Antarctic Research Vessel (ARV)

Engineering Report: Hull Form Trade-Off Study

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1. Executive Summary

The Antarctic Research Vessel (ARV) hull form design was developed and analyzed in accordance with standard practices and team processes in order to maximize performance, improve on the overall ship design, and meet the ARV ship Performance Requirements (P-Spec), Reference (1).

The primary design drivers of the ARV hull form are the objective Key Performance Parameters (KPP) Icebreaking (IB) Capability of 4.5 ft of ice with 12 inches of snow, bubble sweepdown performance, ship displacement, and hull volume, which is discussed in Section 4. In order to evaluate the IB capability of the ARV, a parametric analysis reviewed icebreakers with similar ice breaking capability and used that data to define the beam as a function of ship's length, resulting in a Length to Beam (L/B) ratio of approximately 4.7. The parametric analysis also established the icebreaking hull angles provided in Table 5 of Section 4.3.1.3 of this report. Sufficient displacement was required to support the size of the propulsion plant needed for icebreaking. Additionally, sufficient hull form volume was required to achieve the necessary fuel capacity for a 17,000 NM range and 90 day endurance requirement. The ARV design drivers are discussed in detail in Section 4 of this report.

The ship's length and draft were initially restricted to 345 ft and 28 ft respectively. These dimensional restrictions contributed to excessive risk for early preliminary stage design. The required volume to arrange machinery and fuel, as well as the displacement to support the weight in a balanced condition, was deemed insufficient and identified as a source of risk. As a means to reduce risk, a hull resizing study was completed to determine the minimal increase in length and beam to satisfy the ARV KPP requirements. A total of four size variants went through standard analysis performed on the initial hull form to determine their validity as the new hull dimensions. The study concluded that increasing the length to 365 ft and the beam to 80 ft provided sufficient displacement to support the necessary propulsion machinery weight and fuel load to achieve the ARV KPP. Additionally, a detailed review of the seabed around Palmer Station, revealed a drop off in the seabed to a water depth of 36 ft, allowing for a deeper draft to be used in the design.

Bubble Sweepdown mitigation around the Science Mission Package (SMP) sensors on the hull bottom, drove the next iterations in the hull form design. The increase in water depth at Palmer station provided the opportunity to add an 8 degree deadrise to the hull bottom and to incorporate a Box Keel to house the sensors required for the ships SMP. Six iterations were investigated using Computation Fluid Dynamics (CFD) analysis and resulted in refining the box keel shape. The results of the CFD analysis showed that the addition of the box keel and deadrise provided were efficient in avoiding bubble sweepdown effects. CFD analysis results will be confirmed by future model testing.

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. The resulting hull form used for the preliminary design is estimated to satisfy the KPP. Items that present risk in the hull form include verifying the bubble sweepdown performance and assessing the mooring capabilities at Palmer Station to accommodate the larger 365 ft hull. Hull form development and compliance will continue to be monitored through future stages of design.

1.1. Acronyms

AP	Aft Perpendicular
ARV	Antarctic Research Vessel
BWL	Beam on Waterline
CFD	Computational Fluid Dynamics
CNIIMF	Central Marine Research and Design Institute
DRMC	Design Reference Missions Candidate
DWL	Design Waterline
FT	Feet
FP	Forward Perpendicular
G&C	Gibbs & Cox, a division of Leidos
IB	Icebreaking
IN	Inches
KPP	Key Performance Parameters
LT	Long Ton
L/B	Length to Beam Ratio
NM	Nautical Mile
NSF	National Science Foundation
PD	Preliminary Design
P-Spec	Performance Requirements
SMP	Science Mission Package
VFI	Vendor Furnished Information

2. Introduction

This report documents the approach and trade space that developed the National Science Foundation (NSF) 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
- Review of the increase in hull size after the first iteration in the design spiral

3. Approach

3.1. Overview

A total of 10 iterations of the ARV hull form were considered to ensure compliance with the Key Performance Parameters (KPP) outlined in Reference (1); four iterations investigated the ships size, detailed in Section 4.3, and 6 iterations evaluating the bubble sweepdown performance, detailed in Section 4.5.2. 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

In order to select a hull form to meet the KPP needs of the ARV identifying a hull capable of breaking 4.5 ft of ice, while also optimizing open water performance to meet range and endurance was required. Typical icebreaking hull features are in contrast to typical open water performance features, necessitating careful evaluation and consideration of the trade-offs between the features. In addition, the desired bubble sweep performance of the vessel is hull form dependent, requiring further trade-offs to be evaluated.

Ice breaking vessels may be categized into two groups, conventional and modern. While both are naturally inefficient in open water, modern ice breakers that are designed to optimize the ice breaking capability for science mission, further decrease the open water efficiency. For the ARV, a hull with conventional ice breaker features was selected over the modern ice breaker features for the improved open water performance and open water and ice maneuverability. This was done while maintaining the KPP ice breaking capability of 4.5 ft of ice. The addition of a box keel was then refined and implemented to reduce bubble sweep down effects on selected areas of the hull.

The optimization of the hull was determined using a combination of design best practices, VFI data from vendors, and hull performance results from software analysis. IB capabilities were verified using previously industry established 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 software analysis are provided in the following sections.

3.2. Primary Hull Form Design 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 IB 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 the ARV P-Spec, Reference (1), the ARV hull form features typical icebreaker hull geometry characteristics. The primary IB design features where 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 ARV is dependent on the available piers and their draft restrictions. These considerations outline the design space for the hull below the waterline, while the IB angles determine the upper extents of the submerged hull form.

The mission to scan the seafloor with sensors requires geometry that will reduce, with the goal of entirely removing, the bubble sweepdown effects surrounding the sensors. This is done by incorporating a box keel appendage to the design.

The last three design considerations all relate to the shape of the stern geometry. First is the transition angle from the hull bottom up to the propulsion flat. This is followed by the propulsion flat height as it relates to the azipods and the propeller diameter. Lastly, the design required incorporating a square working deck.

The ARV will feature an azimuth propulsion system, which typically have no difficulty in accomplishing their maneuvering requirements. Final assessment of the ARV maneuvering can be found in the ARV Maneuvering Performance Report, Reference (2). Dynamic Positioning will be assessed after the completion of the propulsion arrangement and include bow thruster sizing. Details of the Dynamic Positioning system and performance can be found in the ARV Dynamic Position System Performance Report, Reference (3).

3.3. Evaluation Criteria

To measure the hull form's ability to provide a safe and capable research platform it was evaluated for its bubble sweep down, sea keeping and maneuvering abilities. To measure its ability to efficiently transit open water to access points of interest, it's speed and powering requirements were estimated to assist in ensuring range requirement and the endurance KPP met. Concurrently, displacement and stability were monitored to ensure the required payloads could be safely transported. Additionally, the icebreaking ability of the hull form was calculated to measure compliance with the icebreaking KPP.

3.4. Initial Assumptions & Constraints

Initial constraints to the ARV's length and beam were driven by the requirement to moor at Palmer Station. Utilizing assumptions from concept design, 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, as discussed in Section 4.1. Assumptions and associated constraints were further revised as detailed below.

