to evaluate stability performance and other hull form characteristics.

Details of all design consideration, calculations, and analysis are provided in the following sections.

3.1. Hull Form Considerations

The ARV hull form must balance the science mission, open water efficiency, and icebreaking demands to be a successful hull form. To meet research and scientific needs, it must minimize bubble sweepdown and provide safe and adequate laboratories. In addition, the hull must be capable of being arranged with functional weather deck working areas. The research and science driven hull form must also be capable of meeting the KPP. A hull form that provides these features will be capable of efficiently performing science missions in the desired operational zones of the Antarctic.

To meet the IB requirements outlined in Reference (1), the ARV hull form features typical icebreaker hull geometry characteristics. The primary IB design features were optimized for the bow hull form angles, entrance angle, stem angle, and flare at the Forward Perpendicular (FP). Additionally, the midship angle and the aft flare and rake angles along the Aft Perpendicular (AP) were examined to ensure maximum icebreaking capabilities. These angles define the foundation of the submerged hull form shape.

The draft for the ARV is dependent on the available piers and their draft restrictions. These considerations bound the design space for the hull below the waterline, while the IB angles determine the upper extents of the submerged hull form.

The use of underwater sensors requires a vessel that will reduce, with the goal of entirely removing, the bubble sweepdown effects surrounding the sensors. This is done by incorporating a rounded ice knife to divert flow around the science mission package.

To accommodate podded propulsion units, several features were incorporated into the stern geometry. First is the transition angle from the hull bottom up to the propulsion flat where the pods are mounted. The height of the propulsion flat height must accommodate the pods and the required propeller diameter without the propellers protruding deeper than the bottom shell of the vessel, while also providing adequate propeller to vessel clearance. Lastly, the stern design required incorporating a square working deck to maximize useable area for science.

3.2. Evaluation Criteria

To measure the hull form's ability to provide a safe and capable research platform, it was evaluated for its bubble sweepdown, sea keeping and maneuvering abilities. To measure its ability to efficiently transit open water to access points of interest, its speed and powering requirements were determined through model testing to ensure that range and KPP endurance requirements were met. Concurrently, displacement and stability were monitored to ensure the required payloads could be safely transported. The icebreaking ability of the hull form was calculated and evaluated in model tests to measure compliance with the icebreaking KPP. Finally, channel clearing ability was demonstrated through model testing to ensure vessel capability of creating a sufficient ice-free area astern to allow the towing of nets and other equipment astern while icebreaking.

In addition to this report, details of individual analysis performed on the hull form are contained in supporting reports. These include assessment of the ARV maneuvering, which can be found in the ARV Maneuvering Performance Report, Reference (2). Details of the Dynamic Positioning system and performance can be found in the ARV Dynamic Positioning System Performance Report, Reference (3).

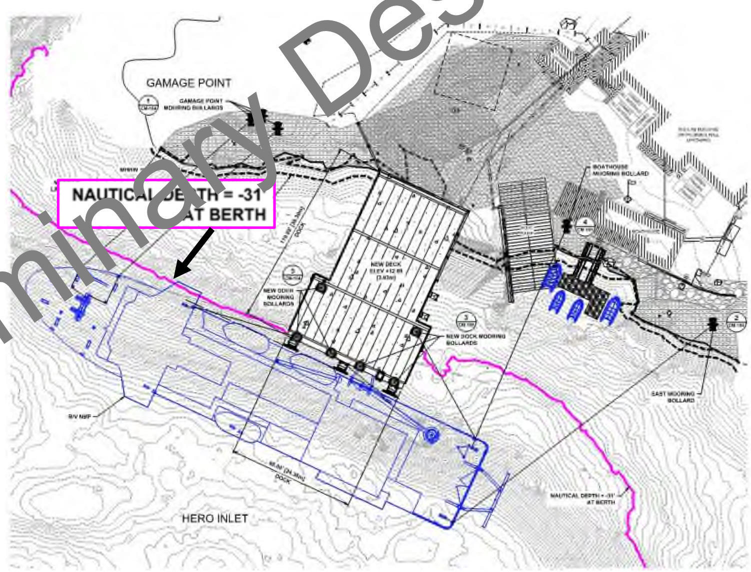
3.3. Timeline of Approach and Evaluation

The hull form development process for the ARV during the Preliminary Design phase commenced with the principal characteristics and constraints established by the Concept Design phase. These initial constraints to the hull's length and beam were driven by the requirement to moor at Palmer Station. Limits to the ship's length and draft to 345 ft and 28 ft, respectively were used. Additionally, a draft constraint of 28 ft was assumed based on Palmer Station's nautical depth of 31 ft. Based on these length and draft assumptions, the beam was determined from a parametric analysis, discussed in Section 4.1. The resulting hull form using the initial constraints was found to be unable to meet the endurance KPP of the ARV. Further details of the initial hull form development may be found in Appendix 2: Initial Hull Sizing and Resizing Study.

To determine the principal characteristics needed to meet all KPPs, a hull sizing study was conducted. The hull sizing study determined that a ship with a length of 365 ft would be required. This new length required the initial assumptions and constraints to be re-evaluated and revised.

The re-evaluation included a detailed analysis of the seafloor at the pier of Palmer Station, revealing a steep drop off in the seafloor to approximately 36 ft. The depth of the seabed around Palmer Station is shown in Figure 1. The additional 5 ft of water depth allowed for an increase in draft in the design. This increased draft allowed the addition of a box keel appendage to aid in reducing bubble sweepdown around underwater sensors. The resultant, Hull Variant 6, was the final result of the hull sizing study. Details on the hull sizing study can be found in Appendix 2 of this report.

Figure 1: Palmer Station Mooring Layout and Seafloor



Hull Variant 6 was physically model tested and the results were compared to the icebreaking and bubble sweepdown requirements. The model tests determined that the icebreaking performance KPP was met, but identified an opportunity to modify the hull form to improve bubble sweepdown performance.

Following the model testing of Hull Variant 6 an additional hull optimization study was conducted to improve the bubble sweepdown and open water performance, while maintaining its KPP-compliant icebreaking ability. In this study, a total of seven additional hull form variations were computationally studied. This resulted in the removal of the box keel and featured iterative reshaping of the ice knife and lower ice belt geometry forward of midship. The details of this study and model testing are discussed in Section 4.2.2. From this study, a new ARV hull form, Hull Variant 11, was selected for model testing and selected as the DR5 design hull form.

4. Design Drivers

Throughout the ARV preliminary design process, the hull form design was driven by the following factors: IB capability, KPP compliance, and bubble sweepdown performance. Details of each driver, method of evaluation, and resulting hull form feature are outlined in the sections below.

4.1. Icebreaking Considerations

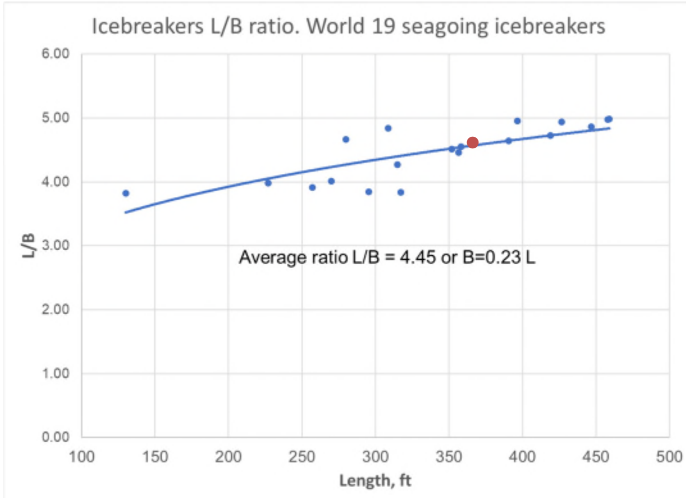
4.1.1. Mainstream Icebreaker Hull Design Parameters

Conventional icebreakers built in the last 50 years have broadly consistent primary dimension ratios and hull angles. In comparison, the current modern icebreaker shape focuses on reducing the icebreaking resistance in order to maximize icebreaking capabilities in a smaller hull form. The consequence of the modern icebreaker design approach is an increase in the open water resistance. While research vessels have utilized modern icebreaker hull form features, available published data does not indicate that these hull types are utilized for ice thicknesses greater than 3.3 ft (1.0m). This could be because the disadvantageous effects of the open water performance for large icebreaking capable ships have proven to be detrimental to the overall ship performance. Since the icebreaking KPP requires 4.5 ft of icebreaking ability and efficient open water transit is required by the National Science Foundation, a hull form using conventional icebreaking design features was selected for the ARV.

The selection of the conventional icebreaker over recently utilized modern icebreaker features for research vessels is intended to provide superior performance in open water resistance and maneuverability in both ice and open water. This superior performance is due to the more slender shape bowform with softer shoulders and a smooth transition of the bow to the midbody. Modern research icebreakers have a fuller bowform, with broad shoulders, and a hard knuckle line in between the bow and midbody transition. While the fuller bow does help minimize icebreaking resistance, it drastically increases open water resistance, and reduces the ship's maneuverability in open water and in ice.

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 average of 4.45, as shown in Figure 2, with the ARV having a L/B ratio of 4.56 at 365 ft.

Figure 2: 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 propulsors 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 IB angles along the waterline. These angles are the stem, half entrance, and the flare at the FP 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 readily available IB angles from ships with well-regarded icebreaking abilities.

Table 1: Examples of Critical Icebreaker Hull Form Angles Compared to ARV

Angle	Healy	Mackinaw	Henry Larsen	Nathaniel B. Palmer	ARV
Stem	20	19	17	28	20
Half Entrance	35	51	35	27	63
Flare @ Stem	58	74	50	48	80
Flare @ Midship	7	10	7	0	6

4.1.2. KPP Requirements Impact

The ARV KPP driving the IB hull design is the requirement to break 4.5 ft of level ice, with the objective Science Mission Requirements (SMR) of 1 ft of snow, at 3 knots. In addition to IB KPP, the ARV is required to meet a 90-day endurance KPP. Icebreaker designs are initially assessed to determine how much installed power is required to break the target ice thickness, since the IB power required will always be larger than what is needed for open water transit.

The ARV hull form design targeted to minimize the required IB power, while maintaining efficient open water transit. This is achieved with the selection of a conventional icebreaking hull form as discussed in Section 4.1.1. Open water efficiency is crucial to meeting the 90-day endurance KPP. Due to the power required for icebreaking, achieving open water transit speeds is not problematic. However, in order to maintain open water efficiency, the ARV hull form design considered reductions in open water resistance, while maintaining the necessary IB design features.

IB and range and endurance design considerations are discussed in the subsequent sections of this report.

4.1.3. Icebreaking Hull Form Design Approach

The hull design uses hull angles that are proven to be efficient for low ice resistance. After developing a hull form with the desired hull angles, the total bollard pull was calculated and used to determine the propeller diameter and the required shaft power. These estimations will be inputs to other design factors such as the available displacement and the stern geometry required to incorporate the Azipods.

Calculating the limiting performance (ice thickness) as a function of hull shape, propeller bollard pull, the ship's dimension, and mass is done by the method developed by Dr. L. G. Tsoy at the Central Marine Research and Design Institute (CNIIMF), which calculates the IB capability at 2 knots, 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 in ice of approximately 2 knots. In order to ensure applicability to the ARV requirements, the calculation was corrected using a power requirement ratio. A ratio of the 3 knots power requirement over the 2 knots power requirement, was used. This correction has a history of accurately depicting IB capability at full scale sea trials. The main equation of Tsoy's method, Reference (4), is as follows:

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

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

f - stem angle

a – waterline entrance half angle

b – flare angle at respective station

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

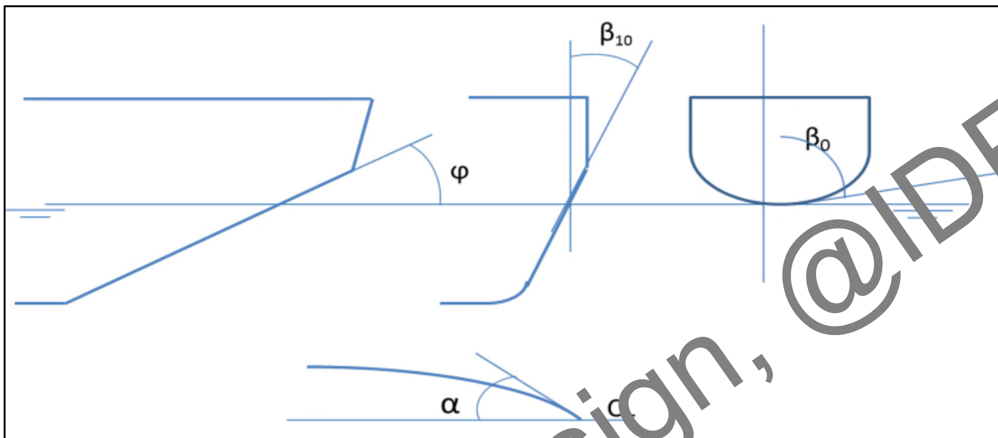
α - waterline entrance half angle is measured between the centerline and the tangent line to the waterline drawn at the point of intersection between the centerline and waterline

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

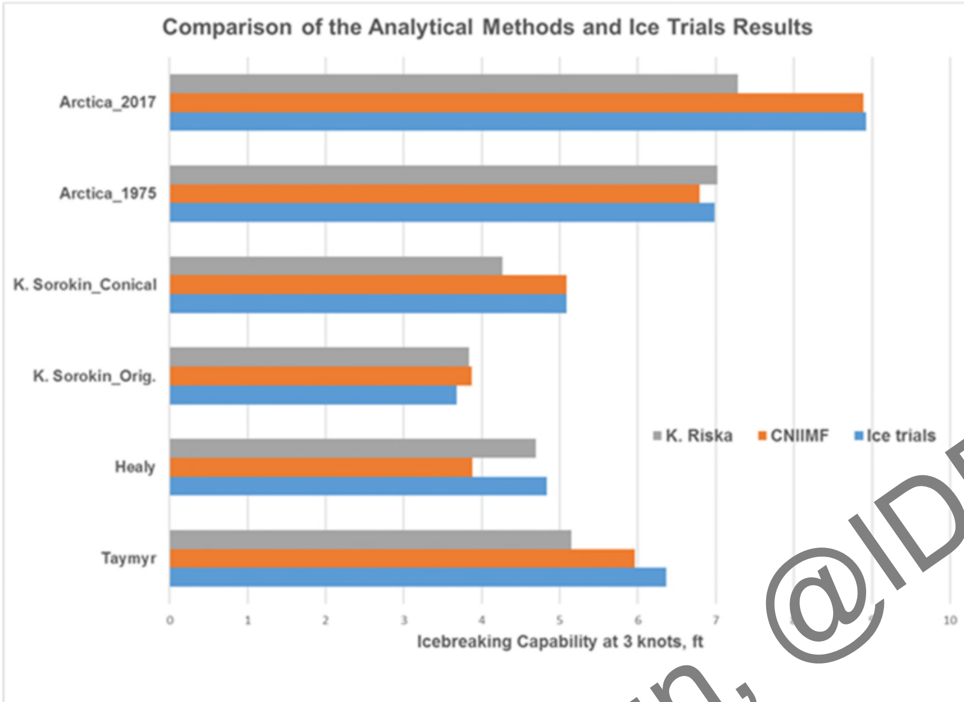
The angles measurements are depicted in Figure 3 below:

Figure 3: Icebreaking Hull Angles



This method is validated by six modern icebreakers with conventional but varying hull forms and IB capability from 3.5 to 9 ft. The Dr. Tsoy/CRIIMF method displays superior alignment with full scale ice trials, in comparison to other common IB capacity estimation methods, such as the K. Riska Method. Figure 4 displays how each IB estimation method aligns with full scale ice trials. Data present is based on ships that had both preliminary icebreaking estimations, and completed full scale ice trials, which is rarely done once the ship is delivered.

Figure 4: CNIIMF vs K. Riska vs Full Scale Ice Trials Icebreaking Estimation



4.1.4. Stern Propulsion Rise Geometry

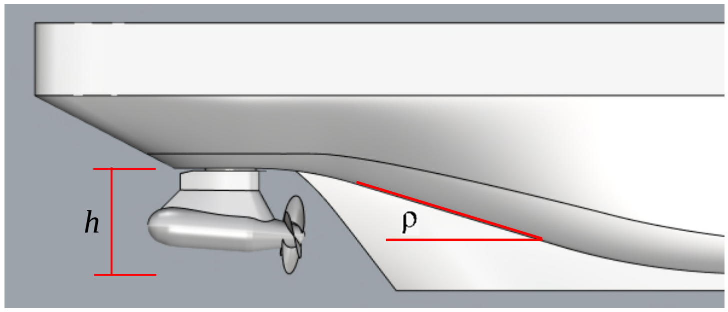
A parametric study was conducted to investigate the required transition angle in the stern, angle ρ shown in Figure 5. The parametric analysis of similar mission hulls investigated the hull geometry with regards to the transition angle from the bottom to the propulsion flat which houses the Azimuth thrusters. Typically, icebreaker hulls require a low slope to allow the waterflow to smoothly follow along the hull plating to avoid any induced turbulent flow. The optimal angle of this slope is between 12 and 17 degrees.

The early phase of the ARV design showed that the hull displacement needed to be maximized to support the required missions. Therefore, the ship used a 17-degree slope for the stern propulsion rise. Model Testing analyzed waterflow along the stern by conducting a wake survey. Results of the wake survey may be found in ARV Model Test Report (Stage 3A), Reference (10).

4.1.5. Optimization of the Azipod Location

The height of the propulsion flat, identified as "*h*" in Figure 5, must be optimized to accommodate the desired Azipods and allow the objective ice thickness to flow passed the propeller tips and the hull itself. The propeller blade is also limited by not exceeding below the baseline of the hull. The importance of maximizing the submerged volume in this area is support the weight of the Azipods. If this is not done properly, then it will immediately cause an aft trim that would need to be compensated with tank configuration within the rest of the ship.

Figure 5: Stern Geometry with Propulsion Configuration



4.1.5.1. Azipod and Propeller Size Selection

ARV will be equipped with two ABB VI1800 Azipods (or equivalent), each with a 16 ft diameter propeller, Reference (6). Considering the required tip clearance of 4.5 ft for the objective ice thickness and an additional 0.5 ft margin, the resulting propulsion flat height, *h*, was calculated to be 25 ft above the baseline.

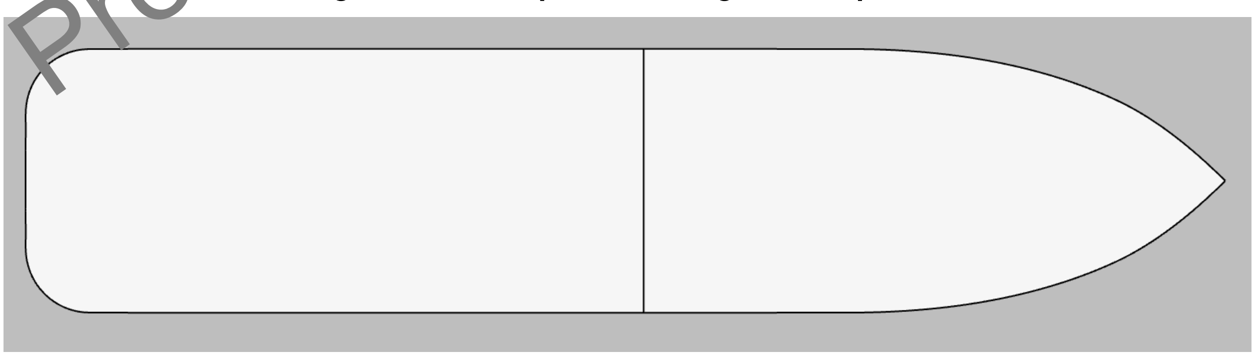
4.1.6. Working Deck Integration

The ARV started with a traditional icebreaker main deck shape, that had its maximum beam at midships and then tapered inward as it reached the transom. However, a secondary mission for the vessel was to take seafloor samples with a large tube housed on the deck edge of the working deck. To sufficiently house and operate this equipment, the ship required a square working deck.

To incorporate this adjustment, the weather deck would run the same width from midship, to approximately 10 ft before the transom. The working deck is rounded by a 10 ft radius which transitions the parallel working deck sides to the transom, as displayed in Figure 6. The vessel would keep this shape with the vertical side shell until it reached the chine. Below the chine, additional flare was added to incorporate the parallel working deck with the submerged hull form.

In addition, the freeboard height of the working deck was initially 10 ft. However due to stability concerns, the freeboard at the main working deck was adjusted to 13 ft. This increase in height preserved the ability for science overboard missions close to the water while increasing stability margins and improving crew safety from onboarding seas.

Figure 6: ARV Square Working Deck Top View



4.1.7. Hull Bottom Considerations

The ARV hull initially had a traditional flat bottom, similar to other icebreakers. However, the bubble sweepdown CFD analysis determined that the hull bottom with a standard ice knife alone does not offer enough bubble sweepdown mitigation around the underwater sensors. In order to reduce the bubble sweepdown impacts on the sensors, a box keel was initially considered, but a modified ice knife integrated into the bow geometry and designed for bubble sweepdown performance improvement was implemented into the design. Additionally, adding deadrise to the hull bottom helps produce better water flow under the ship, reducing the effects of bubble sweepdown and turbulent flow.

4.2. Bubble Sweepdown Considerations

Bubble sweepdown can affect the underwater sensors operations to be installed on the ARV, necessitating the need to mitigate bubble sweepdown around the sensors. To facilitate this, the sensors should be mounted as low as possible and the hull form shaped to divert potential entrained air from the mounting location.

All hull form variants were analyzed for bubble sweepdown with the use of CFD. Each variant used the results from the CFD analysis to optimize the design to meet the ARV requirements. A total of six variations including a box keel were analyzed prior to selecting the hull design for PDR, leading to the final box keel design for the ARV hull form that was tested for PDR. These analyzed hull form variants are discussed in detail in Appendix 3: Box Keel Design Considerations.

Initial model testing demonstrated that the box keel did not prevent bubble sweepdown to the degree desired, with approximately 40% of the widest underwater sensor encountering sweepdown. After the initial model testing, further design efforts were completed to modify the box keel and ice knife to improve the bubble sweepdown, including evaluation of complete removal of the box keel and modification of the hull lines to improve flow diversion. A total of seven additional hull form variants were analyzed, leading to the ARV DR5 hull form, Hull Variant 11. These analyzed hull form variants are discussed in Section 4.2.2.

Additional details for the CFD bubble sweepdown analysis for ARV can be found in Reference (5).

4.2.1. Box Keel Approach

A box keel was the first hull form feature analyzed to mitigate the bubble sweepdown. This is an appendage to the hull that would protrude below the hull bottom and house the underwater sensors. The forward extent of the box keel incorporates the ice knife and aft extent the skeg, thus both protruding below the hull bottom as well. The box keel is flush to the ice knife and skeg side walls, but increases in beam near midship, to accommodate the sensors that must be mounted perpendicular to the centerline. A total of six variations of the box keel were analyzed, leading to the final box keel design for the ARV hull form that was first tested, which is shown in Figure 7 and Figure 8. Discussion on the Box Keel design for Hull Variants 1 – 6 can be found in Appendix 3: Box Keel Design Considerations.

Figure 7: ARV Bottom View with Box Keel

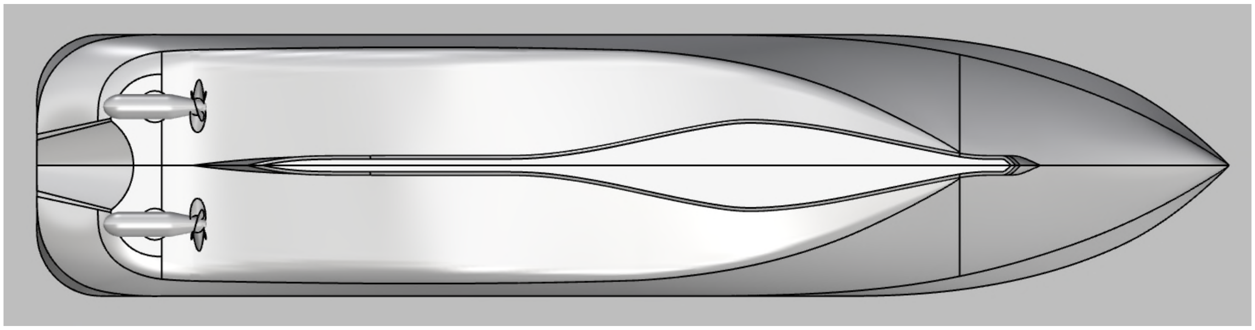
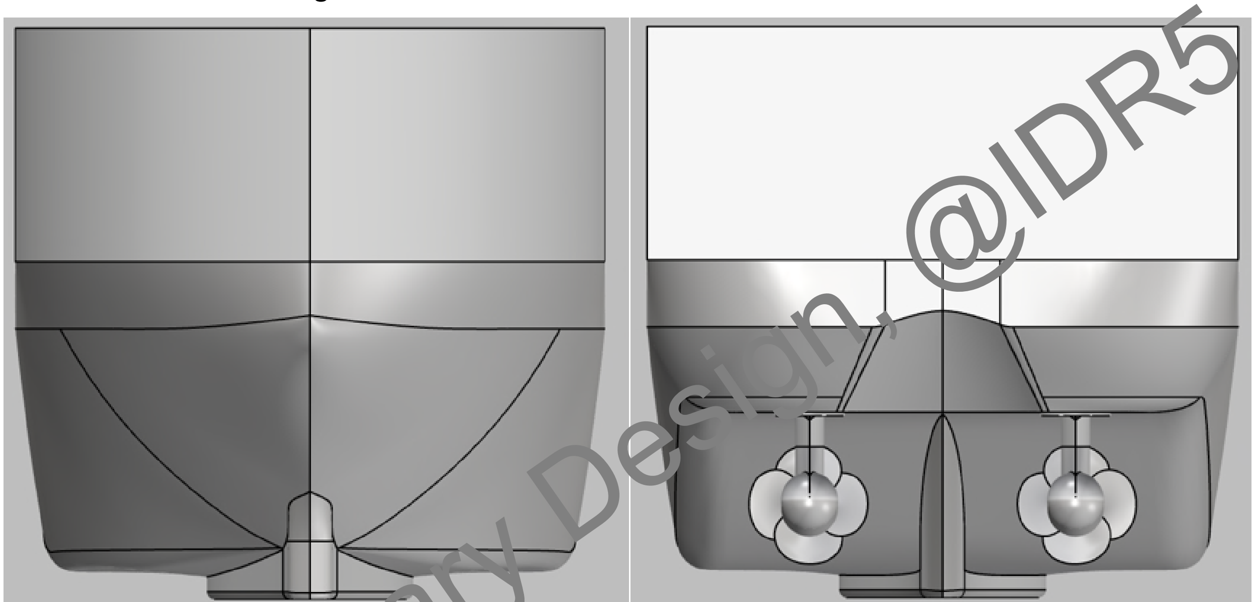


Figure 8: ARV Bow and Stern View with Box Keel



4.2.2. Modified Ice Knife Study Approach

Following PDR, the ARV hull went through seven additional hull variants investigating the size and shape of the ice knife, along with variation to the deadrise angle for the hull bottom. This approach was completed during a Hull Optimization Study.