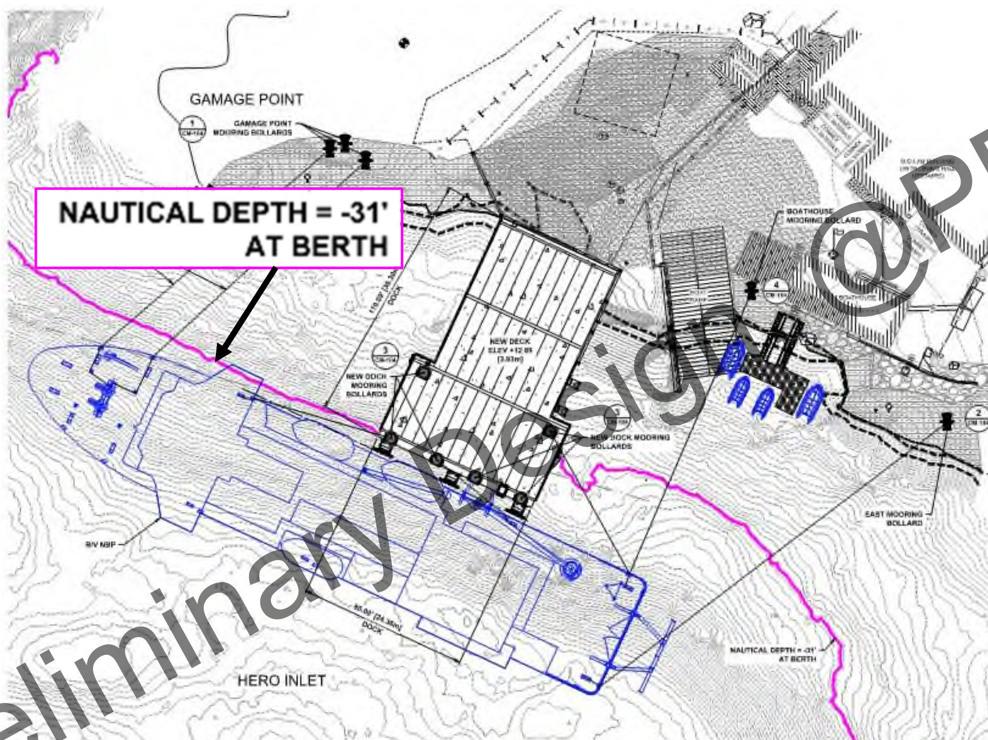
3.5. Revised Assumptions

The ARV hull form selected based in the initial assumptions did not meet KPPs for ice breaking or endurance. In order to determine the optimal length and beam needed to meet all KPP requirements, a hull sizing study was conducted. Details on the hull sizing study can be found in Section 4.2.3 of this report.

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.

A detailed analysis of the seafloor at the pier of Palmer Station, revealed 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. Therefore, a box keel appendage was incorporated, which extends below the baseline draft of 28 ft. The box keel houses the sonar sensors and aides in the mitigation of bubble sweepdown effects.

Figure 1: Palmer Station Mooring Layout and Seafloor



To reduce risk to the design, additional analysis focused on the length of the vessel is ongoing to determine the environmental limitations (wind and current) of mooring the longer hull at Palmer Station, as well as if any modifications to the pier are required. Initial results indicate that there is low risk that an additional dolphin will be needed. Should the analysis indicate changes to the pier are required, additional bollards as well as fender replacements are potential options under consideration.

Please note the results are preliminary, and the analysis is ongoing. Additional information will be provided as part of the PDR presentation / slide package.

4. Design Drivers

4.1. Overview

The ARV hull form design was driven by the following factors: IB capability, KPP compliance, and bubble sweepdown performance. Details for the design approach to achieve these requirements are outlined in the sections below.

4.2. Icebreaking Considerations

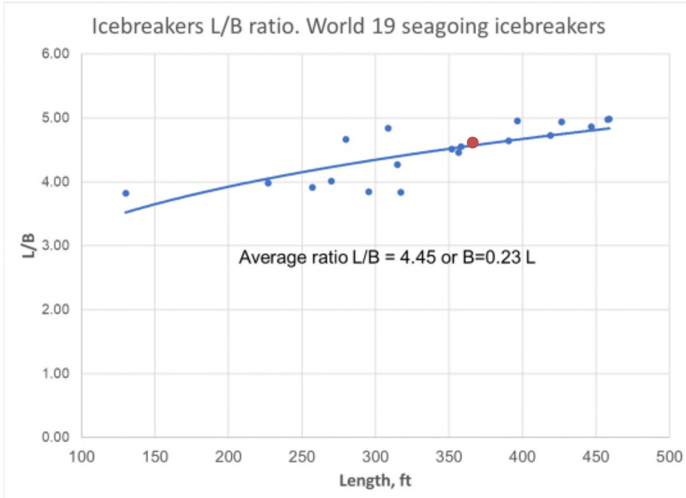
4.2.1. Mainstream Icebreaker Hull Design Parameters

Conventional icebreakers built in the last 50 years have similar primary dimension ratios and hull angles. In comparison, the current modern icebreaker shape focuses on reducing the ice breaking resistance in order to maximize ice breaking capabilities in a smaller hull form. The consequences of these modern icebreakers are that it will increase 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 due to the disadvantageous effects of the open water performance for large ice breaking capable ships is proven to be detrimental to the overall ship performance. Since the KPP require 4.5 ft of icebreaking ability, while also requiring efficient open water transit, 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 the superior performance in open water resistance and maneuverability in ice and in the 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 more full bowform, with broad shoulders, and a hard knuckle line in between the bow and midbody transition. While the fuller bow does help minimize ice breaking 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 ARV having a L/B ratio of 4.56 at 365 ft. It is common to have specification restrictions of the length or beam, which may lead to a non-optimal hull form in terms of ice performance.

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 ice breaking 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	20.0
Half Entrance	35	51	35	27	63.4
Flare @ Stem	58	74	50	48	79.7
Flare @ Midship	7	10	7	0	6.4

4.2.2. 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 4.2.1. Open water efficiency is crucial to meeting the 90-day endurance KPP. Due to the power required for ice breaking, 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.