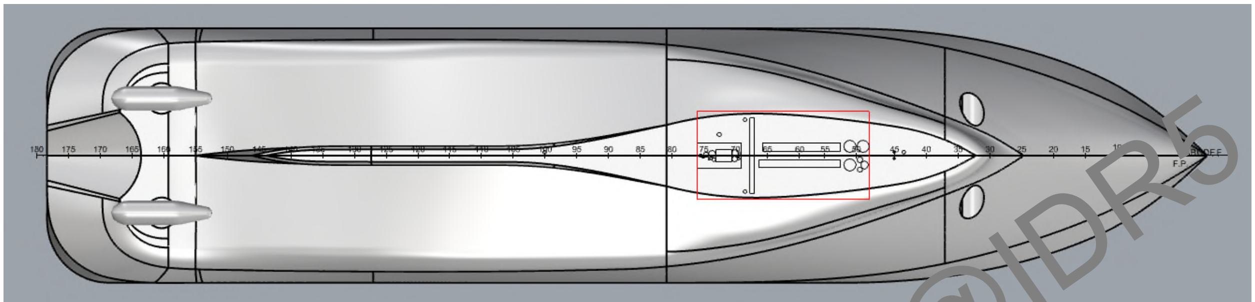
4.2.2.1. Hull Optimization Study

The primary focus of the Hull Optimization Study was to develop a hull that improves upon the bubble sweepdown and open water resistance performance of the hull variants while preserving the icebreaking capability. These changes also preserved all design aspects discussed in Section 4.1.

To reduce the risk of unacceptable Physical Model Testing bubble sweepdown results, the bubble sweepdown criteria for the CFD analysis was modified to add 2 ft of margin. This was done after the initial 13 ft off centerline bubble free area described in Reference (1) was shown to be successful in CFD for Hull Variant 6, but did not perform as well as desired in Physical Model Testing. The resulting 15 ft off centerline bubble sweepdown free area for the transducer equipment is indicated by the red box as shown in the bottom view of the hull in Figure 9.

For each of the hull variants designed in this study, the icebreaking angles on the waterline were measured to ensure the design maintained similar icebreaking characteristics as Hull Variant 6, which, at the time of the study, were proven to successfully achieve the IB KPP in Physical Model Testing. Additionally, to assess changes in displacement and underwater shape of each hull variant, an initial stability analysis was assessed in conjunction with hydrodynamic analyses.

Figure 9: Bottom Transducer Equipment with 2ft Added Bubble Sweepdown Margin – Variant 11



The hull variants in the study following the PDR Presentation include modifications to the ice knife shaping, lower hull deadrise, bilge radius, and box keel. All hull variants were analyzed for bubble sweepdown at speeds of 6 and 8 knots. Descriptions and details regarding the hull variants are discussed in later Sections 4.2.2.2 through 4.2.2.6.

A visual progression of the hull variants beginning from Hull Variant 6 to the final proposed design for DR5, Hull Variant 11 are shown in Figure 10 and Figure 11.

Figure 10: Hull Variant 6 to Hull Variant 9 Design Progression

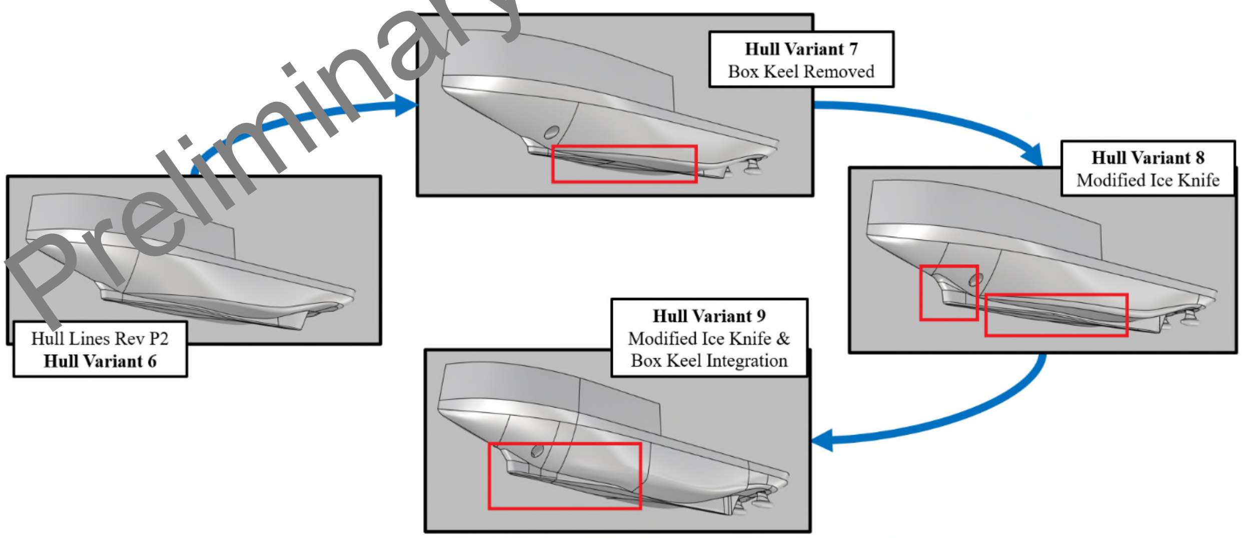
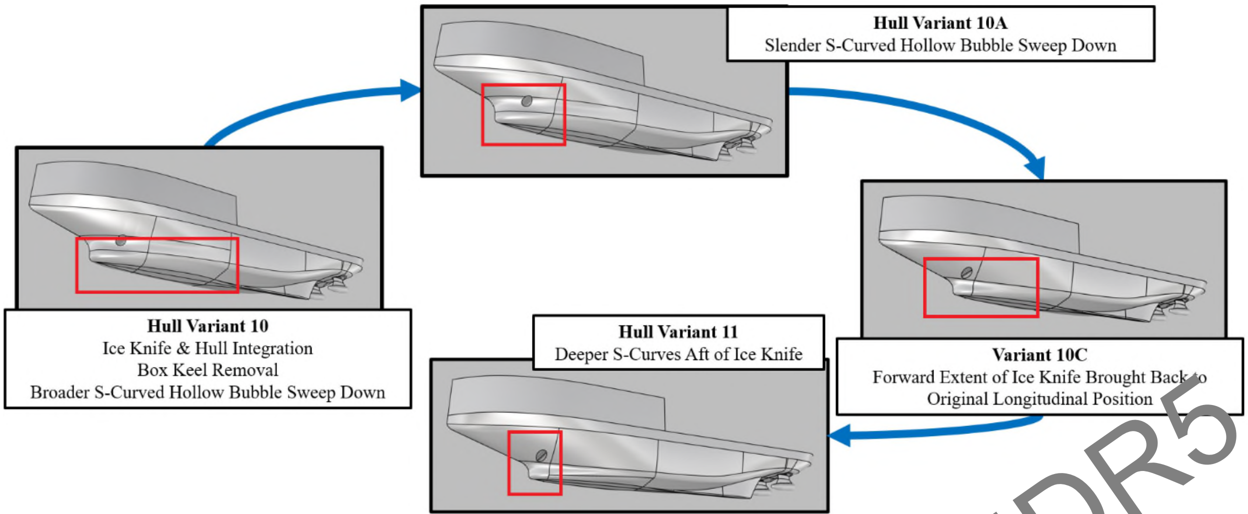


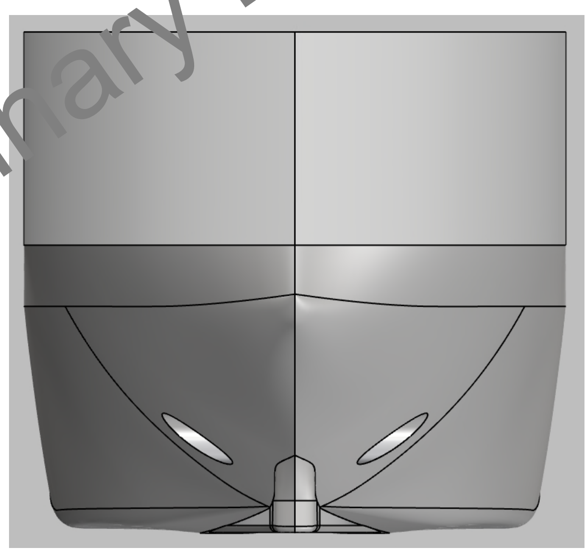
Figure 11: Hull Variant 10 to Hull Variant 11 Design Progression



4.2.2.2. Hull Variant 7: Rebaseline

In order to evaluate the bubble sweepdown mitigation for each variant, the box keel feature, which was intended to improve the bubble sweepdown performance, was removed to evaluate the bare hull performance, as shown in Figure 12. Hull Variant 7 was found to have unacceptable bubble sweepdown results, but contained data used to inform changes for Hull Variant 8.

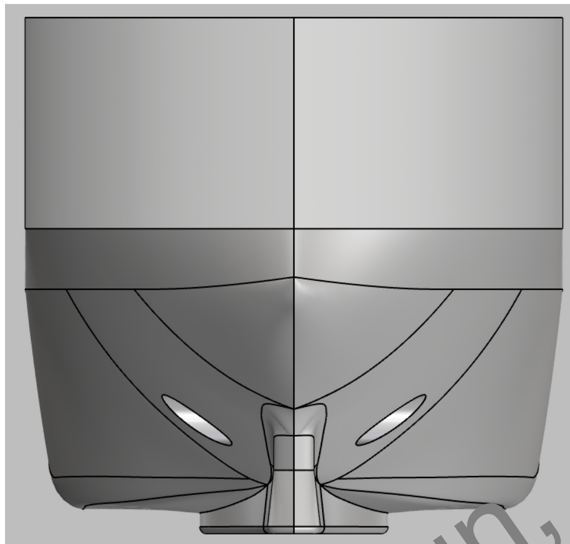
Figure 12: Hull Variant 7 with No Box Keel



4.2.2.3. Hull Variant 8: Larger Ice Knife with Fillet and Added Deadrise

Hull Variant 8, Figure 13, added the box keel back to the hull bottom, and investigated increasing the ice knife size in length and height while giving it sloped sides for the lower half. The ice knife was also modified to incorporate a rounded fillet between itself and the hull along with a larger bilge radius. This was done to study the ability to keep laminar flow along the hull with the larger ice knife to gradually push the bubble flow outboard and prevent the flow from going below the ice knife and into the area of underwater sensors. Hull Variant 8 was found to have unacceptable bubble sweepdown results, but contained data used to inform changes for Hull Variant 9.

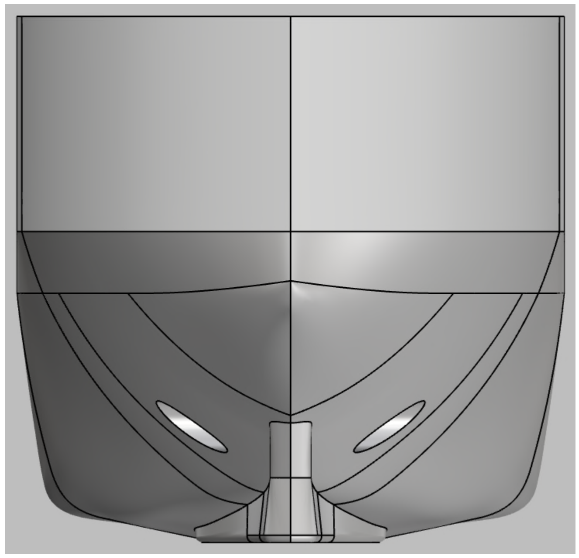
Figure 13: Hull Variant 8 with Larger Ice Knife with Fillet



4.2.2.4. Hull Variant 9: Larger Ice Knife without Fillet and Additional Deadrise

Hull Variant 9, Figure 14, removed the fillet from the ice knife after Hull Variant 8 CFD results showed it did not improve bubble sweepdown. This variant preserved the Hull Variant 8 ice knife size as the CFD results showed that the increase in ice knife size improved bubble sweepdown. Previous results also revealed that the bilge radius was still too small and caused turbulent flow. For Hull Variant 9 the bilge radius was adjusted in the buttock lines by increasing the deadrise more gradually so, by midship, the bottom of the box keel was now integrated with the hull. The intent was to create a smoother buttock line outboard of the ice knife and box keel to prevent inducing turbulent flow from spilling below the box keel and over the underwater sensors. Hull Variant 9 was found to have unacceptable bubble sweepdown results, but contained data used to inform changes for Hull Variant 10.

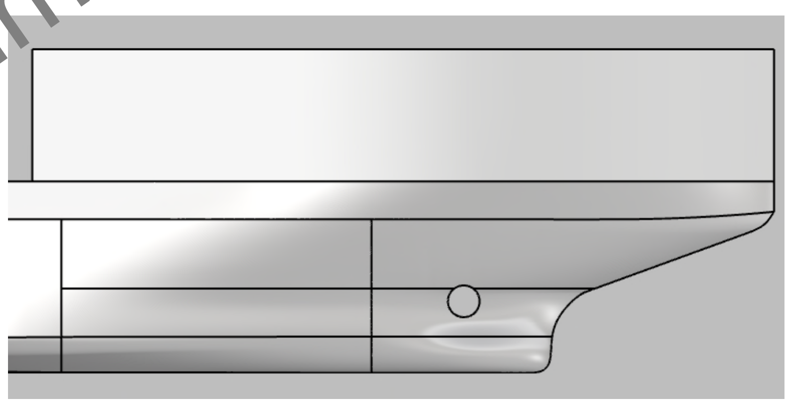
Figure 14: Hull Variant 9 with Larger Ice Knife and Deadrise



4.2.2.5. Hull Variant 10 through 10C: Larger Ice Knife with S-Curve Channels

Hull Variants 10, 10A and 10C investigated a new ice knife design, which can most easily be seen in the S-Curves of the Body Plan views. This ice knife modification largely preserved the overall hull form that was the result of previous iterations. These S-Curve features originated from investigation of other research vessels with strict bubble sweepdown mitigation requirements, though this feature has not been incorporated in any icebreaking hull forms. While developing these variants, attention was given to avoid any concavity in the ice knife in the profile view, as shown in Figure 15. This concavity would become a bulbous bow and greatly increase the icebreaking resistance. These variants also increased deadrise allowing the bottom shell to slope from the bilge radius to the flat of bottom area used to mount the underwater sensors.,. Details of each Hull Variant 10 – 10C are shown below.

Figure 15: Hull Variant 10 Series with Rounded Ice Knife, Profile View



Hull Variant 10 and 10A, Figure 16 and Figure 17, respectively, compared the difference between having deeper versus shallower S-Curves. This allowed the study of the extent of transverse distance required between the inner and outer portion of the ice knife to keep the water flow from spilling below the hull. The ice knife for Hull Variant 10 and 10A was the same position as the ice knife of Hull Variants 8 and 9.

Figure 16: Hull Variant 10 with Broader S-Curves

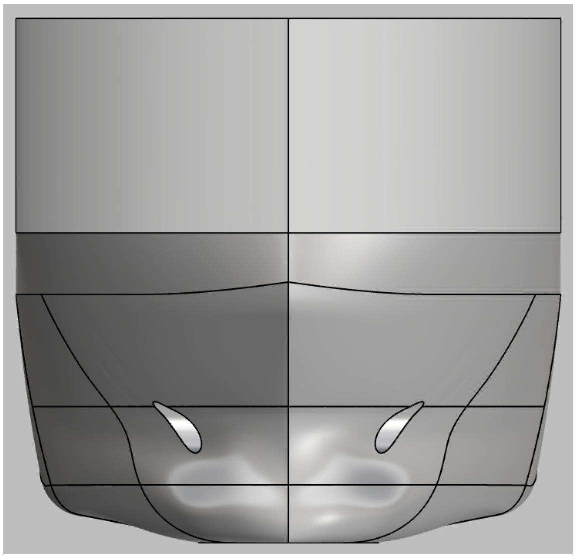
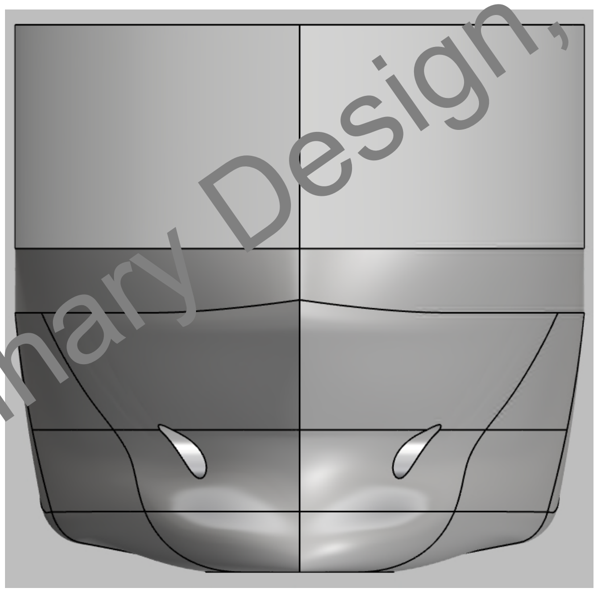


Figure 17: Hull Variant 10A with Shallower S-Curves



Hull Variants 10 and 10A were found to have acceptable bubble sweepdown results. These variants were then evaluated for ship's stability to determine hull feasibility. It was determined that the increased displacement of the hull form, but unchanged waterplane area of the hull, deteriorated the ships stability to a degree that design convergence in this pair of hull variants would be infeasible.

Using the data from the previous variants, Hull Variant 10C scaled the shallower S-Curves from Hull Variant 10A to the original location of the ice knife in Hull Variant 7. Figure 18 displays the round ice knife in the profile view, and Figure 19 shows the smaller rounded ice knife in the Bow View. The reduction in displaced volume improved stability, deeming it feasible, but it did not provide adequate bubble sweepdown mitigation to be successful against the updated bubble sweepdown standoff of 15 ft with the 2 ft margin added for the study following PDR.

Figure 18: Hull Variant 10C with Smaller Round Ice Knife Profile View

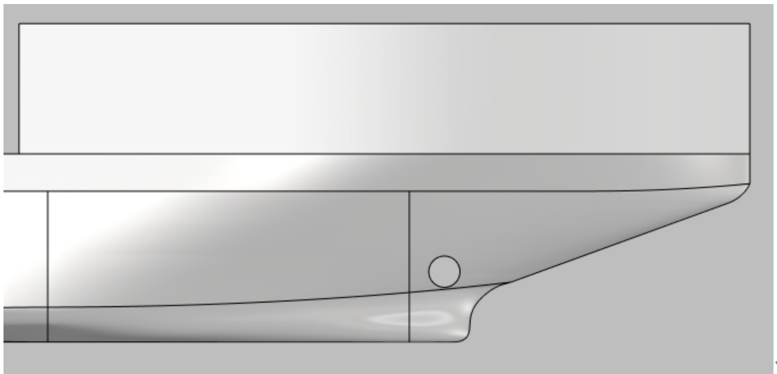
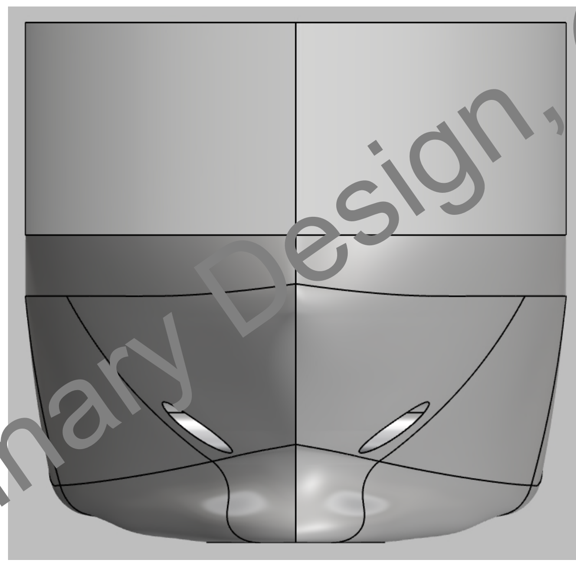


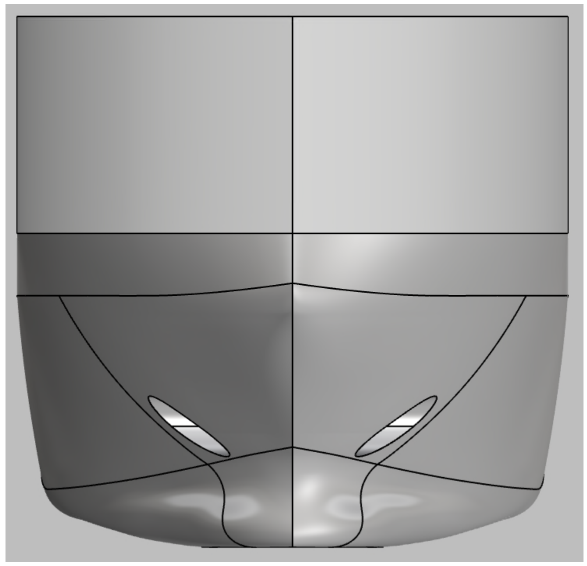
Figure 19: Hull Variant 10C with Smaller Round Ice Knife Bow View



4.2.2.6. Hull Variant 11: Original Ice Knife Size with Deeper S-Curve Channels

Hull Variant 11 began with the rounded ice knife shape and location from Hull Variant 10C, but extended the S-Curve shape further aft to maintain the bubble flow longer as it travels outboard. This successfully diverted the waterflow outboard to mitigate bubble sweepdown in the CFD analysis. Based on the balance between bubble sweepdown, resistance, and stability feasibility, Hull Variant 11 was selected for additional model testing and to form the basis of the optimization design effort following the Preliminary Design Review (PDR).

Figure 20: Hull Variant 11 with Broader S-Curve Ice Knife at Original Location



4.2.3. Hull Optimization Study Results

The results of the Hull Optimization Study showed that incorporating a unique modified ice knife, derived from optimized Research Vessels with strict Bubble Sweepdown requirements, would successfully divert surface waterflow outboard before it flows over the ice knife or bottom of the hull, and therefore interfere with the underwater sensors. Hull Variant 11 was selected as the new hull form for all following design products to utilize. The new variant was also selected for additional Physical Model Testing.

5. Numerical Final Hull Form Results

Computational analysis of Hull Variant 11 demonstrated the hull form's ability to meet the ARV KPPs and mission requirements, outlined in Reference (1). Results for this hull variant are shown in the section below.

5.1. Hull Dimensions

The resulting ARV hull form provides a maximum length of 365 ft, total beam of 80 ft, and a total draft of 32.5 ft. This was determined to be the minimal hull size required to meet the extensive range and endurance requirements defined in the P-Spec, Reference (1), as well as support the required machinery and propulsion systems to break the 4.5 ft of ice plus 12 inches snow at 3 kts as achieved by Hull Variant 6 for PDR. Table 2 displays the Principal Characteristics of the ARV.

To confirm the ability of the lengthened vessel to moor at the current Palmer Station facility, a mooring and towing analysis was conducted. The ARV Mooring and Towing Drawing, Reference (7), contains the details of the arrangement and allowable environmental conditions considered.

Table 2: Final ARV Principal Characteristics

Description	Value
Length, Overall	365 ft
Beam, Overall	80 ft
Freeboard at Main Deck	13 ft
Freeboard at Focsle	52 ft
Design Draft (EOSL)	32.5 ft

The final hull form geometry is shown in Figure 21 through Figure 24, below.