4.2.3. 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:

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

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

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

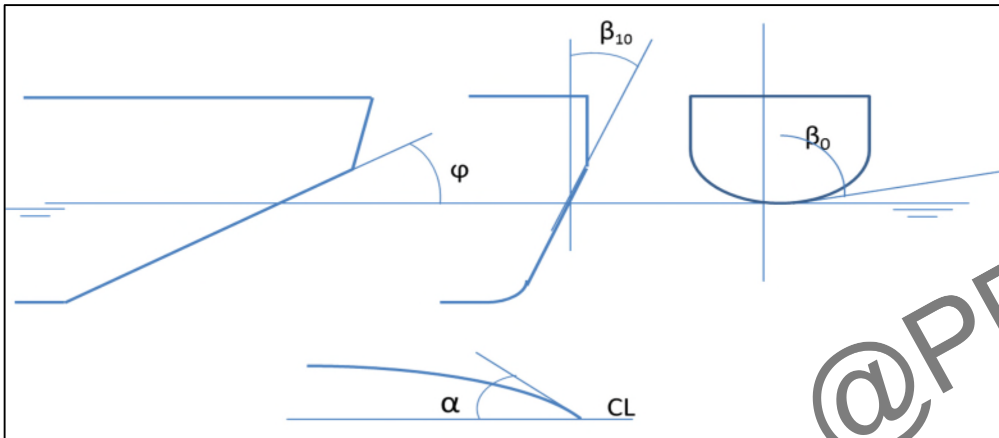
α - waterline entrance half angle is measured between the centerline and the tangent line to the waterline drawn at the point of intersection between the centerline and waterline

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

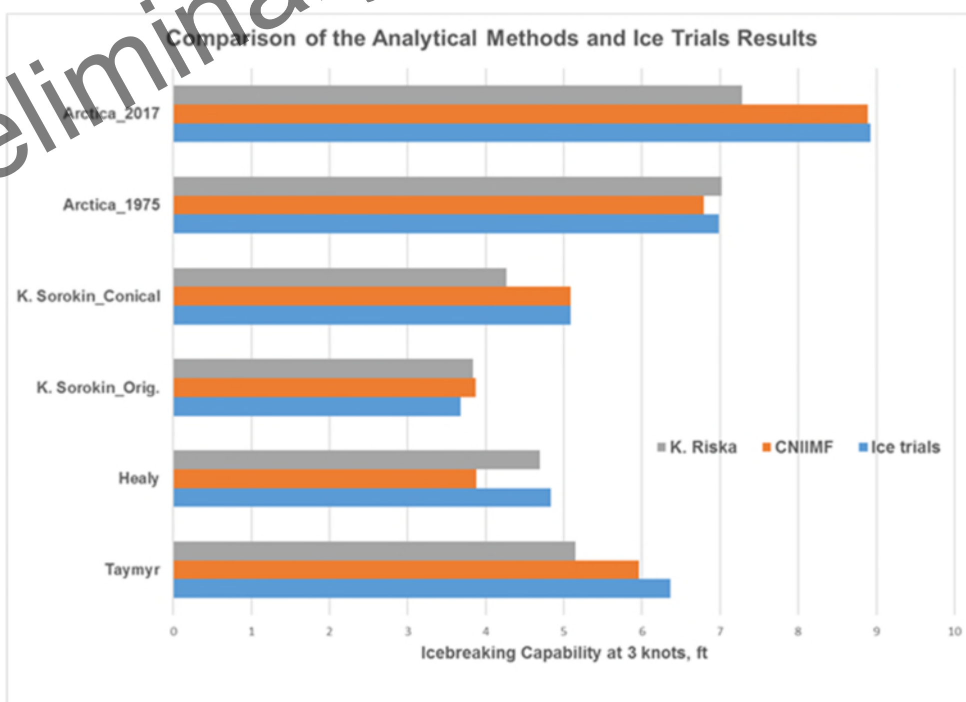
The angles measurements are depicted in Figure 3 below:

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/CNIIMF 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 ice breaking 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



4.2.4. 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 an ice knife alone does not offer enough bubbles sweepdown mitigation around the sonar sensors. Accuracy in sonar readings is a primary mission requirement for a research vessel. In order to mitigate the bubble sweepdown effects, a box keel was implemented into the design.

Since the sonar sensors are housed in the box keel, this places the sensors below the waterflow, ensuring that no bubble sweepdown effects will be encountered. Additionally, adding deadrise to the hull bottom helps produce better water flow under the ship, mitigating the effects of bubble sweepdown and turbulent flow.

4.3. Initial Hull Sizing Assessment

4.3.1. 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 4.2.1. 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 2: 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

4.3.1.1. Hydrostatics and Weight

The initial ARV displacement at the appendage draft of 31 ft was 10,909 LT. Based on the ARV Design Weight Estimate Rev P0-1, Reference (6), 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.

4.3.1.2. 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 ice breaking 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). 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 (7).

Table 3: 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 4: 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

4.3.1.3. Icebreaking Capability

The parametric analysis of other icebreakers resulted in the following hull angles, shown in Table 5. 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 5: 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, 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 6 displays other configurations of the propulsion plant and their resulting IB capabilities in feet.

Table 6: 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 6, 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).

4.3.2. 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.

4.3.3. Hull Resizing Study

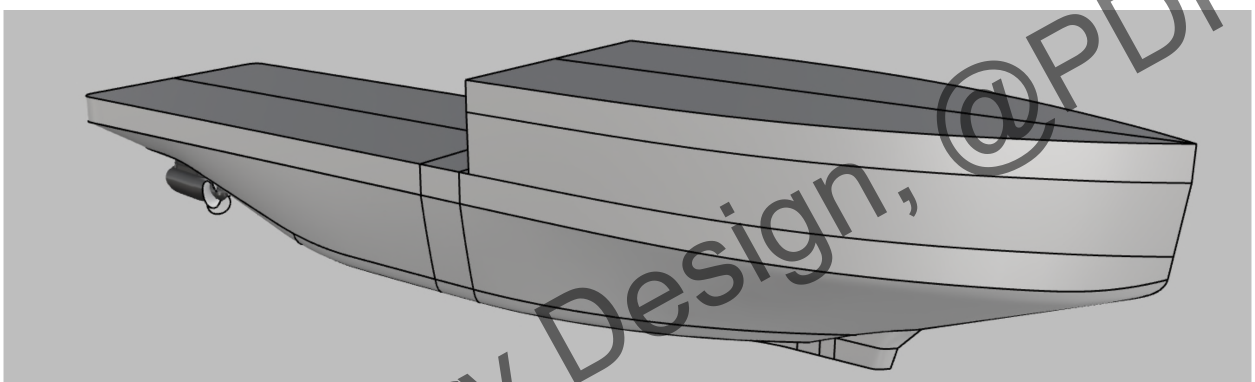
After the first iteration of the ARV hull form was analyzed against requirements, ARV hull size was deemed insufficient to support the mission requirements, as well as maintain stability. It was determined that the hull needed to increase in size to support the necessary equipment to achieve the KPPs 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.

4.3.3.1. 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 DRM 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 5: Hull Sizing Variant with Midship Plug



4.3.3.2. 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 7, 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 7: ARV Sizing Study Initial Hull Variants

LOA (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 7, 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).

4.3.3.3. Additional non-KPP Growth Opportunities

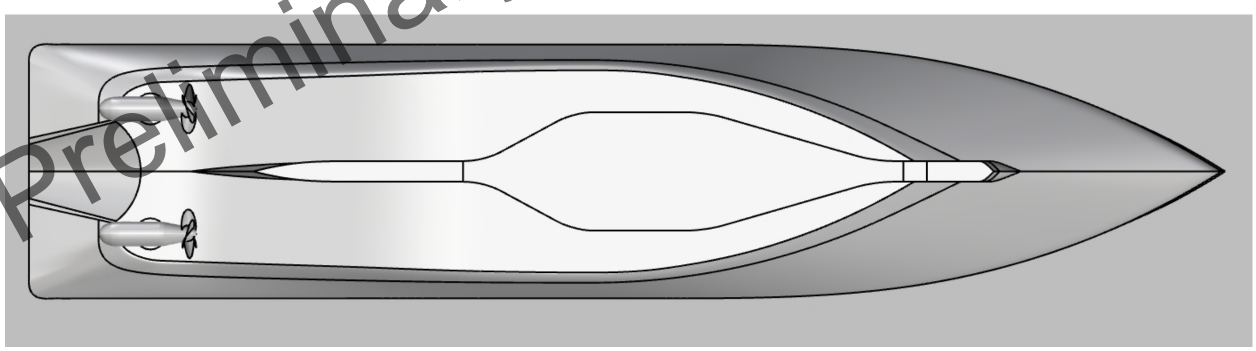
In addition to compliance with all KPPs, increasing the hull size provided opportunities for overall design improvement. Increasing the length and beam of the ship allowed for an increase in superstructure size, providing an opportunity to reduce the vertical height of the ship and facilitate the addition 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.

4.4. Initial Box Keel Concept Design

The box keel houses the sonar equipment needed for seafloor surveying, 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 sonar and the mounting structure, the box keel requires a total width of 30 ft.

The water flow around the sonar 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 6 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, which is detailed in Section 4.5.2.

Figure 6: Initial ARV Box Keel Top View



4.5. Bubble Sweepdown

4.5.1. Overview

Bubble sweepdown can affect the way that the sonar transducer operates. The sonar sensors require a 3 ft clearance from turbulent flow to accurately capture the necessary images and data of the underwater topography. Therefore, the science mission requirements specify the need of mitigating bubble sweepdown around the sonar transducer. In order to ensure there will be no bubble sweepdown impingement over the sonar equipment, the sensors should be mounted as low as possible with regards to the stem and ice knife of the ship.

Several 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 of the box keel were analyzed, leading to the final box keel design for the ARV hull form.

The hull form variants analyzed are discussed in detail in Sections 4.5.2.1 through 4.5.2.3 below.

Additional details for the CFD bubble sweepdown analysis for ARV can be found in Reference (8).

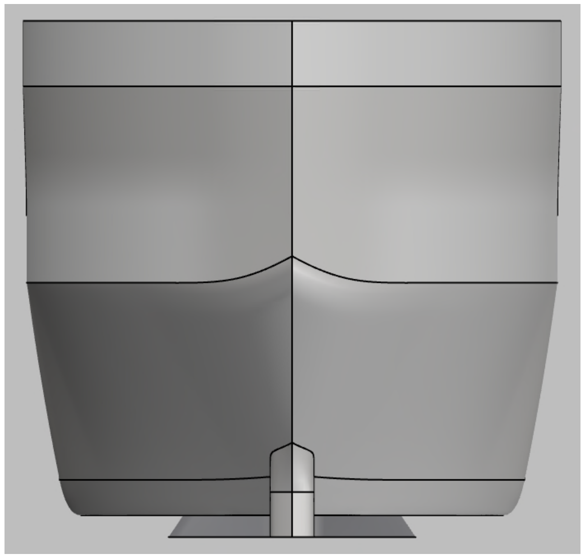
4.5.2. Box Keel

A box keel was the primary consideration to mitigate the bubble sweepdown. This is an appendage to the hull that would protrude below the hull bottom and house the sonar 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.

4.5.2.1. Variant 1 and Variant 2

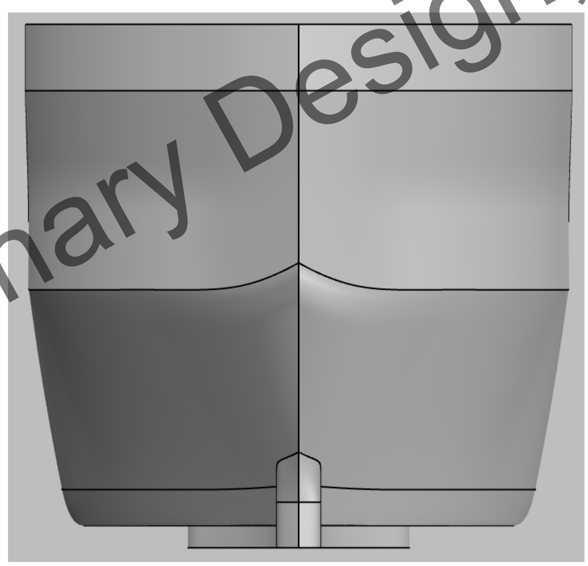
Variant 1 of the box keel design, shown Figure 7, utilized sloped side walls to prevent the turbulent flow from continuing downwards below the bottom of the box keel, entrapping any bubble along the seam of the box keel and the hull bottom.

Figure 7: Variant 1 with Sloped Side Box Keel



Variant 2 of the box keel design, shown Figure 8, 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 8: Variant 2 with Vertical Side Box Keel

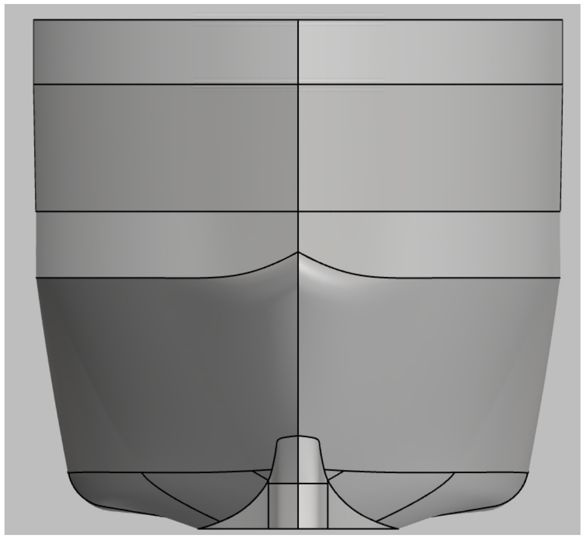


The CFD results concluded that there was no difference between the turbulent flow observed between Variant 1 and Variant 2. Both variants displayed turbulent flow around the sharp bottom edge. Therefore, it was determined that sloped walls were not necessary for the box keel.

4.5.2.2. Variant 3 and Variant 4

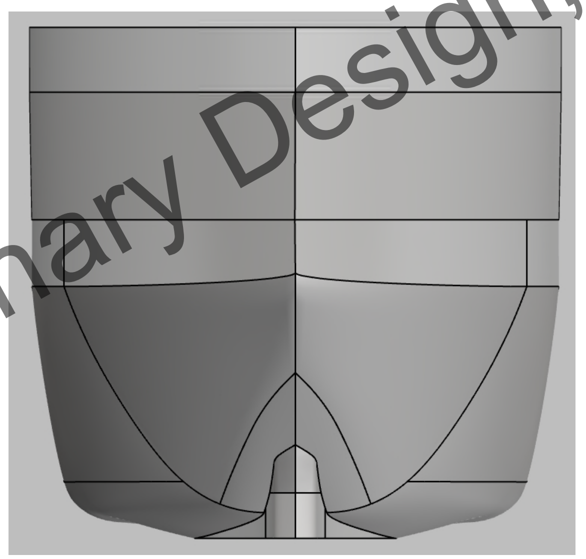
Variants 3 and 4, Figure 9 and Figure 10 respectively, investigated the necessity of the protruded box keel. Variant 3 utilized the existing bow with a widened box keel and a deadrise hull bottom. The design intended for the bubbles from the hull surface to reach the widened ice knife, which would push it outboard past the furthest extents of the sonar equipment.