Figure 21: ARV Profile View

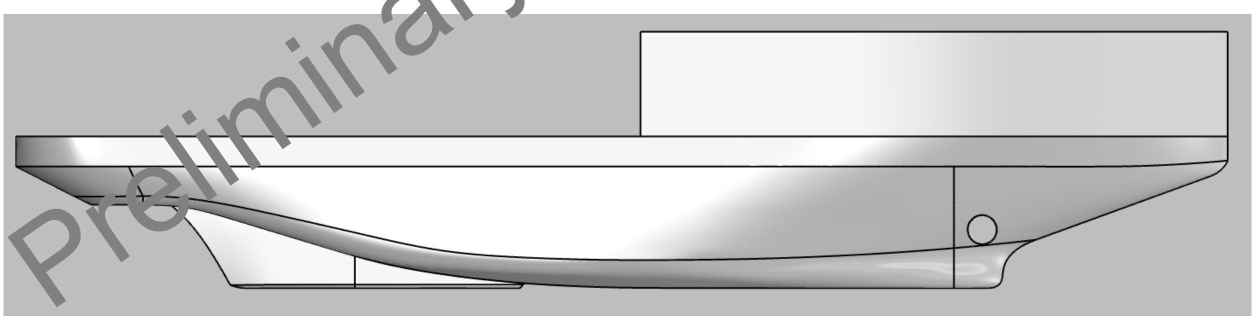


Figure 22: ARV Top View

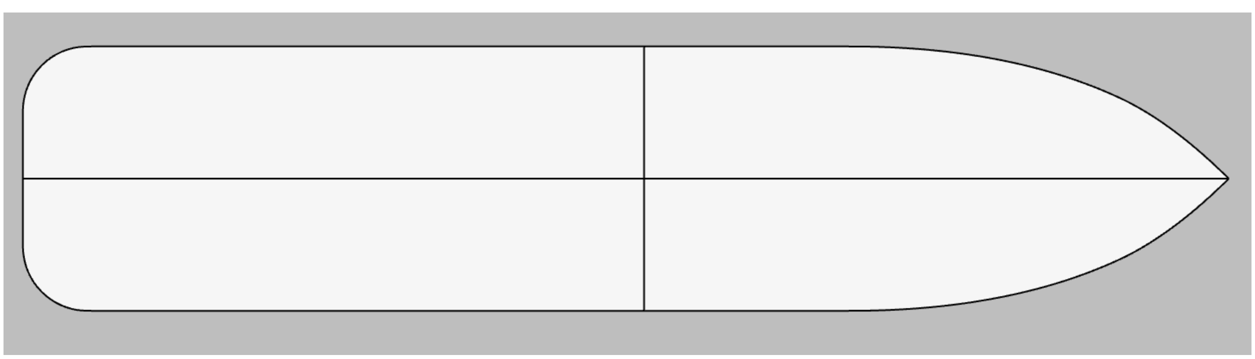


Figure 23: ARV Bottom View

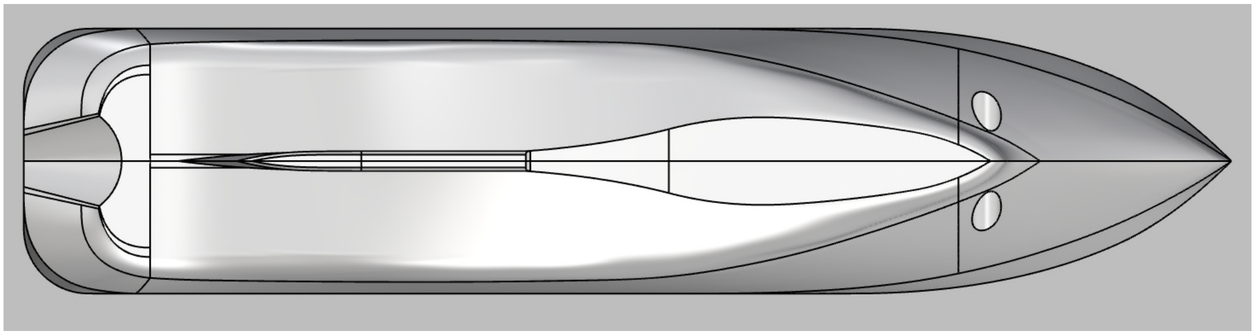
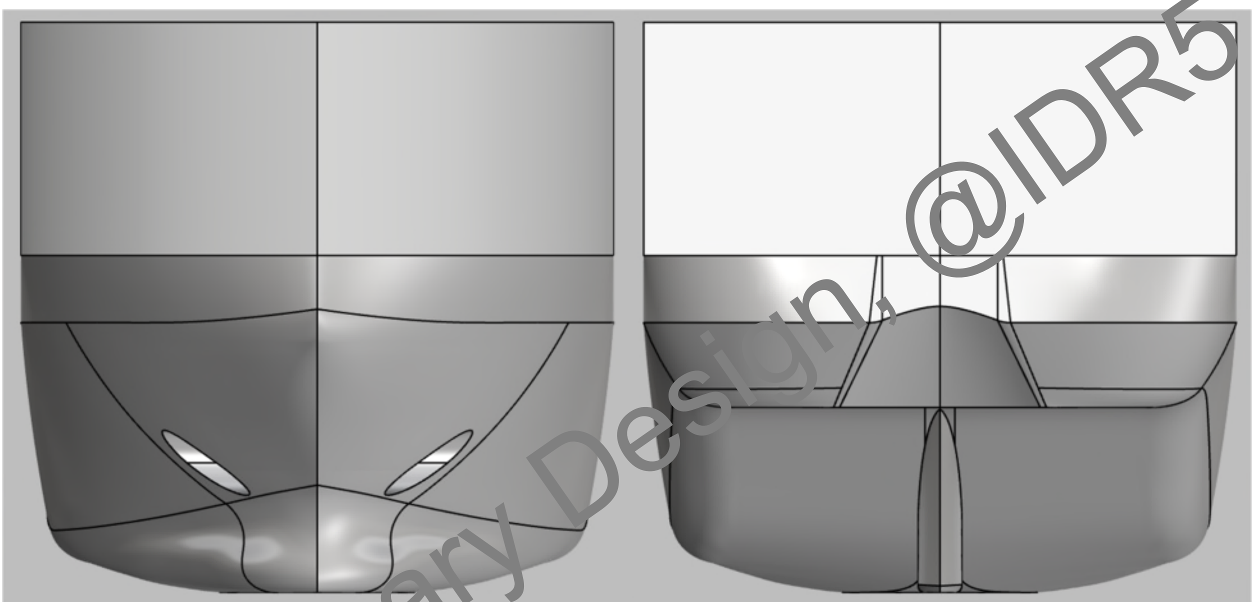


Figure 24: ARV Bow and Stern View



5.2. Icebreaking Capability

As outlined in Section 4.1.3, the icebreaking capabilities result from incorporating the necessary propulsion arrangement to achieve the objective icebreaking capability. With the use of ABB V11800 Azipods (or equivalent), the ARV design is compliant with the objective icebreaking capability of 4.5 ft of ice plus 12 inches snow at 3 kts. Table 3 shows the hull angles for the final ARV hull form design, Hull Variant 11.

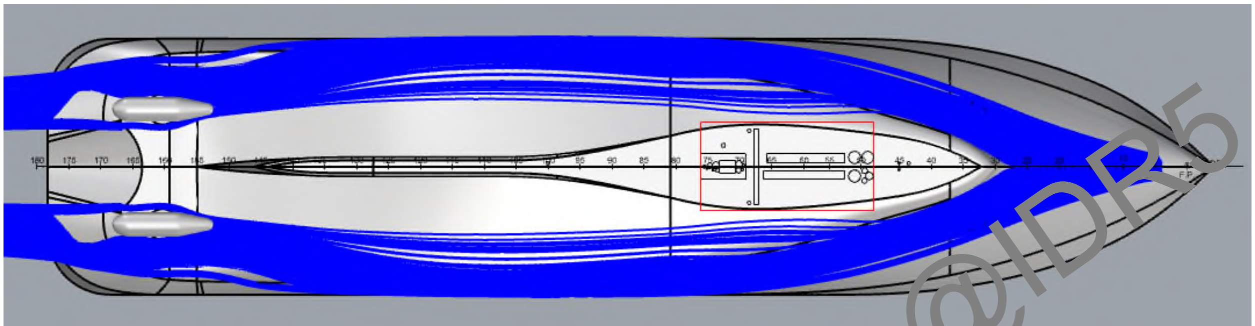
Table 3: Final ARV Hull Angles

Angle	ARV
Stem	20.0
Half Entrance	63.4
Flare @ Stem	79.7
Flare @ Midship	6.4

5.3. Rounded Ice Knife and Bubble Sweepdown

The rounded ice knife design is a result of four hull variants investigating this unique bow future for icebreaker hulls that showed success with preliminary CFD analysis and showed significant validation in model testing, as discussed in Section 4.2.2. The S-Curve shape of the ice knife diverts the laminar waterflow outboard long enough that when the flow does spill below the bilge radius, it successfully avoids the transverse array plus 2 ft additional standoff margin in the CFD results, Figure 25.

Figure 25: ARV Bubble Sweepdown CFD Results



5.4. Hydrostatics and Weights

The ARV displacement for the Full Load at Delivery and Full Load, EOSL, conditions are shown in Table 4. All operating limits of the ARV are within the draft constraints at Palmer Station.

Table 4: ARV Loading Conditions

Condition	Draft (ft ABL)	Displacement (LT)
Full Load, Delivery	31.9	13,046
Full Load, EOSL	32.5	13,429

5.5. Stability

The stability analysis concluded that the ARV hull form is compliant with all requirements outlined in Reference (1). Details for the stability analysis for the ARV are shown in Reference (8).

5.6. Range and Endurance

The range and endurance calculations concluded that the ARV hull form is compliant with all requirements outlined in Reference (1). Details for the Range and Endurance analysis for the ARV are shown in Reference (9).

6. Hull Variant 11 Model Test Results

Physical Model Testing of Hull Variant 11 demonstrated the hull form's ability to meet ARV KPP and mission requirements, outlined in Reference (1). Results for this hull variant are shown in the sections below.

A 1:24.384 scale model of the ARV hull was tested in Hamburgische Schiffbau-Versuchsantalt (HSVA) model testing facility in Hamburg, Germany. The test campaign included thruster open-water evaluation, bubble sweepdown, open-water resistance and propulsion, wake survey and ice resistance and propulsion tests. All propelled tests were conducted with HSVA ice stock propellers on the azimuthing thrusters.

6.1. Open Water Performance

The powering results for open water transit support the objective of efficient operations over the life of the ARV, with indication that the ARV hull is more efficient than other icebreaking hull forms of comparable size. The ARV will achieve sustained speed of 11 kts at 2.3 MW in calm water. Figure 26 shows the ARV 11 kts Calm Water model test.

Figure 26: ARV 11 kts Calm Water Model Test

6.2. Bubble Sweepdown Performance

On-site observations of the bubble sweepdown tests indicate a significant reduction (estimated as 50%) in dye coverage compared to the PDR model tested hull form Hull Variant 6, but there remains some potential for bubble interference with the underwater sensors from bubbles originating near the waterline that could cover up to 20% of the outer edges of the widest sensor. Figure 27 shows the model test of the potential bubble sweepdown interference with lines provided by HSVA displaying the coverage area. SME observations provided by HSVA indicate that the ARV performance exceeds bubble sweepdown mitigation achieved by other icebreaking vessels.

Figure 27: ARV Bubble Sweepdown Model Testing Results

6.3. Icebreaking Capability

According to the model test results, the ARV will achieve 3 knots ahead in 4.83 ft of level ice (equivalent to include impact of 12 inches of snow) 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 28 and Figure 29 show model icebreaking tests at objective ice thickness for Ahead and Astern, respectively. Further details regarding other level icebreaking performance are available in Reference (10).