Figure 9: Variant 3 with Existing Bow, Widened Ice Knife and Deadrise



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 10: Variant 4 with Spoon Bow, Widened Ice knife and Deadrise

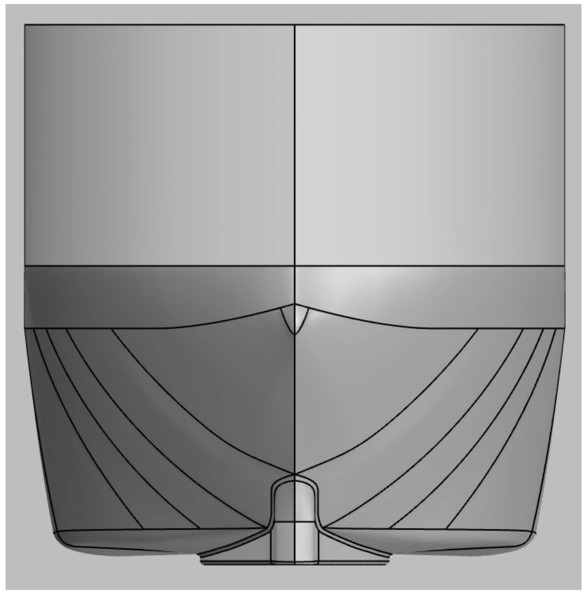


The CFD analysis showed that the deadrise for Variants 3 and 4 reduce turbulent flow around the bilge radii; however, this was not enough to provide adequate bubble sweepdown mitigation. Therefore, it was concluded that the ARV required a protruded box keel below the hull bottom, deadrise, and the established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

4.5.2.3. Variant 5 and Variant 6

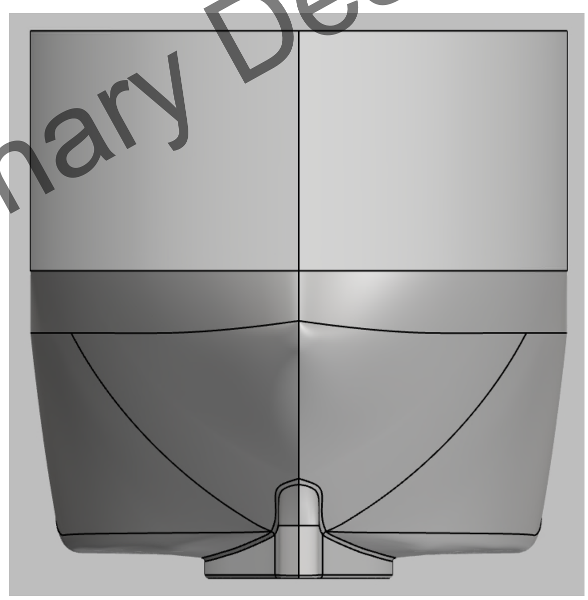
Variants 5 and 6 investigated the required depth of the box keel, with the incorporation of the deadrise hull bottom. Variant 5, shown in Figure 11, included a 1.5 ft deep box keel, resulting in a total draft of 31 ft. Additionally, the 6-degree deadrise angle was included in the design. Hull Variants 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 11: Variant 5 with 1.5 ft Box Keel



Variant 6, Figure 12, maintained the same deadrise, but extended the box keel to 3 ft in depth, resulting in a total draft of 32.5 ft.

Figure 12: Variant 6 with 3.0 ft Box Keel



The CFD analysis for 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 Variant 6 confirmed that the 3 ft box keel provided enough mitigation of bubble sweepdown, resulting in no streamline flow through the sonar equipment. Therefore, Variant 6 was selected as the new baseline ARV hull form design. Both Variants confirmed that the increased hull size did not negatively affect bubble sweepdown.

4.6. Stern Propulsion Rise Geometry

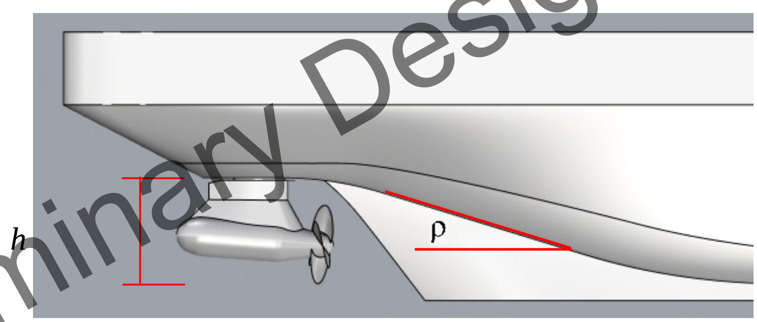
A parametric study was conducted to investigate the required transition angle in the stern, angle ρ shown in Figure 13. The parametric analysis of similar mission hulls investigated the hull geometry with regards to the transition angle from the bottom to the propulsion flat which houses the Azimuth 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 will review waterflow along the stern and determine the possibility of any turbulent flow that would damage the azipod propellers or shell plating during the ship's lifespan.

4.7. Optimization of the Azipod Location

The height of the propulsion flat, identified as "*h*" in Figure 13, 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 13: Stern Geometry with Propulsion Configuration



4.7.1. Azipod and Propeller Size Selection

ARV will be equipped with two ABB VI1800 Azipods (or equivalent), each with a 16 ft diameter propeller, Reference (5). 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.

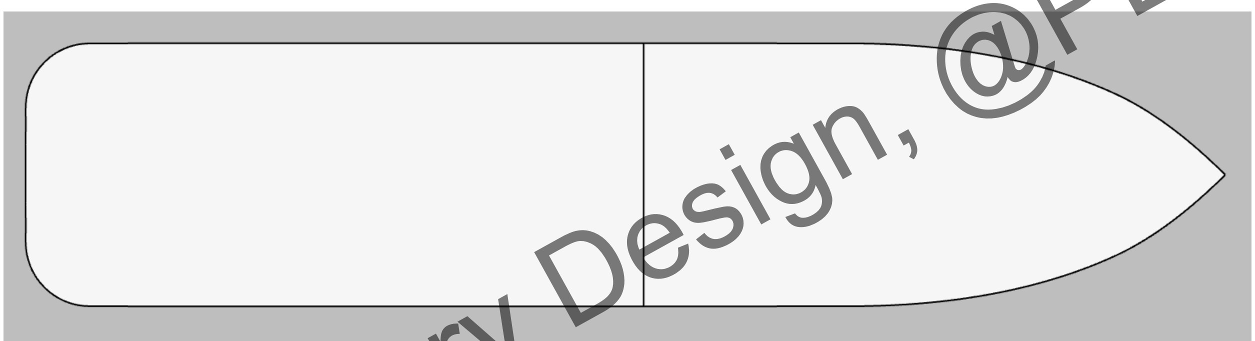
4.8. Working Deck Integration

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 14. 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 14: ARV Square Working Deck Top View



5. Final Hull Form Results

With the selection of the final hull variant, the ARV design displayed compliance with all KPP, and mission requirements, outlined in Reference (1).