Figure 28: Icebreaking Ahead in Objective Ice Thickness

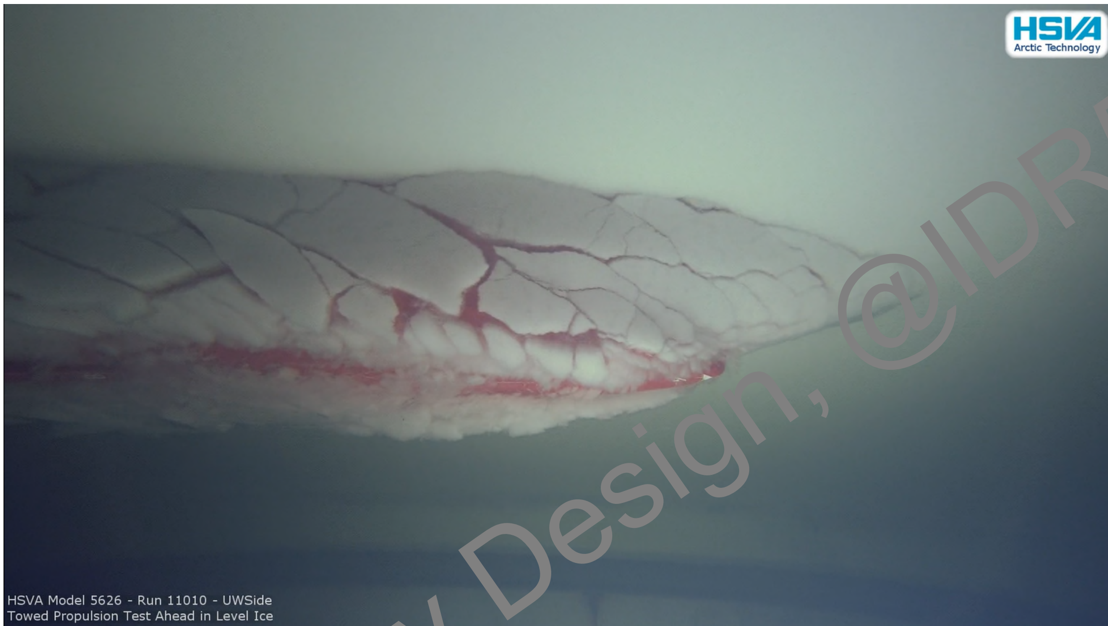
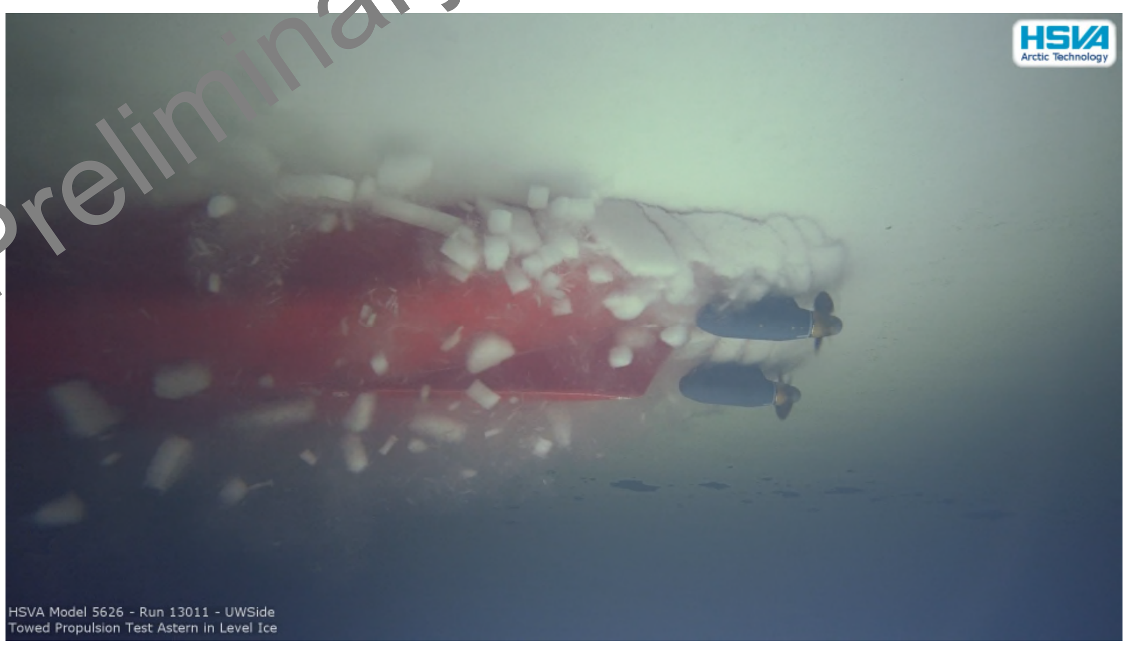


Figure 29: Icebreaking Astern in Objective Ice Thickness

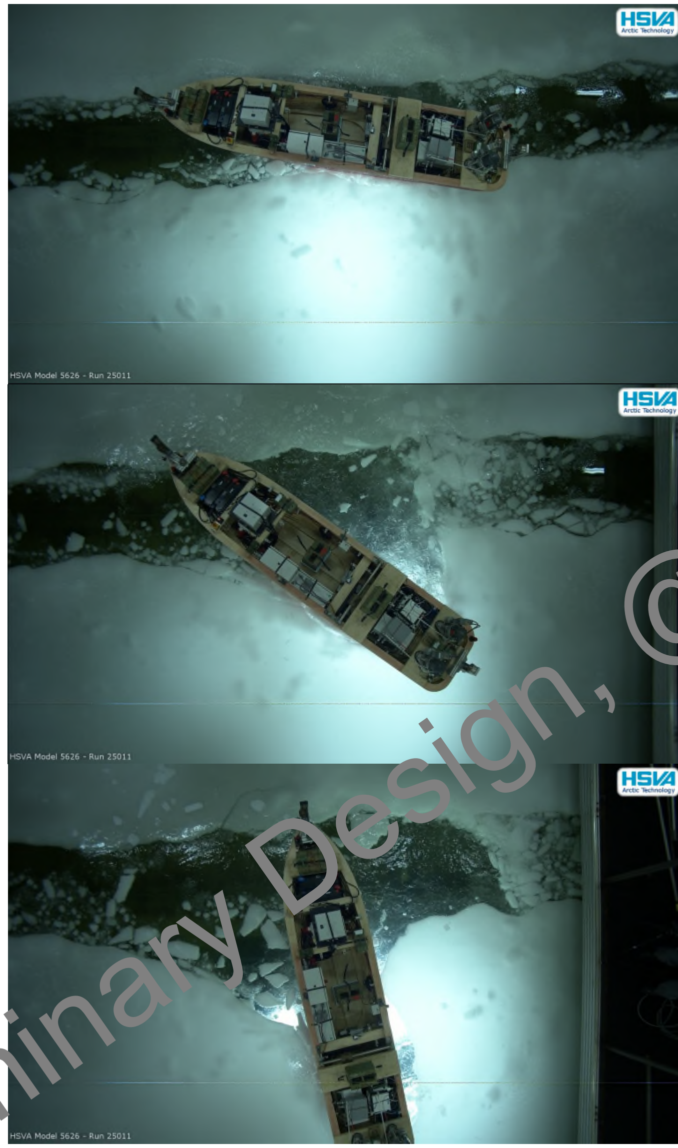


6.4. Additional Icebreaking Performance

The ARV hull achieved breaking out of the cleared channel, both ahead and astern, in both ice conditions to satisfy the KPPs. Figure 30 and Figure 31 show the Break Out Tests, Ahead and Astern, respectively.

Figure 30: Break Out Test Ahead in Objective Ice Thickness

Figure 31: Break Out Test Astern in Objective Ice Thickness



Breaking through ridges with keel depths of 23 ft and 37.7 ft is achievable, with little loss of speed in the shallower ridge depth, and with two ramming attempts in the deeper ridge. Figure 32 shows the ARV successfully traversing over a 37.7 keel depth ridge.

Figure 32: ARV Ridge Ramming 37.7 ft Keel Depth

Ice Model tests also demonstrated the ARV's ability to clear the channel from an unbroken ice sheet in order to support scientific towed missions. Figure 33 shows the clear channel in 3.3 ft of unbroken ice.

Figure 33: Clear Channel in 3.3 ft of Unbroken Ice

The full model test assessment can be found in the ARV Model Test Report (Stage 3A), Reference (10).

7. PDR Concerns and Resulting Resolutions

The following list describes concerns that remained at PDR and Resolutions completed by the design team since PDR.

Concern 1: The Bubble Sweepdown performance is pending CFD verification from model test results. Model test results are preliminary at this time and additional hull optimization is required following PDR to further enhance the bubble sweepdown performance.

Resolution 1: Hull Optimization Study discussed in Section 4.2.2.1 presents the design efforts to improve Bubble Sweepdown performance and preliminary CFD showed success to divert the flow away from the transverse sensor, and Model Testing showing a minimal amount of flow passes over the Transverse Underwater Sensor, covering approximately 20%. This result was a 50% improvement in comparison to the original Hull Variant 6 Model Test Results.

Concern 2: The Palmer Station Mooring arrangement will need further study to verify that it can support the larger 365 ft hull. Previous study only investigated a ship length of 345 ft and will require confirmation that it can support the larger ship.

Resolution 2: To confirm the ability of the lengthened vessel to moor at the current Palmer Station facility, a mooring and towing analysis was conducted. The Mooring and Towing drawing contains the details of the arrangement and allowable environmental conditions considered.

Concern 3: There is concern for the Ice Channel following the icebreaker to have ice chunks, which would impact Towed Array Operations. Studies have shown that hull geometry cannot assist in clearing the ice channel following the ship, but use of the azimuth thrusters during operations can have positive effects. Further investigation on Azipod orientation during icebreaking operations and its impact on ice clearing will be further investigated during hull development.

Resolution 3: Ice Model testing included a series of ice clearing tests in order to support science missions by orientating the Azipods in varying positions, as shown in Figure 33.

8. Conclusions and Recommendations

This report details the hull form design process and results for the ARV. The development of the hull form considered many requirements and the balancing of hull features to allow for a vessel capable of icebreaking, having adequate bubble sweepdown performance, open water efficiency, stability, and maintaining weight and displacement balance.

Computational and Physical Model Testing Results indicate that the selected hull form can meet the KPPs for the ARV. The optimization process conducted following PDR has improved the bubble sweepdown performance and open water resistance of the hull while maintaining Objective icebreaking capability. These improvements were made while balancing the hull displacement with estimated ship weights and loads and provide a foundation for the design to accommodate the facilities required for successful support the research and scientific missions.

9. References

(1) *ARV Performance Specifications*, Rev. A, Change 05. 23 June 2023.

(2) *ARV Maneuvering Performance Report, Document No. 5E1-050-R001, Rev P2.*

(3) *ARV Dynamic Positioning System Performance Report, Document 5E1-065-R001, Rev P3.*

(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

(5) *ARV Bubble Sweepdown Computation Fluid Dynamics Report*, Document No. 5E1-050-R101, Rev. P3.

(6) VI1800 Azipod Main Dimensions, 3AFV6139234 Rev A, 28 December 2021

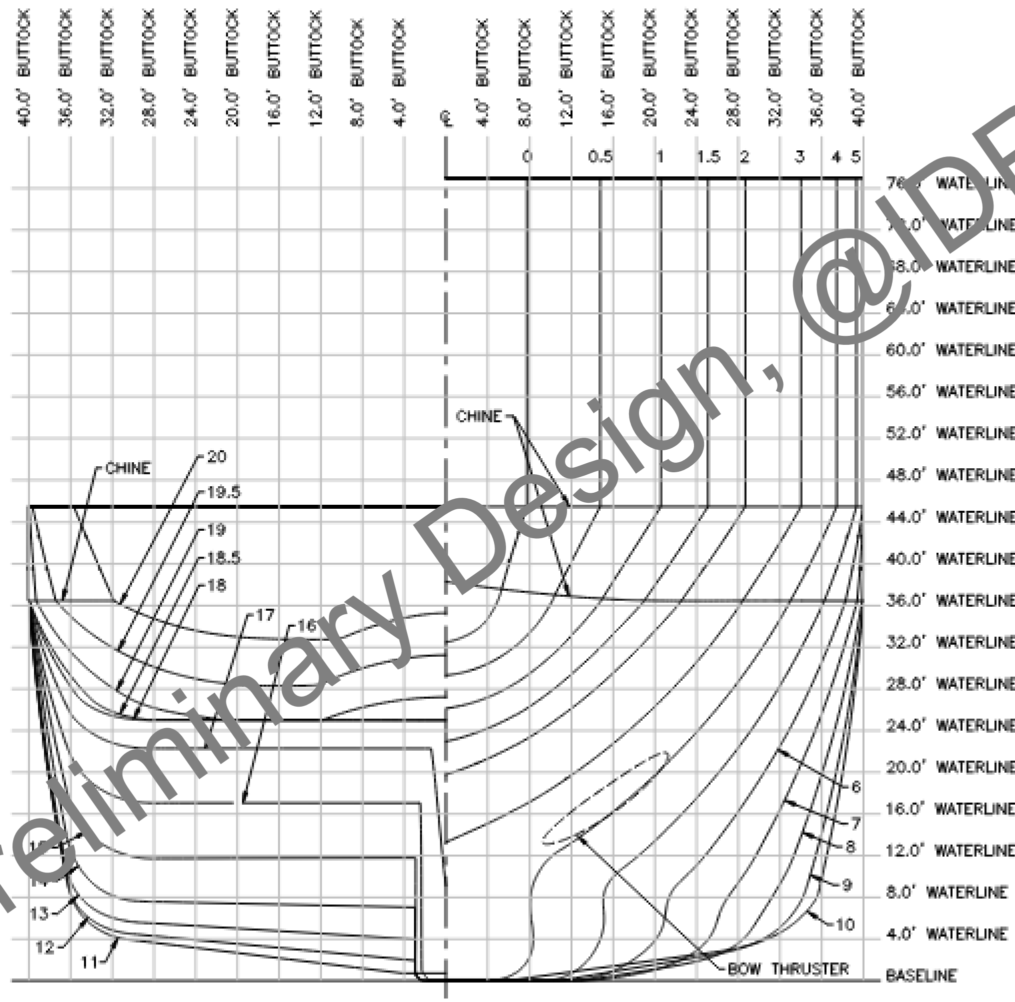
(7) *ARV Mooring and Towing Drawing*, Document No. 5E1-582-D001, Rev P0.

(8) *ARV Design Weight Estimate*, Document No. 5E1-096-R001 Rev P1.

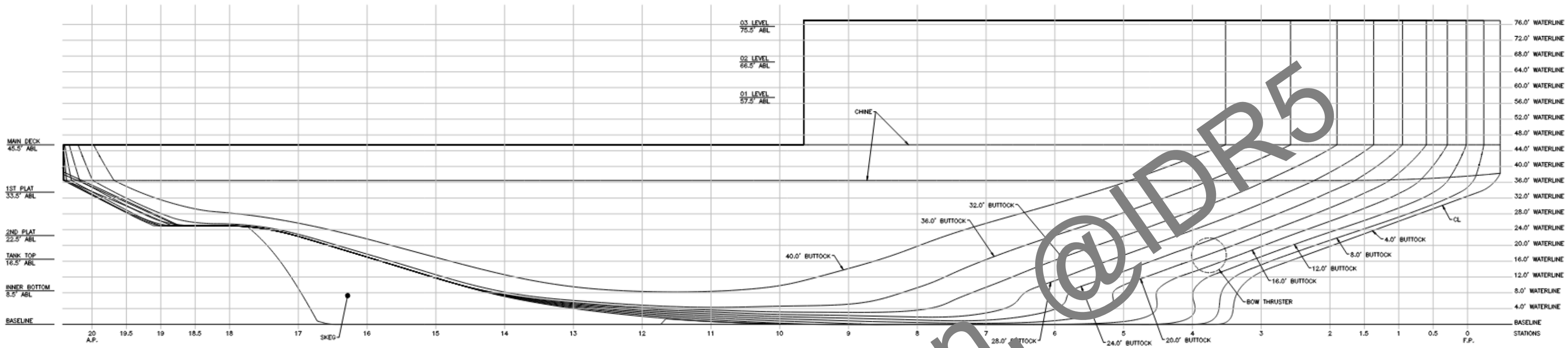
(9) *ARV Engineering Report: Range and Endurance Calculation*, Document No. 5E1-050-R021, Rev. P4.

(10) *ARV Model Test Report (Open Water and Ice)*, Document No. 5E1-098-R101, Rev P2.

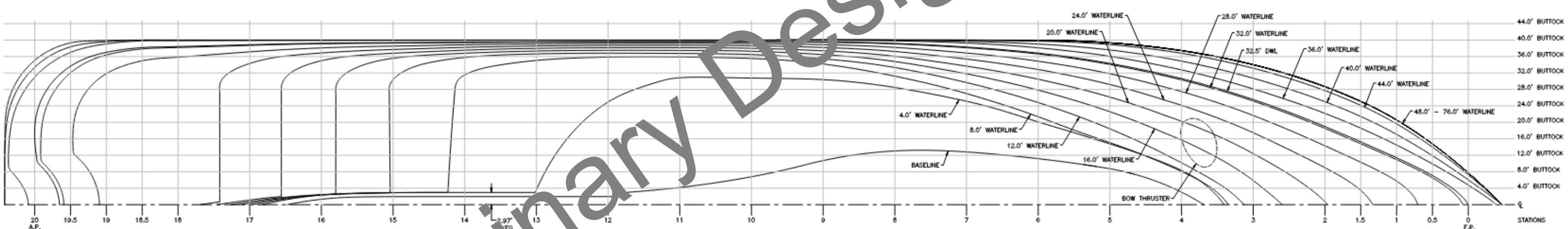
10. Appendix 1: Lines Plan



Body Plan



Buttock Lines



Waterlines

11. Appendix 2: Initial Hull Sizing and Resizing Study

11.1. Initial Hull Sizing Assessment

11.1.1. Initial Hull Size

The initial ARV hull form was 345 ft in length overall, 73.4 ft beam overall, with a total draft of 31 ft. The length was determined from the original length restriction assumption for the Palmer Station; a length restriction was assumed due to mooring capabilities. The beam was established by using the L/B ratio of 4.7, as outlined in the parametric analysis shown in Section 4.1.1. The draft restriction was based on the Palmer Station seafloor with a 28 ft depth below the waterline by the pier. However, the drop off to 36 ft allowed the inclusion of a box keel, which resulted in an appendage draft of 31 ft.

Table 5: Initial ARV Principal Characteristics

Description	Value
Length, Overall	345 ft
Beam, Overall	73 ft 4 in
Freeboard at Main Deck	10 ft
Freeboard at Focsle	49 ft
Draft	28 ft
Appendage Draft	31 ft

11.1.1.1. Hydrostatics and Weight

The initial ARV displacement at the appendage draft of 31 ft was 10,909 LT. Based on the available ARV Design Weight Estimate Rev P0-1, the ARV Full Load at Delivery was 10,568 LT and a draft of 27.4 ft. The Full Load at End of Service Life was 10,876 LT and draft of 27.9 ft. All operating limits of the ARV were within the draft constraints at Palmer Station.

11.1.1.2. Range and Endurance

The initial open water resistance and power estimates confirmed that the ARV hull form can achieve the required cruise speed. The conventional IB hull form with softer shoulders and a slender bow achieves the icebreaking capability of 4.5 ft. The incorporation of a box keel for bubble sweepdown mitigation, does not sacrifice open water performance. However, the volume and weight limits restricted fuel capacity. The initial hull provided 1,407 LT of fuel to be stowed on board. This total fuel load is insufficient to achieve the range and endurance requirements as stated in the P-Spec, Reference (1). The ARV is required to travel 17,000 nm at 11 knots and perform three Design Reference Mission Candidate (DRMC). The initial hull could only reach 14,203 nm and could not meet the DRMC requirements. The Range and Endurance calculations are discussed in detail in Reference (9). Initial hull range and endurance capability was evaluated using Revision P1 of Reference (9).

Table 6: ARV Range Capability

Speed	Range (nm)	Threshold Requirement (nm)	Additional Range Needed (nm)
11 kts in calm seas	14,203	17,000	2,797
10 kts in calm seas	14,427	17,000	2,573

Table 7: Mission Required Fuel Capacity Summary

Mission	Mission Fuel Required (LT)	10% Fuel Reserve Margin (LT)	Total Burnable Fuel Required (LT)	100% Fuel Capacity Required (LT)	Additional Fuel Capacity Required (LT)
DRMC1	1,668	185	1,854	2,060	654
DRMC2	2,014	224	2,238	2,487	1,081
DRMC3	1,733	193	1,926	2,139	734
11 kts in calm seas	1,514	168	1,683	1,869	464
10 kts in calm seas	1,491	166	1,656	1,840	435

11.1.1.3. Icebreaking Capability

The parametric analysis of other icebreakers resulted in the following hull angles, shown in Table 8: Initial ARV Hull Angles. These angles provide the bow form capable of breaking the objective IB requirement of 4.5 ft, when paired with the properly sized propulsion plant.

Table 8: Initial ARV Hull Angles

Angle	ARV
Stem	21.0
Half Entrance	69.0
Flare @ Stem	81.6
Flare @ Midship	8.0

The specification requirement for IB is defined as 4.5 ft of level continuous ice with 12 in of snow at 3 knots. This corresponds with estimated equivalent ice thickness of 4.83 ft, assuming snow thickness is equivalent to 33% of ice thickness.

With the use of the VI1600 Azipods, and the 15 MW of shaft power, the ARV can achieve 4.26 ft of IB. This is approximately 0.24 ft (2.9 in) below the objective IB capability of solid ice, or 0.57 ft (6.8 in) when including the snow thickness. Table 9 displays other configurations of the propulsion plant and their resulting IB capabilities in feet.

Table 9: Propulsion Configuration and Icebreaking Capability

Propeller Diameter (ft)	Propulsion Motors MCR (MW)	Azipod Frame	Icebreaking Height (ft)	KPP Compliance	Deficiency to Objective KPP (ft)
14	17.8	VI1800	4.5	Meets Threshold	-0.33
	15	VI1600	4.26	Below Threshold	-0.57
16	15	VI1800	4.5	Meets Threshold	-0.33
	13	VI1800	4.26	Below Threshold	-0.57
	19.3	VI1800	4.83	Meets Objective	0.00

Based on the evaluation shown in Table 9, it was determined that the use of an ABB V11800 Azipod (or equivalent), would be required to comply with the requirements outlined in Reference (1).

11.1.2. Limitations of Initial Hull Size

The 345 ft hull form failed to meet all KPP and range requirements as defined in the P-Spec, Reference (1). In addition, intact stability was identified as deficient. The bow form is shown to be sufficient to break the required 4.5 ft of ice, with a properly sized propulsion plant. The restricted 345 ft hull had limited ability to support the ship weight, size of the larger azimuth thrusters, and larger machinery.

The 345 ft hull form failed all endurance and range requirements. The volume available for fuel allowed a range of 14,203 nm, below the required 17,000 nm at 11 knots. Additionally, the ARV failed to meet the three Design Reference Mission Candidates (DRMC) endurance requirements.

The 345 ft hull also displayed significant intact stability deficiencies. The hull geometry and onboard systems significantly constrained the allowable VCG calculated in the initial stability assessment. Limiting factors in the stability assessment included a low working deck freeboard of 10 ft which restricted the margin line immersion, and the Anti-Roll Tank which contributed to a high free surface correction.

11.1.1. Hull Resizing Study

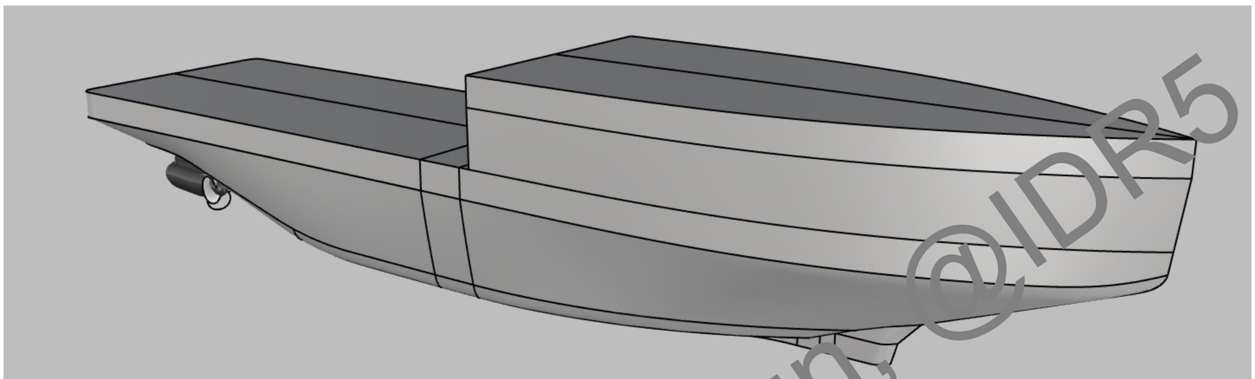
After the first iteration of the ARV hull form was analyzed against requirements, the ARV hull size was deemed insufficient to support the mission requirements, as well as maintain stability. It was determined that the hull needed to increase in size to support the necessary equipment to achieve the KPPs and provide a stable design. The objective of this Hull Size Increase Study was to determine the minimal increase in length and beam to provide a compliant ship. A total of four hull size variants were completed and analyzed, with the fourth and final variant selected for the revised hull size.

11.1.1.1. Size Increase Study Approach

The size increase study considered length overall increments ranging from 10 ft to 20 ft, in 5 ft increments. The increase in length maintained the current L/B ratio of 4.7. Draft variations were not considered due to the draft restrictions at Palmer Station. Each variant was evaluated for speed/power estimation, fuel load requirements, weight estimation, and intact stability. The hull form would be considered compliant if the hull's displacement could support the new ship weight and the required fuel to meet the range and DRMC requirements.

The initial hull variants were increased in length by inserting a plug at midship, and then scaled in one direction for beam. This ensured the icebreaking angles would remain similar to the baseline hull form. The fully compliant variants were refined to remove the midship plug and fair the hull. Using the faired hull, a final assessment of speed/power and stability was conducted. This faired hull was then used to modify the General Arrangements and determine the new watertight subdivisions required to meet the damage stability requirements.

Figure 34: Hull Sizing Variant with Midship Plug



11.1.1.2. Size Increase Study Analysis

Three variants, with a constant L/B and draft, were investigated. All variants considered the use of ABB V11800 Azipods (or equivalent) in their analysis. As shown in Table 10, the analysis concluded that the 355 ft and 360 ft variants did not meet requirements and failed stability. The 365 ft variant did show some compliance but failed several stability requirements.

Table 10: ARV Sizing Study Initial Hull Variants

Length, Overall (ft)	Beam (ft)	L/B	Reason for Elimination
355	75.5	4.7	Inadequate displacement and FO capacity balance + Stability
360	76.6	4.7	Inadequate displacement and FO capacity balance + Stability
365	77.7	4.7	Stability

Based on the assessment on the variants shown in Table 10, it was determined that the approach of maintaining the L/B ratio did not yield a favorable solution. In order to improve the stability limits, the beam was modified, resulting in a change in the L/B ratio. The beam was increased to 80 ft, resulting in a 4.56 L/B ratio. This change in L/B ratio was still within acceptable limits for icebreakers.