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 required 4.83 ft of ice. Additionally, in order to accommodate stability improvements, the final ARV hull form provides a depth at Main Deck of 45.5 ft. Table 8 displays the Principal Characteristics of the ARV.

Table 8: 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
Draft	32.5 ft

The final hull form geometry is shown in Figure 15 through Figure 18, below.

Figure 15: ARV Profile View

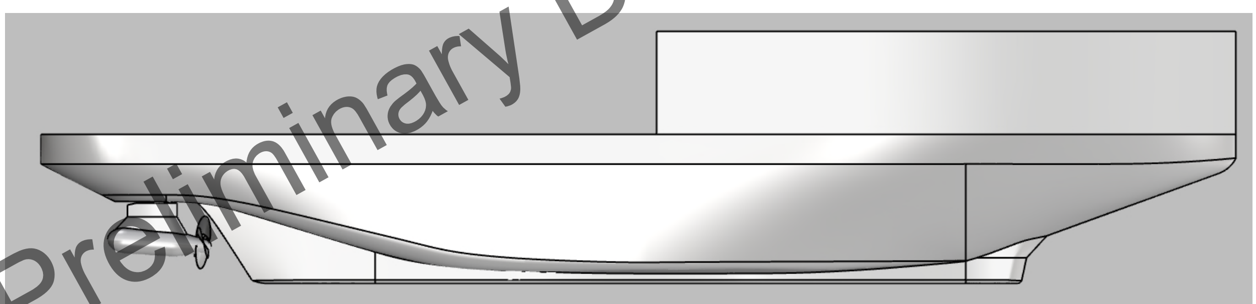


Figure 16: ARV Top View

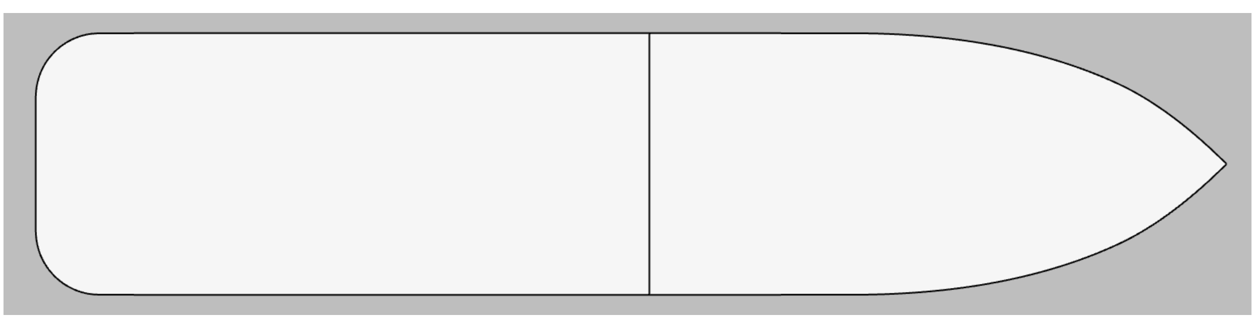


Figure 17: ARV Bottom View

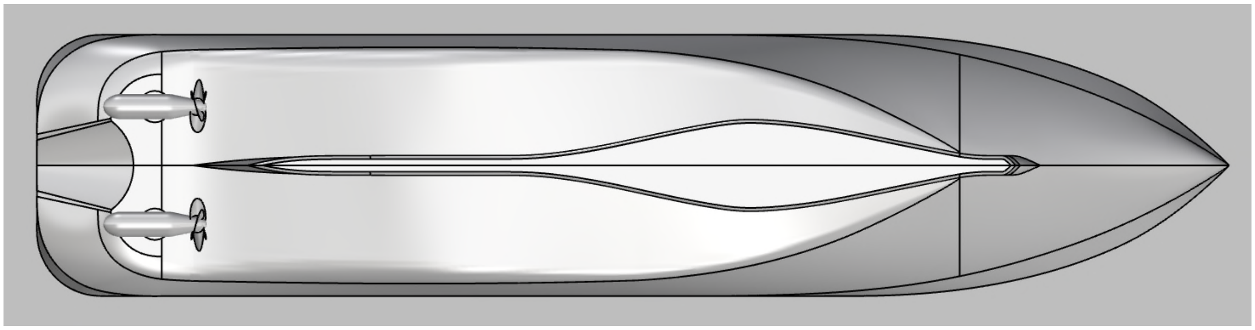
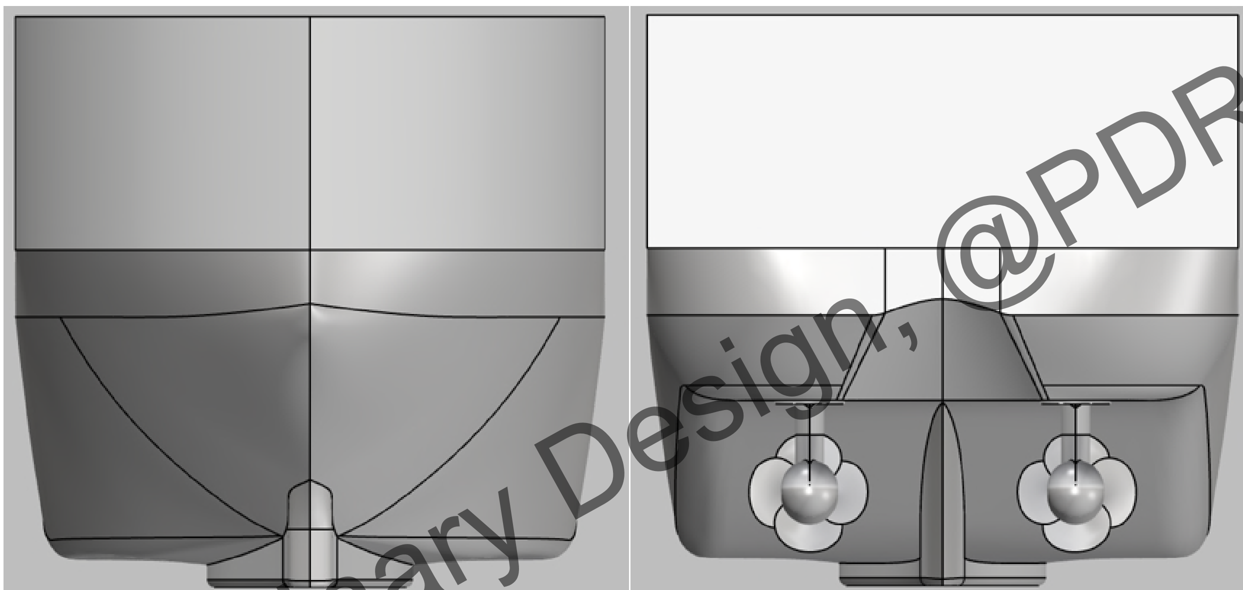


Figure 18: ARV Bow and Stern View



5.2. Icebreaking Capability

As outlined in Section 4.2.3, the icebreaking capabilities result from incorporating the necessary propulsion arrangement to achieve the objective icebreaking capability. With the use of ABB VI1800 azipods (or equivalent), the ARV design is compliant with the objective icebreaking capability of 4.83 ft of ice. Table 9 shows the hull angles for the final ARV hull form design.

Table 9: Final ARV Hull Angles

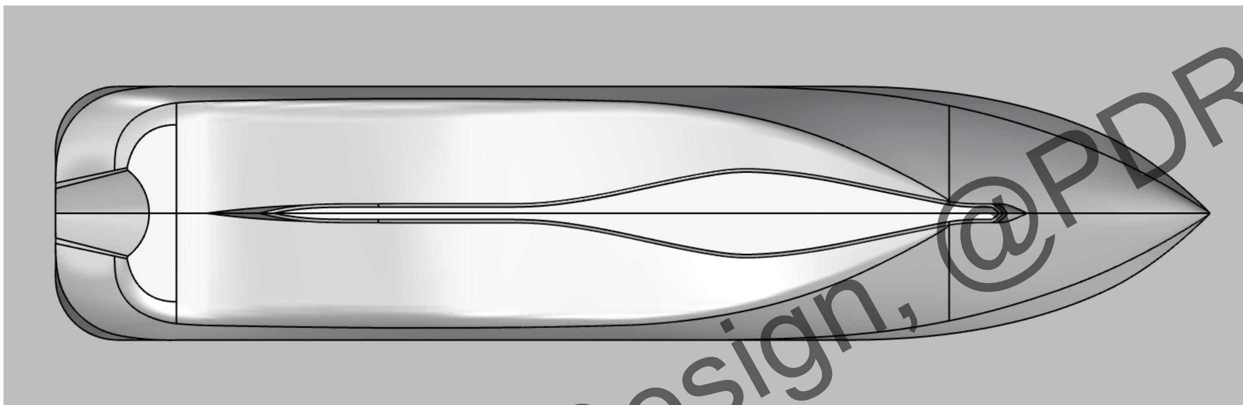
Angle	ARV
Stem	20.0
Half Entrance	63.4
Flare @ Stem	79.7
Flare @ Midship	6.4

With the adjusted hull size, ARV has the displacement to support the larger ABB VI1800 azipods (or equivalent), along with any supporting machinery. The thrusters can accommodate a 16 ft propeller which greatly assists in performance efficiency over the original 14 ft propeller.

5.3. Box Keel Design and Bubble Sweepdown

The box keel design is a result of 6 hull form variant that were analyzed with CFD analysis, as detailed in Section 0. The inclusion of a deadrise hull bottom from the bilge radius to the box keel showed benefits to maintain laminar flow. The box keel was confirmed to be necessary to avoid any streamline flow below the sensors. A 3 deep box keel was selected for the ARV design, in order to fully mitigate the effects of bubble sweepdown. The shape of the box keel provides a smooth transition from the ice knife, to the max width to accommodate the sensor equipment, and then smoothly transition back to the width of the skeg. Additionally, the box keel has a 6 inch fillet surface to avoid inducing turbulent flow along the bottom edge, while provide sufficient internal area to mount the sensors. Figure 19 displays the box keel for ARV.

Figure 19: ARV Box Keel Bottom View



5.4. Hydrostatics and Weights

The ARV displacement for the Full Load at Delivery and Full Load, EOSL, conditions are shown in Table 10. All operating limits of the ARV are within the draft constraints at Palmer Station.

Table 10: ARV Loading Conditions

Condition	Draft (ft ABL)	Displ (LT)
Full Load, Delivery	31.4	12,496
Full Load, EOSL	32.5	13,342

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 (9).

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 (7).

5.7. Open Issues

The following list describes open issues that have been assessed by the design team that are planned to be resolved during the post-PDR phase. All of th4ese open issues are considered relatively low risk at this phase in the design and have follow-on actions and assessments to ensure that they are addressed post-PDR.

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 post-PDR to further enhance the bubble sweepdown performance.
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.
3. There is concern for the Ice Channel following the ice breaker 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 ice breaking operations and its impact on ice clearing will be further investigated during hull development.

6. Preliminary Model Test Results

A 1:21.336 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, bubble sweepdown, open-water resistance and propulsion, wake survey and ice resistance and propulsion tests. All propelled tests were conducted with HSVA stock propellers on the azimuthing thrusters.

On-site observations of the bubble sweepdown tests indicate some potential for bubble interference with sonar operations from bubbles originating near the waterline in a narrow band within approximately 430 mm of the centerline of the hull.

The power results for open water transit are promising, with indication the ARV hull is more efficient than other ice breaking hull forms of comparable size.

In ice breaking ahead, the ARV is capable of maintaining speeds of over 3 knots in 4.5 ft of thick ice with 1.0 ft of snow. The ARV is also capable of maintaining 7 knots in 3.0 ft of thick ice with 1.0 ft of snow.

In ice breaking astern, the ARV is capable of maintaining speeds of 3 knots and 4.5 knots in the 4.5 ft of ice and 3.0 ft of ice respectively.

The ARV hull achieved breaking out of the cleared channel, both ahead and astern, in both ice conditions.

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.

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

7. Future Development and Considerations

The resized ARV hull design currently meets the ARV objective requirements. The results outlined in Section 5 will continue to be validate in future design iterations. Hull model testing will validate the speed/power capabilities, icebreaking capability, and the bubble sweepdown performance. Model Test result data will assist in identifying if additional changes are necessary to further improve the ship performance.

8. Conclusions and Recommendations

This report details the hull form design for ARV. Optimization has been completed to determine the minimal hull size to support the necessary machinery weight and fuel loads to achieve icebreaking, along with range and endurance requirements. The ARV hull form, equipped with two VI1800 Azipods (or equivalent), is capable of breaking the objective 4.5 ft of ice and 1 ft of snow, which equates to 4.83 ft of total ice. The tankage accommodates the required fuel load to achieve a range of 17,000 nm at 11 knots, as well as the satisfying the 3 DRMs. The box keel design is successful in mitigating the bubble sweepdown away from the sonar sensors, thus supporting the science missions of ARV.

Currently, the ARV hull form satisfies the KPP requirements based on the preliminary analyses performed. The hull with undergo physical model testing to verify these results. Model Test result data will assist in identifying if additional changes are necessary to further improve the ship performance, with a focus on IB performance. The open issues that present risk in the hull form are verifying the bubble sweepdown performance and assessing the mooring capabilities at Palmer Station can accommodate the larger 365 ft hull. Hull form development and compliance will continue to be monitored through future stages of design.

9. References

(1) *ARV Performance Specifications*, Rev. -, Document No. 19136.01, 30 November 2021.

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

(3) *ARV Dynamic Positioning System Performance Report, Document 5E1-065-R001, Rev P2.*

(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., 1990

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

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

(7) *ARV Engineering report: Range and Endurance Calculation,* Document No. 5E1-050-R021, Rev. P1.