The 365 ft x 80 ft hull form resulted in a compliant design for icebreaking, range and endurance, DRM, and stability requirements specified in the P-Spec, Reference (1).

11.1.1.3. Additional non-KPP Growth Opportunities

In addition to compliance with all KPPs, increasing the hull size provided opportunities for overall design improvement. Increasing the length and beam of the ship allowed for an increase in superstructure size, providing an opportunity to reduce the vertical height of the ship and facilitate the addition of one-person staterooms. Finally, the increased hull size allowed an increase in weather deck area for the inclusion of incubation areas and a small boat compliment.

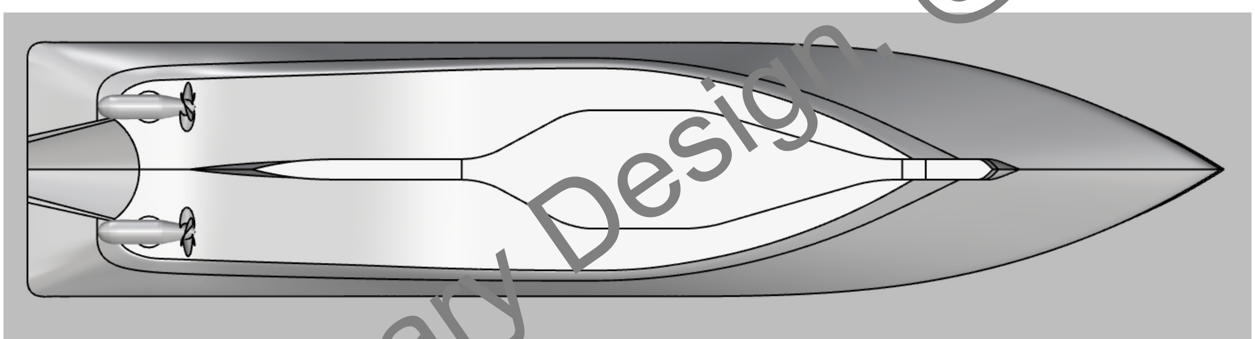
12. Appendix 3: Box Keel Design Considerations

12.1. Initial Box Keel Concept Design

The box keel houses the underwater sensor equipment needed for scientific missions, therefore making it an important design characteristic for the ARV. The Palmer Station offers a total water depth of 36 ft. This allows the box keel to extend below the hull bottom by an additional 3 to 4.5 ft, resulting in a total draft of 31 to 32.5 ft. Additionally, in order to accommodate the underwater sensor and the mounting structure, the box keel requires a total width of 30 ft.

The water flow around the underwater sensor must pass along the box keel side without inducing turbulent flow. In order to aid in producing a more laminar flow, the side shell of the box keel is designed to smoothly transition from the ice knife width, 5.93 ft, as it moves aft along the hull to its maximum width of 30 ft at 138 ft aft of FP. The box keel was initially designed with a parallel midsection before it smoothly transitions back to the width of 5.93 ft at 170 ft aft of FP, as it continues aft until it connects to the skeg. The layout of the box keel is shown in Figure 35 below. The box keel and other bubble sweepdown mitigation designs were analyzed with CFD, to determine the optimal hull bottom and box keel shape to achieve the ships scientific missions.

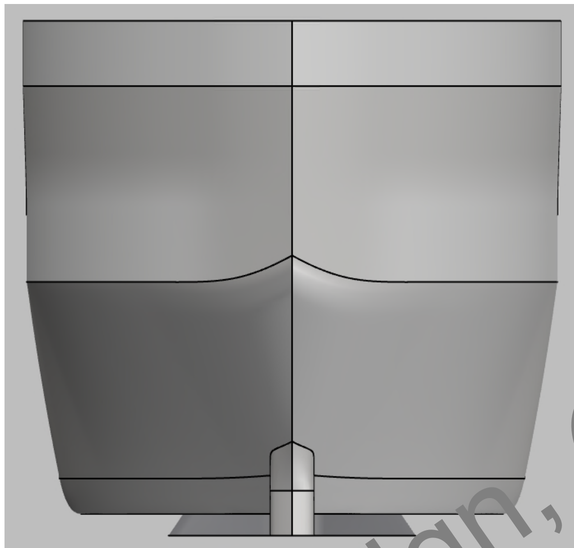
Figure 35: Initial ARV Box Keel Top View



12.1.1.1. Hull Variant 1 and Hull Variant 2

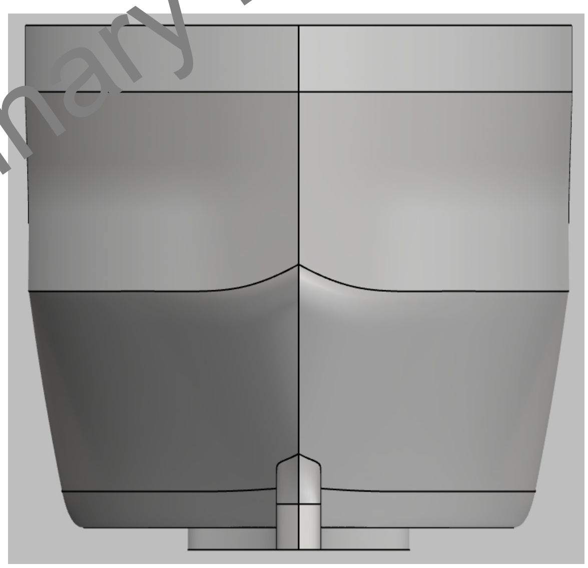
Hull Variant 1 of the box keel design, shown Figure 36, utilized sloped side walls to prevent the turbulent flow from continuing downwards below the bottom of the box keel, entrapping any bubble along the seam of the box keel and the hull bottom.

Figure 36: Hull Variant 1 with Sloped Side Box Keel



Hull Variant 2 of the box keel design, shown Figure 37, utilized vertical walls to determine if the depth of the box keel below the hull was enough to isolate the sensors away from the bubble sweepdown effects.

Figure 37: Hull Variant 2 with Vertical Side Box Keel

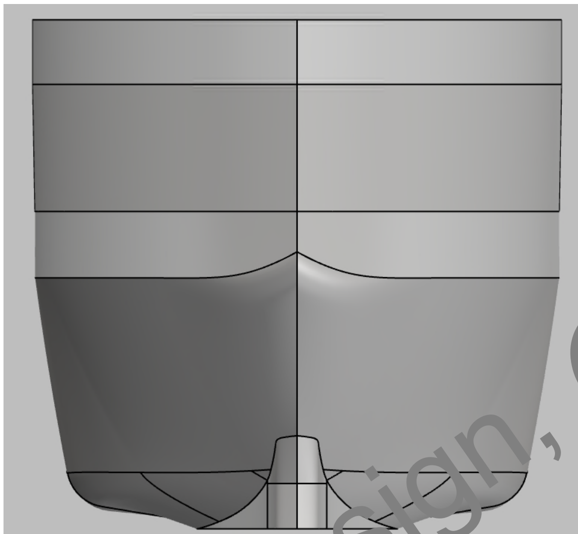


The CFD results concluded that there was no difference between the turbulent flow observed between Hull Variant 1 and Hull Variant 2. Both variants displayed turbulent flow around the sharp bottom edge. Therefore, it was determined that sloped walls were not necessary for the box keel.

12.1.1.2. Hull Variant 3 and Hull Variant 4

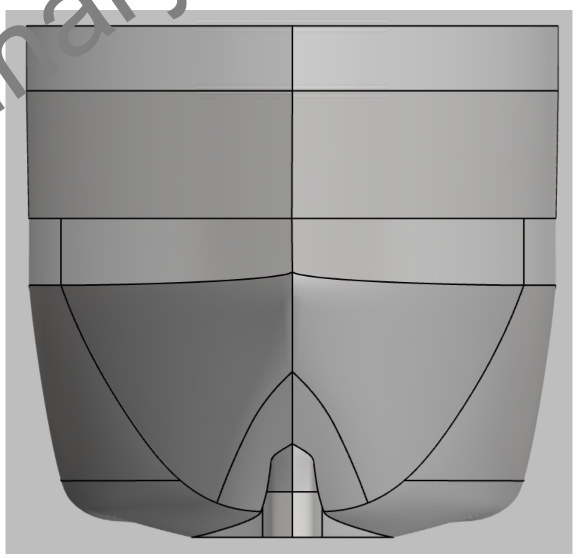
Hull Variants 3 and 4, Figure 38 and Figure 39 respectively, investigated the necessity of the protruded box keel. Hull Variant 3 utilized the existing bow with a widened box keel and a deadrise hull bottom. The design intended for the bubbles from the hull surface to reach the widened ice knife, which would push it outboard past the furthest extents of the underwater sensor equipment.

Figure 38: Hull Variant 3 with Existing Bow, Widened Ice Knife and Deadrise



Hull Variant 4 followed the same approach with the widened ice knife and deadrise but included a fuller spoon bow. The fuller spoon bow was designed to help direct the bubble flow outboard before it reached the ice knife.

Figure 39: Hull Variant 4 with Spoon Bow, Widened Ice Knife and Deadrise

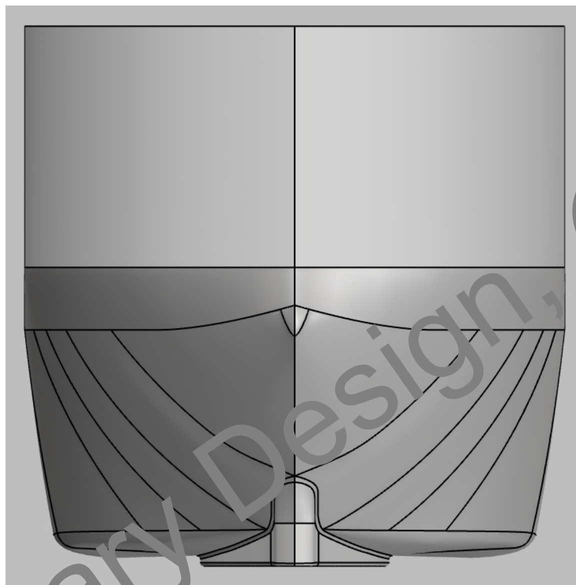


The CFD analysis showed that the deadrise for Hull Variants 3 and 4 reduce turbulent flow around the bilge radii; however, this was not enough to provide adequate bubble sweepdown mitigation. Therefore, it was concluded that the ARV required a protruded box keel below the hull bottom, deadrise, and the established icebreaking bow, in order to effectively mitigate the effects of bubble sweepdown on the underwater sensor.

12.1.1.3. Hull Variant 5 and Hull Variant 6

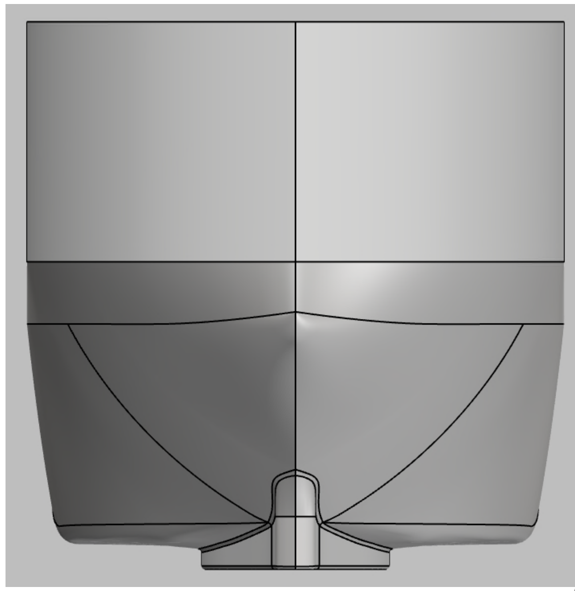
Hull Variants 5 and 6 investigated the required depth of the box keel, with the incorporation of the deadrise hull bottom. Hull Variant 5, shown in Figure 40, included a 1.5 ft deep box keel, resulting in a total draft of 31 ft. Additionally, the 6-degree deadrise angle was included in the design. Hull Variants 5 and 6 incorporating the new Hull Dimensions with a length of 365 ft and Beam of 80 ft, in order to validate that the new hull size would not negatively impact bubble sweepdown effects.

Figure 40: Hull Variant 5 with 1.5 ft Box Keel



Hull Variant 6, Figure 41, maintained the same deadrise, but extended the box keel to 3 ft in depth, resulting in a total draft of 32.5 ft.

Figure 41: Hull Variant 6 with 3.0 ft Box Keel



The CFD analysis for Hull Variant 5 confirmed that the 1.5 ft box keel did not provide enough depth to mitigate the effect of bubble sweepdown, resulting in streamlines flow below the box keel.

The CFD results for Hull Variant 6 confirmed that the 3 ft box keel provided enough mitigation of bubble sweepdown, resulting in no streamline flow through the underwater sensor. Therefore, Hull Variant 6 was selected as the PDR baseline ARV hull form design. Both hull variants confirmed that the increased hull size did not negatively affect bubble sweepdown.