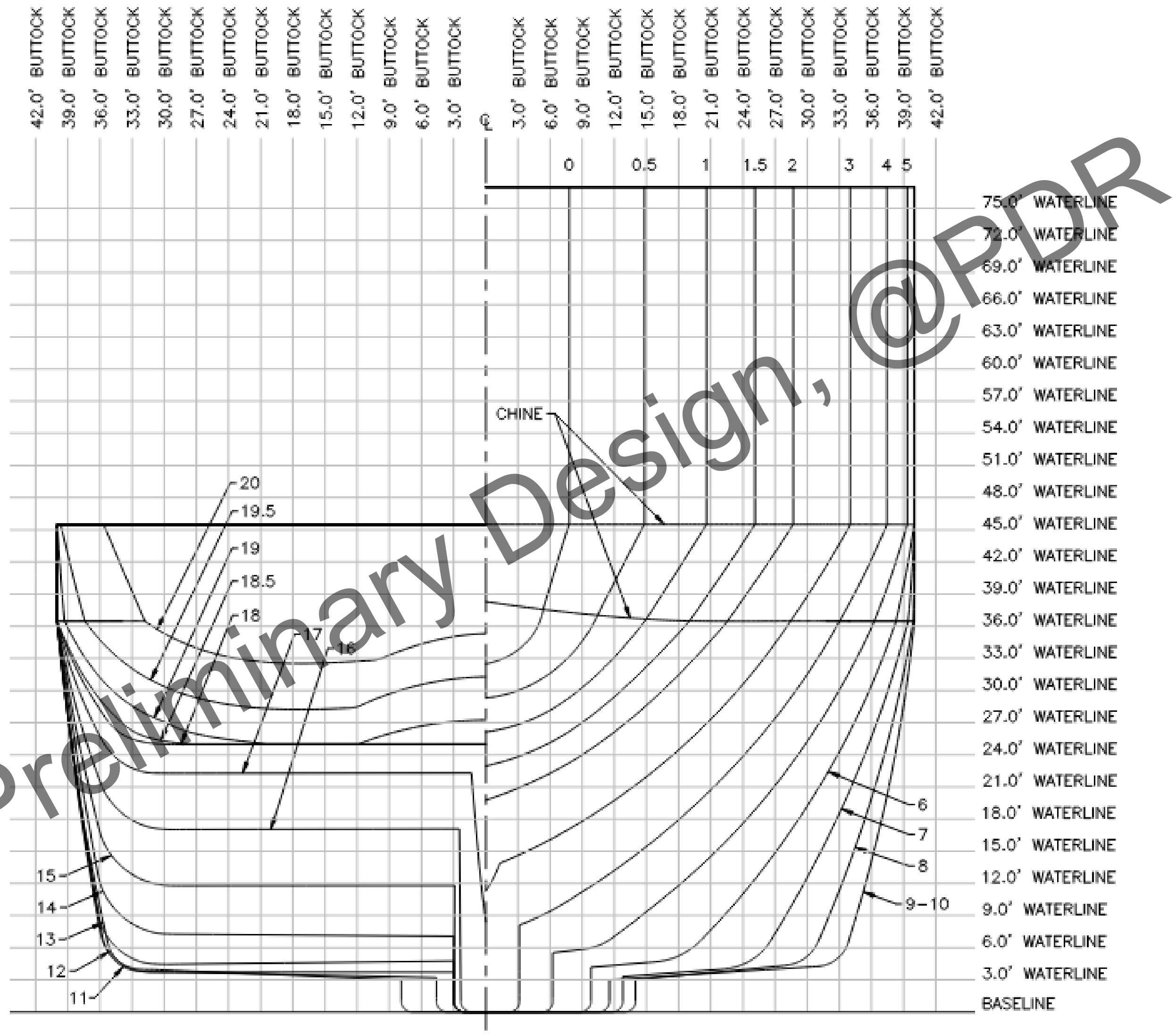
(8) *ARV Bubble Sweepdown Computation Fluid Dynamics Report,* Document No. 5E1-050-R101, Rev. P1.

(9) *ARV Intact and Damage Stability Report*, Document No. 5E1-079-R001, Rev P1.

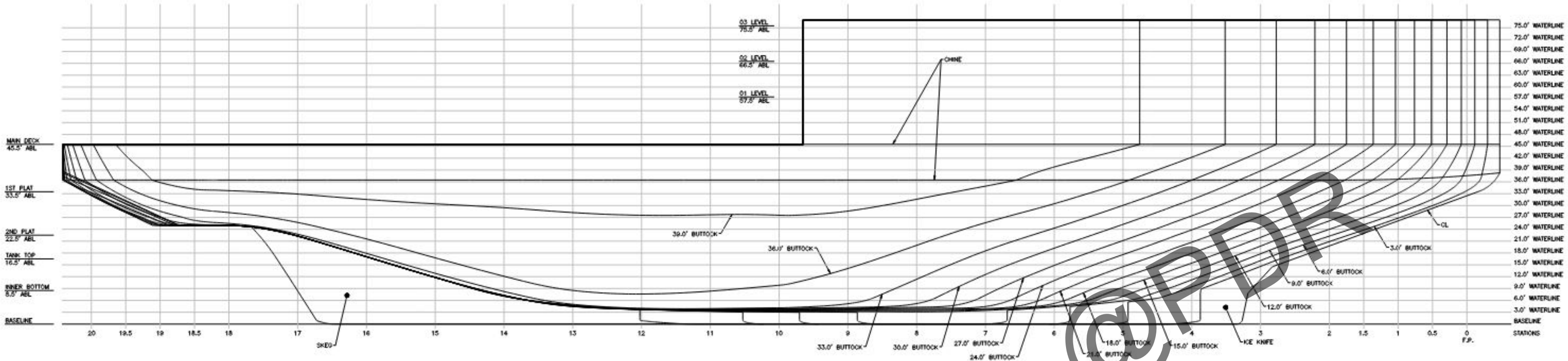
(10) ARV Model Test Report (Stage 3A), Document No. 5E1-098-R101, Rev P2.

(11) *ARV Lines Plan*, Drawing No. 5E1-100-D001, Rev P1

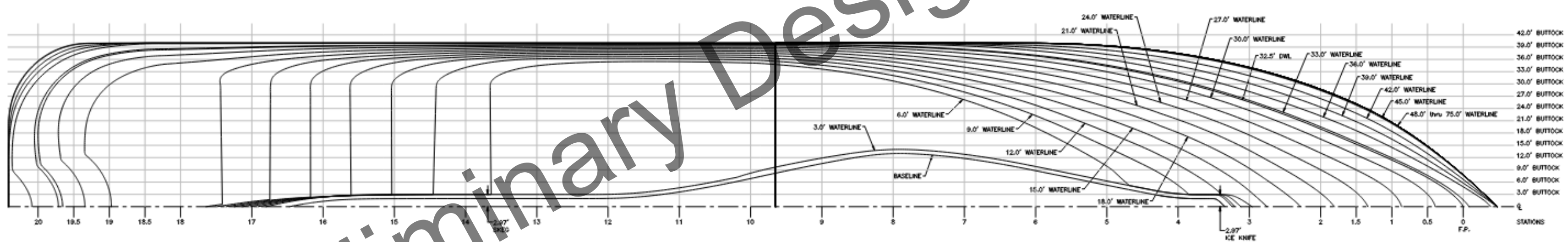
10. Appendix 1: Lines Plan



Body Plan



Buttock Lines



Waterlines